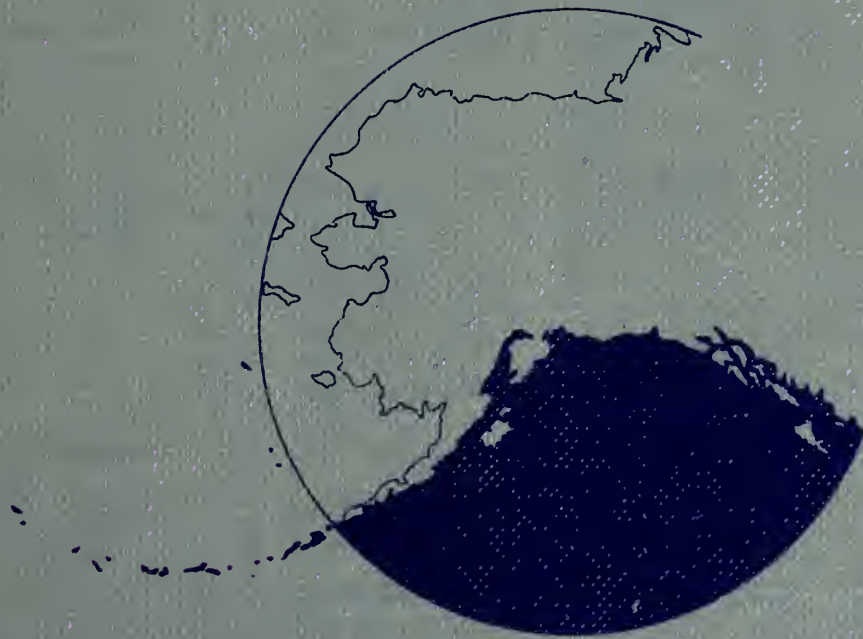


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The Gulf of Alaska

Physical Environment
and
Biological Resources






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The Gulf of Alaska





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The Gulf of Alaska

Physical Environment and Biological Resources

Edited by Donald W. Hood and Steven T. Zimmerman



U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Ocean Service
Office of Oceanography and Marine Assessment
Ocean Assessments Division
Alaska Office



U.S. Department of the Interior
Minerals Management Service
Alaska OCS Region

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Foreword

In response to President Nixon's 1974 national goal of attaining energy self-sufficiency by the end of the 1980s, the nation's outer continental shelf (OCS) regions were targeted for immediate petroleum development. Because a large proportion of the nation's OCS is located adjacent to Alaska and because this area was estimated to contain vast quantities of both oil and gas, development of Alaska's OCS resources was given high priority. The Gulf of Alaska in particular was identified as very promising and, in 1974, it was the first Alaska area to be considered for leasing by the Bureau of Land Management.

Although it was recognized that the development of energy resources on the Alaska OCS was essential to the national interest, it was also recognized that this development could endanger Alaska's marine environment and its living resources. There was a question concerning the extent to which oil and gas development would effect the environment. As a result of the public concern about the potential effects, the Department of the Interior's manager of the OCS leasing program (then the Bureau of Land Management and now the Minerals Management Service) initiated an environmental studies program which was designed during a series of planning meetings held by both the BLM and NOAA in 1974. The program became the Alaska Outer Continental Shelf Environmental Assessment Program (OCSEAP). This program was managed by the Department of Commerce (through the National Oceanic and Atmospheric Administration) as part of an interagency agreement with the Department of the Interior's Minerals Management Service. The study, which started in 1975, was multidisciplinary in design. This approach was necessary in order to provide the Secretary of the Department of the Interior, other decision makers, and members of the public with a source of information to use both for managing OCS oil and gas development and for minimizing potential effects on both the marine and the coastal environments.

The data that were collected and analyzed under the OCSEAP program substantially aided the decision makers in the design and execution of the leasing program on the Alaska OCS. From 1975 to 1985 there were over 100 studies either directly or indirectly applied to Gulf of Alaska issues. Numerous scientists from a wide range of disciplines participated in these studies. The area they investigated was found to have one of the richest assemblages of biological resources on the Alaska outer continental shelf.

Prior to the advent of OCSEAP, much of the data were collected by those agencies that managed the commercial fisheries, and integrated multidisciplinary studies had never been performed. By 1982, six lease sales had been held in the Gulf of Alaska, and the subsequent exploratory drilling had resulted in over 20 dry wells. This lack of success dampened enthusiasm and contributed to a shift in emphasis away from this area to other OCS regions of Alaska, namely the Bering, Chukchi, and Beaufort Seas. However, the information collected in the Gulf of Alaska under OCSEAP has contributed greatly to the advancement of knowledge about this rich marine environment.

Based largely on the results of OCSEAP studies, this volume constitutes the most current and the most comprehensive description of the OCS physical and biological environment in the Gulf of Alaska. It provides a consolidated source of scientific data and information previously unavailable for the Gulf of Alaska and it will be of great use to the scientific community as well as to resource managers for many years.

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Office of Marine Assessment
National Ocean Service
National Oceanic and Atmospheric Administration
Department of Commerce

Preface

“To the majority of mankind... the sea is little else than a vast abyss without limits or bottom”

Élisée Reclus (1873)

Much has been learned of the oceans in the century since those words were written. But until the 1960s, the Gulf of Alaska remained largely a frontier, and knowledge of it came mainly from expedition reports, the yearly cruises of fishery research vessels, and from the lonely vigil at the Canadian Ocean Weather Station ‘P’.

Following Alaska’s admission to statehood in 1959, several geographically limited studies were conducted in the Gulf. Most of these studies were in response to events such as the Great Alaskan Earthquake of 1964 and the proposed development of a petroleum loading facility at Port Valdez. However, it was not until the inception of the Outer Continental Shelf Environmental Assessment Program (OCSEAP) in 1974 that attempts were made to undertake a truly comprehensive examination of the oceanography of the Gulf of Alaska.

OCSEAP was an outgrowth of President Nixon’s *Project Independence*—a program whose goal was to make the United States self-sufficient in oil production. Following the call for *Project Independence*, interest in the Gulf of Alaska ran quite high because Alaska’s first producing oil fields had been developed there—near Katalla in the eastern Gulf in 1902 and in Cook Inlet several years later. In anticipation of the oil and gas leases for the outer continental shelf, which had been scheduled for the northeastern Gulf of Alaska in 1976, the Bureau of Land Management (BLM; now the Minerals Management Service—MMS) asked the National Oceanographic and Atmospheric Administration (NOAA) to undertake a research program that would determine resources that would be at risk if oil development began in that area. OCSEAP grew out of this cooperative effort between NOAA and MMS.

Most of the early OCSEAP work took the form of broad-scale environmental assessments—either extensive plant- and animal- distribution studies or descriptions of the physical, chemical, or geological properties found over wide geographic areas. Much of this research, because it was ‘mission-oriented’ in style and therefore not easily publishable in scientific journals, has since languished in the gray literature—buried in quarterly or annual reports, summarized in difficult-to-obtain synthesis reports and environmental impact statements, or archived in file drawers.

It is to the credit of the early leaders of OCSEAP that they recognized the problem of gray literature and required that the data collected be archived in repositories such as the National Oceanographic Data Center, the National Geophysical and Solar-Terrestrial Data Center, and the National Institutes of Health. But even though the data are available, recovering them is a lengthy process that is not undertaken by many scientists—especially those just entering the field or those seeking quickly available information.

That, then, is the purpose of this volume: to provide an authoritative, comprehensive, and readily available reference for those wishing to acquaint themselves with what is currently known about the Gulf of Alaska. We asked knowledgeable scientists to synthesize and summarize what is known about their research disciplines in a manner that is understandable to the non-specialist.

To help in this regard, a glossary of difficult-to-find terms has been included. We have also asked the authors to document extensively the sources of their information, particularly those sources where the information and data were still contained in unpublished documents. There will be gaps in such an endeavor and, because not all insights will survive the summarizing process, some specialists may feel the treatments are incomplete. It is our hope, however, that this book will be of value in providing both a beginning point for the newcomer and a ready reference for the academic veteran of Alaska’s southern coast.

The roots of this book can be traced back to the establishment of OCSEAP and to the millions of dollars worth of oceanographic research that the program supported in the ensuing years. But the final form of this book was influenced by the fact that none of the Gulf's lease sales ever yielded commercial quantities of gas or oil. As a result, oil-industry interest in the area was virtually gone by the early 1980s, and OCSEAP's research in the region nearly ceased.

Concurrent with the *de facto* completion of OCS research in the Gulf of Alaska was the publication, in 1981, of *The Eastern Bering Sea Shelf: Oceanography and Resources*, edited by D.W. Hood and J.A. Calder. The purpose of that two-volume treatise—also OCSEAP-sponsored—was to compile current information about the eastern Bering Sea shelf. The success of that endeavor, as measured by demand and references to it in the literature, led us to consider preparation of a similar treatise for the Gulf of Alaska. We felt that the largely completed nature of OCSEAP-funded research in the Gulf of Alaska would allow a more broadly topical and integrated approach than had been possible in the Bering Sea treatise, where much of the research was still underway when the document was being written.

Approval to begin this project occurred at research planning meetings held by MMS and NOAA in 1982. The initial funding was made available by MMS in 1983. In late 1983, the editors met in Friday Harbor, Washington to draw up a list of potential chapter titles and authors, and in March 1984, the first general meeting was held in Seattle to bring together the prospective authors. At this meeting, the structure and overall purposes of the project were defined, and the general outlines of individual chapters were finalized.

In January 1985, a second general meeting was held so that the authors could both verbally and graphically present drafts of their chapters. Discussions at this meeting focused on how each chapter might be integrated and cross-referenced with the others. During the following months, drafts suitable for peer review were prepared. During summer and fall of 1985, the editors were busy marking up manuscripts and involved in dialogues with reviewers and authors.

By the end of 1985, virtually all of the final drafts were complete. In the meantime, Northwest Cartography, Inc. was retained to undertake the technical editing and graphics production, and to prepare the book for printing. By late 1986, this process was complete, and the book was ready for printing.

This compendium of research could not have been brought to fruition by the two editors alone. We are pleased to acknowledge the efforts of many others who contributed their energies to this project, and without whom the book could not have been completed. Foremost among these is Laurie Jarvela, who was involved in the project from its inception, and who has served as the OCSEAP project manager. Others who encouraged and supported the production of this volume include the three directors of OCSEAP since 1981—Herbert Bruce, Jawed Hameedi, and Robert Bunney. They are joined by the two managers of BLM's (later MMS's) Alaska Studies Program who served during that same period—Jerry Imm and Cleveland Cowles.

Each of the reviewers who provided detailed comments on the chapters are also gratefully acknowledged here, as are the efforts of Betty Hood, Heidi Sickles, Cheri Hendren, and Billie Barb who attended to the many administrative matters that arose during the project. The outstanding efforts of Northwest Cartography, Inc., led by William E. Shiels, Project Manager, are also gratefully acknowledged.

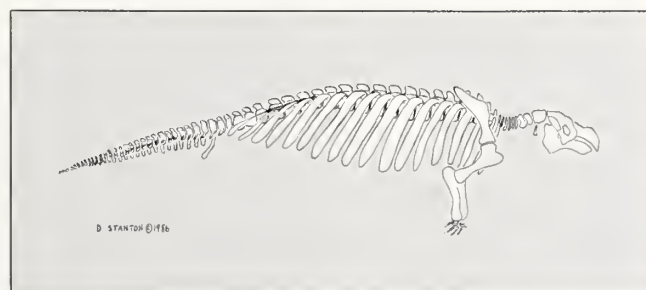
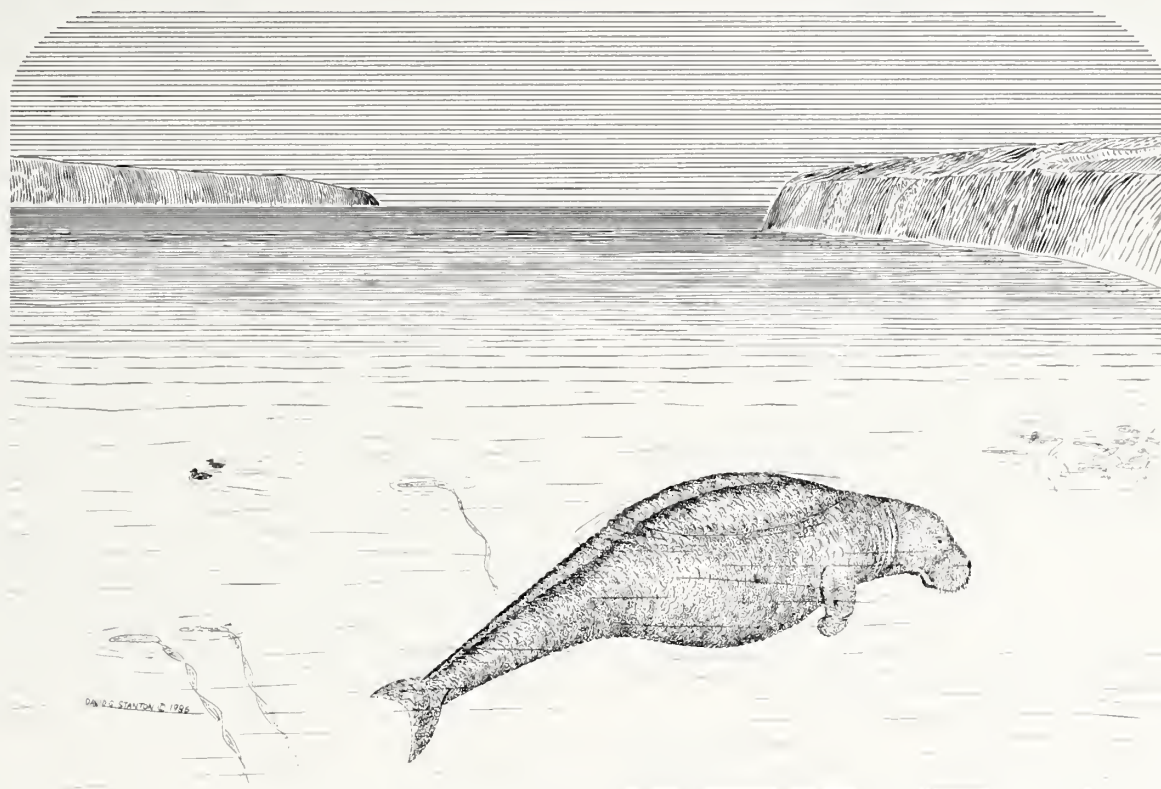
DONALD W. HOOD

STEVEN T. ZIMMERMAN

Dedication

Steller Sea Cow

Gentle Martyr to Northern Discovery



Steller Sea Cow (*Hydrodamalis gigas*)

Discovered 1741

Extinct 1768

Advances in human understanding are often achieved slowly, and man's desire to exploit new frontiers has nearly always exceeded his attempts to understand them. So it was with the Steller sea cow. The existence of this behemoth was documented by a single scientist on a single voyage of discovery. Before Western man had even a slight understanding of the animal it was gone, consumed as part of the chase after otters and seals in a newly discovered territory.

This volume is dedicated to the memory of the Steller sea cow. We hope that the information synthesized herein will provide a basis to better understand the important links binding all the species that remain in northern waters.

Features of a Northern Sea Cow as described by Georg Wilhelm Steller

Hydrodamalis gigas

Order: Sirenia Family: Dugongidae

Size: Length—to 35 ft; weight—to 10 t; girth—to 25 ft; heart—18 kg; stomach—2 m long by 1.5 m wide; length of intestinal tract—152.6 m; body fat—up to 16.5 cm thick.

Head: Appearance likened to that of Buffalo; long snout with bristles around mouth; double, bifurcated lips; small eyes; no external ear.

Forelimbs: Sixty-one centimeters in length, terminating in skin-covered stubby forefeet; bristles on bottoms of forelimb termin instead of external digits or nails.

Hindquarters: Horizontally flattened tail fin in place of hind limbs.

Dentition and nutrition: No teeth, but broad, furrowed, horny, gum plates covering palate and anterior part of mandible. Herbivorous dietary preference for selected species of seaweed, including *Nereocystis* and *Laminaria*.

Reproduction: Low reproductive rate; only one young born at a time; gestation period presumed to be more than a year; dual mammae; behavioral indications of monogamy; conjugal courtship.

Social features: Observed to travel and forage as family units of three (male, female, and small calf) within small herds; docile, passive temperament except when injured or harrassed.

Discovery and Natural History

Western man's encounter with the Steller sea cow happened quite by accident, and the experience might never have been recorded but for the presence of Georg Wilhelm Steller, ship's surgeon and naturalist aboard the Russian ship *St. Peter*. While sailing home in 1741 from a voyage in the North Pacific Ocean, the scurvy-scourged crew aboard the *St. Peter*, under the command of Vitus Bering, was shipwrecked on a small island (later known as Bering Island) 100 miles from Amchitka Island. The already tattered ship was wrecked almost beyond repair, necessitating reconstruction through the long winter. The first days after landing saw the death of Captain Bering and many of his crew as a result of sicknesses caused by poor nutrition and foul water aboard the *St. Peter*. The survivors initially obtained adequate food from the otters, seals, and vegetation found close at hand, but as time went on this became more difficult, and hunger began to invade the camp.

However, in nearby shallow waters the crew noticed large animals grazing in "sea cabbage meadows." These enormous creatures were a species of sirenian mammal. When feeding in the shallows, the animals appeared much like overturned boats, with their broad backs fully exposed above water. Although these docile animals could be stroked as they calmly grazed in their slow, bovine manner, the huge bulk and fierce struggle that occurred when the animals were 'hooked', along with their vigorous attempts to save each other, made capture difficult. After many failures in which wounded animals escaped, a man in a rowboat finally managed to use a large hook forged from some of the ship's metal to harpoon an animal. The attached line held by thirty men on shore connected predator and prey for a lengthy tug-of-war until finally the sea cow was dragged ashore and butchered. In later struggles to beach the sea cows, the impaled animals' companions, as a group, tried to dislodge the harpoon, break the rope, and disrupt the men's efforts to bayonet, club, and knife the struggling animal. The sea cows provided a savory meat and sweet oil, which enabled the 45 surviving sailors of Bering's last cruise to complete the reconstruction of the wrecked *St. Peter* and return home singing the praises of a bountiful treasure in sea otter and seal furs and of the food provided by the gentle Steller sea cow.

While awaiting reconstruction of the *St. Peter*, Steller painstakingly documented in Latin his dissections of a female sea cow along with other unique observations he made during his ten-month stay on Bering Island—observations that included the famous ornithological finds of the rare sea eagle and spectacled cormorant.

Evolutionary Speculations

Origin

The sirenians are believed to be descended from a hoofed beast that probably lived during Paleocene time roughly 50- or 60 million years ago. Their common ancestor might have resembled a primitive Egyptian animal (*Moeritherium*), which was the size of a pig and which had the lifestyle of a hippopotamus. Only two families of Sirenia exist today, both of them tropical forms: the manatees (Trichechidae) of the Atlantic and Caribbean, and the dugong (Dugongidae) of the Indian Ocean and waters of Africa and Australasia Indo-Malaysia.

Largest of any sirenian, the Steller sea cow was the only member of the dugong family to adapt to cold water. *Hydrodamalis*' ancestral stock migrated to the Pacific, where it evolved during the Pliocene and Pleistocene epochs by adapting both to cold water and to a diet of coastal algae species. As teeth gave way to broad palatal plates suited for grinding soft plant material, slender finger digits were also replaced by stubby, bristled forefeet that facilitated movement and helped tear kelp from along the bottoms of shallow coastal inlets.

Distribution

It is conjectured that the Pleistocene distribution of *Hydrodamalis* might have coincided with that of the sea otter, which ranged along the coast of the North Pacific Ocean from Japan to Baja California. A supportive ecological tie existed between the otter and sea cow in coastal habitats, in that the otter was a natural predator of the sea urchin, which competed with the sea cow for kelp.

The sea cow's adaptation to cold water may have begun in Californian latitudes during a late Miocene interlude of presumed cooling. The sea cow grazed along the California coast as recently as 20,000 years ago, before it began to die off for reasons that are still not clear. By the eighteenth century, however, its last bastion of survival was the protective shallow waters around the Commander Islands (Bering Island and Copper Island).

Skeletal remains of three *Hydrodamalis gigas* specimens were found in 1969 in a small interglacial deposit on Amchitka Island, Alaska. This was the first discovery of this species in Pleistocene deposits outside the Commander Islands. This finding suggests that the sea cow might have been widely distributed in the Aleutian Islands and could conceivably explain both the rapid westward migration of the Aleut and the disappearance of the sea cow from the Aleutian Islands. The discovery also gives evidence that the water was apparently warm enough to sustain the kelp growth required to support the sea cow, despite the icecaps which occurred on at least some of the Aleutian Islands. Although it remains a puzzle as to why the bones of *Hydrodamalis* have not shown up in the Aleut middens, favored explanations are insufficient excavation or submergence of older sites with rising sea levels.

Disappearance

After the *St. Peter's* shipwreck survivors returned home in 1742, they spread the word of their serendipitous discovery. Soon the Commander Islands became the annual winter headquarters for fur hunting expeditions that subsisted on sea cow meat for months at a time. The killing of the last Steller sea cow was recorded in 1768, at the end of an unregulated process of wasteful slaughter in which it was estimated that only one in every five animals was actually consumed. The rest of the wounded animals escaped to the open ocean, where they died of their wounds. Although it is possible that this giant sirenian was on its way to extinction before the intervention of modern man, the hunting pressure that led to its extinction a mere 27 years after its discovery is unprecedented in the history of man's interaction with large mammals.

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The Gulf of Alaska

Section 1

Introduction

Donald W. Hood

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Roll on, thou deep and dark blue ocean – roll!
Ten thousand fleets sweep over thee in vain;
Man marks the earth with ruin – his control
Stops with the shore.

Lord Byron (1788–1824)

Introduction

Though ten thousand fleets, both peaceful and war-minded, may fail to change powerful ocean processes, the collective waste-making capacity of nearly five billion people who impact earth's shore does make inroads. No longer can man's indiscriminate use of earth's resources be ignored. It is the responsibility, and privilege, of marine scientists/philosophers to explore and understand how the natural processes of the ocean function—and to share their understanding with ocean users and managers.

As a highly emotional and often irrational being, man tends to follow the swing of a giant pendulum in extremes of attitude towards environmental issues. Compare, for instance, the historically unregulated exploitation of marine mammals with today's general moratorium on their use. Or compare the nearly uncontrolled ocean dumping of wastes in the past with some of today's tightly restrictive practices. Clearly, well-informed management of earth's resources is needed to avoid the mistakes that are both environmentally and economically costly. Under utilization can be as inexcusable as over utilization if it is at the expense of other resources.

Sir Francis Bacon wrote, "Nature, to be commanded, must be obeyed."^a But man is often unwilling or unprepared to obey. Much of the problem rests with our limited understanding of how nature works. An in-depth understanding requires insight, perseverance, and the resources required to investigate. The particular challenge of understanding how the ocean functions requires a long-term commitment on the part of highly skilled scientists who must often cross conventional disciplinary boundaries in applying the most advanced technology towards goals not always discernible to the unskilled.

The terms 'mission oriented' or 'applied research' have evolved to describe research which is financed by industrial or government entities seeking to further specific goals. These terms reflect society's skepticism concerning investi-

gations proposed "merely for the sake of knowledge." Frequently the limited perspective of these 'mission-oriented' studies has resulted in a less than adequate understanding of ocean processes: studies have often been incomplete, parochial in scale, or have been inadequately or improperly reported. It is curious how goals that sidestep basic understanding can be justified in studying an ocean that works as an integrated system. A case, perhaps, of trying to command without a willingness to obey....

This book attempts to provide a comprehensive and integrated summary of the available oceanographic data from sources encompassing not only the historic and traditional literature, but also unpublished reports and material from relevant disciplines of natural science. This introductory chapter provides an historic and scientific framework for the Gulf of Alaska, intended to orient the reader toward the subject matter that will follow. Initially, prominent geographic and oceanographic features of the Gulf of Alaska are discussed, then geographic orientation, maps, and descriptions of each region are provided. To lend perspective on the historical development of scientific knowledge, a background summary describing the course of scientific inquiry—beginning with the early period of discovery and settlement—is provided. Then, the exploratory and early development phases of research in the region are summarized. Finally, the chapter closes with a section reflecting on the present level of understanding of this region and suggesting areas of research which might be undertaken to enhance our understanding and use of the Gulf of Alaska.

Prominent Geographic and Oceanographic Features

The topography along the Gulf's continental margin is extremely irregular, reflecting both tectonic and glacial influences. It includes many of the most spectacularly scenic coastal features on the North American continent. Contrib-

uting to the overall beauty of the region are such areas as the Misty Fjords National Monument near Ketchikan; Glacier Bay National Park and Preserve in the northern panhandle; the prominent scenic Mendenhall, Muir, Malaspina, and Columbia Glaciers; glacial fjords such as Tracy and Endicott Arms, Taylor Bay, and the recently glacially blocked Russell Fjord; and many mountainous islands and other coastal vistas, such as Mount Pavlof on the Alaska Peninsula. Dominating the coastal horizon of the northeast Gulf, whether seen by air or by sea, are the imposing mountain peaks of Mount Fairweather (4,663 m), rising abruptly from Glacier Bay, and Mount St. Elias (5,489 m) near Icy Bay.

As one of the most active meteorological regions on earth, the coastal area is characterized by a very severe and variable climate, caused primarily by the passage of storm systems along a well-defined Aleutian storm track. Dominant and often severe winds gust from the south along the eastern Gulf, prevail easterly in the central Gulf, and are highly variable from the western Gulf near the Aleutian Islands and associated mountain ranges. The area is frequented by ocean storms with wave heights of seven or more meters—as severe as any in the Northern Hemisphere (Brower, Diaz, Prechtel, Searby, and Wise 1977; Danielsen, Burt, and Rattray 1957). In these waters, catastrophic losses to shipping have been common and are well documented (McDonald 1984). A most notable disaster was the sinking of the S.S. *Pennsylvania* in January 1952. The ship went down with 45 men aboard in an unusually severe storm with gale winds of nearly 60 kt and wave heights of 15 m (Danielsen *et al.* 1957).

Storm prediction in the Gulf is particularly complicated, partly owing to lack of sufficient weather reporting stations but also to the configuration of the coastal mountain ranges. Many storms stall for periods of days and sometimes dissipate within the Gulf. Ocean temperatures in the winter are generally warmer than the surrounding land masses, leading to persistent fog coverage. Annual precipitation is about one meter, although combinations of more than eight meters of rain and snow are not uncommon in the coastal mountains (Wilson and Overland, Ch. 2, this volume).

Coastal runoff finds its source in the snow and ice stored in the Alaska coastal ranges, together with high but variable rainfall. This runoff causes salinity gradients which drive the Alaska Coastal Current, a current that extends from British Columbia, Canada to Unimak Pass in the Aleutian Islands. Such currents are rare in the world's oceans but may be duplicated off the Norwegian coast (Reed and Schumacher, Ch. 3, this volume). Flow in the Alaska Coastal Current is between 0.1- and 1.2×10^6 m³/s at speeds of 13 to 133 cm/s; maximum values occur in the early fall near the Kenai Peninsula.

Formed by the bifurcation of the North Pacific Current near 50°N, the Alaskan Current lies offshore from the Alaskan Coastal Current and is the dominant transport system of surface waters in the Gulf. Its movement parallels the shelf break at velocities between 30 and 100 cm/s, with highest speeds observed west of Kodiak Island where it becomes the Alaskan Stream, as the width narrows from about 400 km in the east to 100 km in the west. In contrast to the upwelling situations off the coast of the western United States,

downwelling occurs in the Gulf of Alaska when dominant easterly winds converge the surface waters near the shore (except for short periods of the summer when weak westerlies occur).

On casual observation it would appear that the downwelling effect of cross-shelf coastal transport and subsequent sinking would cause the depletion, rather than the supply, of nutrient-rich deeper waters to the productivity regime of the continental shelf. Other physical processes, however, provide a very rich environment for the support of abundant and diverse biological species in most regions of the Gulf (Sambrotto and Lorenzen, Ch. 9, this volume).

Another important feature of the Gulf that influences the circulation and transport of its waters is the persistent occurrence of an atmospheric low over the Gulf during the winter, which causes a cyclonic gyre in the wind system. This leads to a divergence in Ekman transport, causing onshore transport of surface waters near the coast and upwelling in the central Gulf. Favorite (1970) estimates a five-fold increase in the circulation of the central gyre between summer and winter based on wind-stress transport.

The system is driven when dry, cold, Arctic air masses from the continents flow out over the warm Gulf waters where heat and moisture are rapidly exchanged. Most pronounced in winter, the heating leads to vertical convection with attendant horizontal divergence and cyclonic vorticity. This major atmospheric influence, coupled with other phenomena, resupplies surface nutrients to the highly productive continental shelf and coastal regions on both an annual and seasonal basis.

The deep waters of the Gulf of Alaska contain the world ocean's most developed oxygen minimum zone and the highest concentrations of dissolved silicate, phosphorus, and nitrate (Mantyla and Reid 1983). As is the case elsewhere in oceanic deep water, the oxygen and nutrient concentrations result from the decomposition of surface-fixed organic matter. The concentrations differ markedly, however, and do not result from higher productivity in the surface waters. Rather, the cause is the slow circulation of deep waters from other oceans which enter the Gulf of Alaska. The Gulf contains the oldest abyssal waters in the world ocean in terms of the greatest distance removed from bottom-water formation and ventilation (Reeburgh and Kipphut, Ch. 4, this volume). Nutrient concentrations that do not usually occur above the 1,000-m depth in the North Atlantic Ocean, for example, may be found at less than 250 m in the Gulf of Alaska (Hood 1978).

Controlled by movement of the Pacific Plate in a north-northwesterly direction at speeds of about 5 to 7 cm/yr, the Gulf of Alaska region is tectonically one of the most active in the world. The Pacific Plate is outlined along the Aleutian Trench by seismic zones which dip to 250 km beneath the Alaska Peninsula, Cook Inlet, and Prince William Sound. Movements of the Pacific Plate manifest themselves in numerous earthquakes, some of which reach extraordinarily high magnitudes about once each century (*e.g.*, $M_W = 9.2$ registered by the Great Alaskan Earthquake of 1964, one of the largest ever recorded worldwide; see Jacob, Ch. 6, this volume). Local devastation caused by shaking, subsidence, landslides, avalanching, seiches, and soil liquefaction

is accompanied by tsunamis that can strike as far away as California, Hawaii, and Japan. Volcanic eruptions are also frequent, the most recent occurring at Mount Augustine in lower Cook Inlet in March 1986.

Although the long-term geomorphic evolution of the Gulf of Alaska basin has been controlled by tectonism (localized uplift of up to 15 m occurred during the Great Alaskan Earthquake of 1964), the modern seafloor owes its geomorphology more to glaciation than to tectonism. Grounded ice extended to the shelf break at least once during Pleistocene time, covering most of the shelf and sculpturing broad flat banks and deep elongated troughs. During the advance of the ice cover, glacial-marine and glacial-fluvial sediments were deposited on most of the shelf.

After the ice retreated, the area was inundated by the sea, and gradually the present environment was established. Remnant glaciers, aided by a few large rivers, still contribute a heavy sediment load to the coastal regions. A strong vertical gradient of suspended sediment exists over much of the shelf. Surface coastal waters are often so heavily loaded with suspended sediments that they limit light transmission and thus inhibit primary production. This is particularly true in embayments and glacier-fed fjords. Since sediment distribution varies widely throughout the Gulf (Hampton, Carlson, Lee, and Feely, Ch. 5, this volume), an understanding of the complex sedimentary processes can be gained only through careful study on a region-by-region basis.

Primary production—the dominant source of energy for biological systems of the marine environment—is very high in the Gulf of Alaska when compared with other oceanic regions. In some coastal regions, such as lower Cook Inlet and the Kenai shelf, daily values of over 7 g C/m² have been measured and annual values over 300 g C/m²y have been estimated. Frequent storms, high tidal energy, and persistent currents appear to be the primary mechanisms that enhance vertical mixing along the coastal shelf. This mixing supplies essential nutrients to the euphotic zone in support of high production throughout the summer season. In the central oceanic region of the Gulf, yearly production may exceed 100 g C/m². Here productivity is not limited by nutrient supply (which always remains high in the euphotic zone), but by herbivores. Zooplankton, in particular, can graze down enough phytoplankton to result in chlorophyll *a* values in the water column of less than 1 mg/m³ (Sambrotto and Lorenzen, Ch. 9, this volume).

Zooplankton abundance varies both geographically and seasonally. In the open ocean, at Ocean Station 'P', abundance values ranging from 1.5 g/m² in winter to 30 g/m² in summer have been observed. In the deep (>900 m) coastal waters of Prince William Sound, values ranged from 1,320 g/m² in winter to 1,600 g/m² in summer. Zooplankton production on the shelf probably does not exceed 60 g C/m²y, resulting mostly from growth of 30 dominant species (Cooney, Ch. 10, this volume).

Phytoplankton production in the temperate, fertile waters of both the continental shelf and the coastal regions of the Gulf provides the basic energy that supports a varied and abundant pelagic and benthic biological community.

Probably the most intensely studied area of the entire region is lower Cook Inlet, which includes Kachemak and Kamishak Bays. In all aspects, this large estuary benefits from the interaction of vigorous physical factors such as high tidal currents and supporting offshore conditions (Sambrotto and Lorenzen, Ch. 9, this volume). These factors lead to an unusually rich biological regime.

While lower Cook Inlet owes much of its source of energy to high primary production (7.8 g C/m²d from May to August), allochthonous carbon is also derived from both land runoff and coastal macrophytes. This contribution to the benthic detrital load amounts to an annual contribution of 60 g C/m² in Kachemak Bay, 17 g C/m² in the central Inlet, and 40 g C/m² in Kamishak Bay. Because of the vigorous currents and coarse bottom sediments here, most of the macrobenthic biomass (52–400 g C/m²) is contributed by suspension-feeding benthic organisms dominated by echinoderms and mollusks. Other areas which have been examined in detail—such as the eastern shelf of the Kodiak Archipelago—show a somewhat lower benthic biomass but are still rich in epifaunal organisms, particularly Tanner crabs (Feder and Jewett, Ch. 12, this volume).

The Gulf of Alaska contributes significantly to the world fisheries. It is the main oceanic habitat for most North American salmon stocks, as well as for some Asian stocks, for a significant part of their life cycles. Salmon constitute about 95% of the large epipelagic fish caught in offshore waters, leading all other species in economic importance (Rogers, Ch. 15, this volume). Major fisheries for demersal species include those for Alaskan pollock, sablefish, Pacific cod, Atka mackerel, flatfish, Pacific ocean perch, and halibut. Except for Pacific ocean perch, the present catch of all species appears to be stable or on a slight increase, yielding a total annual combined catch of about 3.6×10^5 metric tons.

A relatively new fishery for Alaska pollock in Shelikof Strait is on the incline and is expected to increase the total annual catch in the Gulf significantly. This, however, must occur in face of a severe decline in the shellfish fishery. King crab catch in Kodiak was 9.07×10^3 mt in 1980 but had fallen to 50 mt in 1983, and the shrimp catch reached a high of 5.23×10^4 mt in the northern Gulf in 1972, but had declined to 5×10^3 mt in 1982.

The 'boom and bust' nature of fisheries in the Gulf of Alaska is closely associated with several environmental factors. Our inability to predict potential harvests (a failing of fishery biologists throughout history), is well illustrated in the Gulf of Alaska fishery (OCSEAP Staff, Ch. 14, this volume) and indicates our continuing lack of an overall understanding of oceanic processes.

Marine birds and mammals abound in the Gulf. Over 20 million waterbirds visit the deltas of the Copper and the Bering Rivers to fatten up and rest during spring migration. Dominant species include the western sandpiper, dunlin, and northern pintail duck—a favorite of waterfowl hunters. Over nine million seabirds representing 26 species nest in the Gulf, making it one of the largest marine bird resources in the Northern Hemisphere (DeGange and Sanger, Ch. 16, this volume). This combination of birds forms an important group of apex predators in the food chain. They consume ~

8.3×10^5 mt of their prey in nearshore and shelf habitats and 2.5×10^5 mt of prey in the oceanic habitat during the 120-day summer season.

The rich and diverse inventory of marine mammals includes seven species of large cetaceans, 12 medium and small cetaceans, six pinniped species, and one marine mustelid (Calkins, Ch. 17, this volume). These animals use the Gulf as a migratory corridor, as summer feeding grounds, or as a year-round range.

All seven species of great whales that inhabit the Gulf for some part of the year are on the endangered species list. The gray whale now appears to be reaching pre-exploitation population levels, although the Pacific right whale is at such low levels that recovery is uncertain. The marine mammals' food-consumption rate is estimated to be 7.8×10^6 mt/y, about 10 times that of birds or eight times the amount of carbon taken in the ground-fish harvest.

Areal Description

The northeastern extremity of the Pacific Ocean, bordered by the mainlands of British Columbia and Alaska, had not yet been identified as the Gulf of Alaska at the time that a now-classic volume, *The Oceans*, was published (Sverdrup, Johnson, and Fleming 1946). In early Russian history the waters bounding southern Alaska were known as Alaska Bay. This region—now recognized as the Gulf of Alaska—can be designated as lying north of 52°N and between about $127^\circ30'\text{W}$ on the east, where it meets the British Columbia coast, and 176°W on the west, near Great Sitkin Island in the Aleutian Islands. The arc formed between these longitudes by latitude 52°N extends nearly 3,600 kilometers. Its most northern extension is at about 62°N in Cook Inlet, near the city of Anchorage (note inside front or back cover for a detailed map of the Gulf of Alaska).

Included within these boundaries are the southern coast of most of the Aleutian Islands, the coast and offshore islands south of the Alaska Peninsula, (including the Shumagin and Kodiak Island groups), Cook Inlet, Prince William Sound, and the Alexander Archipelago. The area of the Gulf's continental shelf is estimated to be 3.69×10^5 km² (107,536 nmi²) (Lynde 1986), which is 16.9% of the entire Alaskan shelf (2,860,000 km² total) (McRoy and Goering 1974) or equivalent to 12.5% of the total continental shelf of the United States (3,860,000 km² total).

Regions of the Gulf of Alaska

Literature on the Gulf of Alaska is not consistent with respect to the boundaries that have been used to delineate regional areas. Standardized regional designations would not only reduce uncertainties for the reader, but they would allow investigators to compare data on an equal areal basis. In the absence of an existing set of regional areas, descriptive standards for the following four regions are defined here as a framework of reference for material presented in this book:

- 1) The western Gulf of Alaska begins at 176°W longitude, near Great Sitkin Island, and extends eastward

to Cape Igvak on the west side of Shelikof Strait at $153^\circ3'\text{W}$ longitude and $57^\circ25'\text{N}$ latitude (Fig. 1-1).

- 2) The central Gulf of Alaska extends from Cape Igvak eastward to Cape St. Elias at $144^\circ37'\text{W}$ longitude and $59^\circ48'\text{N}$ latitude (Fig. 1-2).
- 3) The northeastern Gulf of Alaska (NEGOA) lies between Cape St. Elias on the west and Cape Spencer at $136^\circ38'\text{W}$ longitude and $58^\circ18'\text{N}$ latitude (Fig. 1-3).
- 4) The southeastern Gulf of Alaska extends from Cape Spencer on the northwest to 52°N latitude on the Canadian mainland, near the south end of Queen Charlotte Island (Fig. 1-4).

The International North Pacific Fisheries Commission (INPFC) has designated specific areas within the 200-mile Fisheries Conservation Zone (FCZ) as fisheries management areas (Forrester, Bakkala, Okada, and Smith 1983). The INPFC partitions shown for the coastal area of the Gulf of Alaska in Figure 1-5 generally correspond to those regions listed above for the entire Gulf. Differences (other than the 200-mile limitation) are that the western Gulf region is equivalent to Areas 7B and 7C combined, except for a portion of 7B which falls into the Central Gulf region. The INPFC areas have been further classified into shelf regimes according to their distance from shore: inshore (shore to 50 m); inner shelf (50–100 m); middle shelf (100–200 m); and outer shelf (200–1,000 m). The area of each of these divisions has been carefully estimated (Lynde 1986); these data, presented in Table 1-1, indicate that the total Fisheries Conservation Zone (FCZ) of the Gulf is 3.69×10^5 km². The difference between the area of the FCZ as defined here and the area of the continental shelf as given by McRoy and Goering (1974) probably occurs because the FCZ includes only the area to 200 miles offshore, whereas the continental shelf includes all the area to the shelf break.

The western Gulf is characterized by steep rugged mountains (Fig. 1-6) that descend to the sea, a highly irregular coastline, and many islands and island groups. It includes Unimak Pass, gateway to the Bering Sea, and the Shumagin Islands. The coastline is heavily indented by inlets, fjords, bays, and many natural harbors. Occasional narrow beaches mark shallow-water habitats nestled between predominant stretches of rocky pinnacles and sea cliffs. The continental shelf south of the Alaska Peninsula is about 250 km wide, breaking rapidly to the Aleutian Trench and the abyssal plain (Wahrhaftig 1965). Circulation is dominated by westerly flow of the Alaska Coastal Current near shore and by the Alaskan Stream near the shelf break.

The Central Gulf encompasses the Kodiak Archipelago, Shelikof Strait, Cook Inlet, Prince William Sound, and the Copper River Delta and estuary. Cook Inlet is separated from Prince William Sound by the Kenai Peninsula, and it penetrates the Alaska mainland approximately 370 km toward the Alaska Range and Mount McKinley (6,194 m), the highest mountain in North America. The northern part of Cook Inlet, including Knik and Turnagain Arms, has a tidal range of about 9 m, one of the highest in the world. The Susitna River, with a drainage basin of 68,400 km² and average flow of 1,300 m³/s, is the largest river that drains into the Gulf of Alaska. Combined with the Knik and other smaller

ivers, the Susitna provides large quantities of freshwater that flow in a direction that opposes the tidal flow from the south. The result is strong horizontal stratification in the system north of the Forelands, with denser seawater occupying the eastern portion.

The highly productive southern portion of Cook Inlet is bounded by Kachemak Bay on the east, Kamishak Bay on the west, and Shelikof Strait to the south. The continental shelf in this region is about 220 km wide, reaching to the 600-m depth contour and the eastwardly shallowing Aleutian Trench. Here the Alaska Current sweeps westward along the continental shelf parallel to the Alaska Coastal Current which intensifies as it flows toward Shelikof Strait past the Kenai Peninsula and becomes known as the Kenai Current (Reed and Schumacher, Ch. 3, this volume).

Although the Copper River is best known as an important habitat for migrating birds, it is also a major route for anadromous fish between their freshwater spawning grounds and the sea. Prince William Sound, where Captain Cook and his flagship HMS *Resolution* first landed in the Gulf of Alaska, includes the Columbia Glacier and Port Valdez, site of the trans-Alaska pipeline terminal. The Great Alaskan Earthquake of 1964 was also centered in this region, at 61°N, 147°30'W, just north of Montague Island. During that earthquake, the land mass southeast of a line between this epicenter and Kodiak Island rose as much as 15 m, while land northwest of the line sank as much as 1.5 meters.

The northeastern Gulf of Alaska (NEGOA), which derived its designation largely from the Outer Continental Shelf Environmental Assessment Program (OCSEAP), has been the subject of extensive study in recent years due to the interest in oil and gas development. The region encompasses two of the world's largest individual glaciers, the Malaspina and the Bering, as well as many smaller ones that directly enter tidal waters or drain into the coastal domain. The continental shelf in this area narrows to less than 100 km on the east. The offshore currents are northerly in the east (as a result of bifurcation of the North Pacific Current), and then they turn westerly near Yakutat Bay. Near the coast, the freshwater-driven Alaska Coastal Current is well established by the time it flows north past Cross Sound (Royer 1982).

The southeastern Gulf of Alaska, consisting mostly of the Alexander Archipelago, is a labyrinth of inlets, passages, and fjords that exist among hundreds of forested islands. An annual rainfall of 100 to 200 inches (~2.5–5.1 m) is common in this region, and North America's largest icefields supply the many glaciers that empty their meltwater and sediments into the coastal regime. Currents offshore are northerly along a continental shelf that is less than 100 km wide. The oceanography of this complex region has received relatively little study.

Exploration and Early Human History

The first European to see the Pacific Ocean was Balboa, who claimed it for King Ferdinand of Spain in 1513 and named it the South Sea because of the orientation of the coast from which he observed it. Before Balboa's exploration there was little information written or transmitted

about the Pacific Ocean, despite the substantial knowledge that had been acquired by the Japanese, Malaysians, Polynesians, Incas, and Aleuts. Ferdinand Magellan was the first explorer to navigate around the world and, in 1581, became the first European to sail into the North Pacific. The next circumnavigator, Sir Francis Drake, explored the northwest coast of North America in 1578 as far north as the present state of Washington and claimed the west coast, which he called New Albion, for Queen Elizabeth.

After an initial voyage through the Bering Strait in 1728, Vitus Bering made The Great Northern Expedition in 1741, sailing aboard the *St. Peter* as far east as Cape St. Elias and landing on Kayak Island (Golder 1922, 1925). Meanwhile, the sister ship *St. Paul*, under the command of Lt. Alexsei Chirikov, became separated from the *St. Peter* and sailed to the lower tip of the Alexander Archipelago. This completed the discovery of the North American continent.

Some of the additional voyages made into the North Pacific during the discovery period included those by: Bezerra and Grijalva, 1532; Valle, 1536; d'Ulloa, 1539; Cabrillo, 1542; Mendaña, 1567–1569; Cavendish, 1586–1588; Mendaña and Quiros, 1595–1596; Quiros, 1605–1606; Spilbergen, 1614–1617; Hamel, 1653; Nowosilzoff, 1745; Byron, 1764–1766; de Pages, 1767; Wallis, 1766–1768; Carteret 1766–1769; Bragin, 1772; and Hecta and Ayala, 1775. Few of these voyages reached the northeast Pacific Ocean, however, and few had any impact on discovery in the Gulf of Alaska. Additional information on North Pacific expeditions is contained in Humboldt (1836–1839), Murray (1895), Beaglehole (1966), and Kenyon (1980).

During this early period of geographic exploration, mariners were actively seeking out new lands. They plotted the locations of islands and continental coastlines and described the hydrometeorological conditions they encountered. At the discretion of the ship's captain, data important to navigation were often entered into the ship's log, including information on winds, waves, currents, and variations in shoreline heights. Magellan, in the first of many efforts that would follow, attempted to measure the ocean depth; 2,500 ft (762 m) of manila rope was let out without reaching the bottom.

More serious scientific studies of the North Pacific Ocean began in about 1776 with the voyages of Captain James Cook (Rienits and Rienits 1968), who remains today (with the possible exception of Lord Nelson) the most famous of British captains. Cook's superb cartography, his acute and accurate observations, and his matchless seamanship set a standard for all to follow.

Cook's third voyage, in quest of a northwest passage between Baffin Bay or Hudson Bay and the North Pacific Ocean, first touched the North American continent at 44°33'N, on what is now the coast of Oregon. In his passage at night, Cook failed to discover the Strait of Juan de Fuca, an oversight which afforded his midshipman George Vancouver a later opportunity to explore this region. As he sailed further north, Cook named Cape Edgecumbe, Mount Edgecumbe, Cross Sound, Cape Fairweather, Mount Fairweather, and Mount St. Elias. He anchored to repair his vessel, the *Resolution*, in an area he named Sandwich Sound, now known as Prince William Sound.



Figure 1-1. Detailed map of the western Gulf of Alaska. (Map scale 1:3,125,000; approximately 1 inch to 49 miles.)

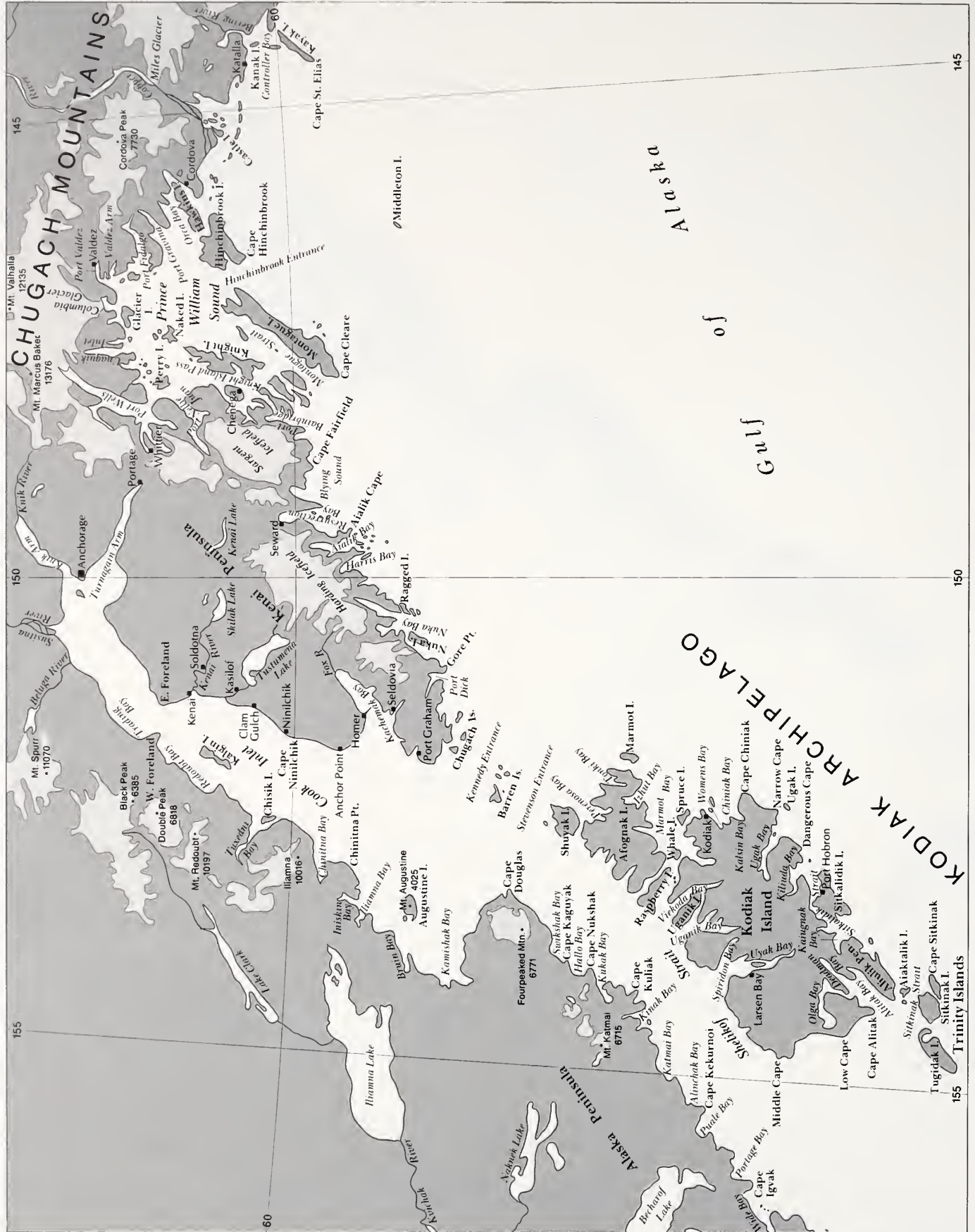


Figure 1-2. Detailed map of the central Gulf of Alaska. (Map scale 1:3,125,000, approximately 1 inch to 49 miles.)



Figure 1-3. Detailed map of the northeastern Gulf of Alaska. (Map scale 1:3,125,000; approximately 1 inch to 49 miles.)

On his journey westward, he explored Cook Inlet before continuing along the Alaska Peninsula to Unimak Pass and into the Bering Sea, also exploring the Bering Strait and Chukchi Sea. This completed the first recorded exploration of the Gulf of Alaska.

On returning from the Bering Sea journey, the *Resolution* called at the village of Unalaska, where Russian fur traders were well established and were able to add detail to some of Cook's charts of the North Pacific coastline. Cook's mariner skills and tenacity provided the information needed to establish the gross features of North American borders. During the next one hundred years, scientific investigations became a primary or secondary objective of many subsequent expeditions to the North Pacific. Detail continued to be added in the course of many voyages, sparked with courage and the same curiosity that has advanced our level of understanding to the present by verifying and correcting existing knowledge (Table 1-2).

Among the many voyages that added to our geographic knowledge of the eastern Pacific north of 40°N are two that are notable for their length and thoroughness: that of Ales-

sandro Malaspina, an Italian who sailed under the flag of Spain, and that of George Vancouver. Malaspina, with the ships *Descubierta* and *Atrevida*, spent 1790 and part of 1791 looking, as had so many others, for a passage into Hudson Bay from the Gulf of Alaska. The scientific discoveries that Malaspina made on this cruise were among the most important made under the flag of Spain.

Vancouver examined the west coast (New Albion) as far as the Alaska Peninsula with the *Discovery* and *Chatham* between April 1791 and October 1795 (Anderson 1960). As a result of his meticulous and painstaking efforts, Vancouver's explorations are now ranked among the best ever accomplished. In 1792 he passed through the Strait of Juan de Fuca, discovered the Strait of Georgia, and circumnavigated the island that now bears his name. It was during the 1793 exploration of the Alexander Archipelago that a party from the *Discovery* and *Chatham* became involved in the first recorded case of paralytic shellfish poisoning near what is now called Carter's Bay in northern British Columbia. After consuming mussels, John Carter, a crewman, died after all efforts to save him failed. Other cases have occurred even to

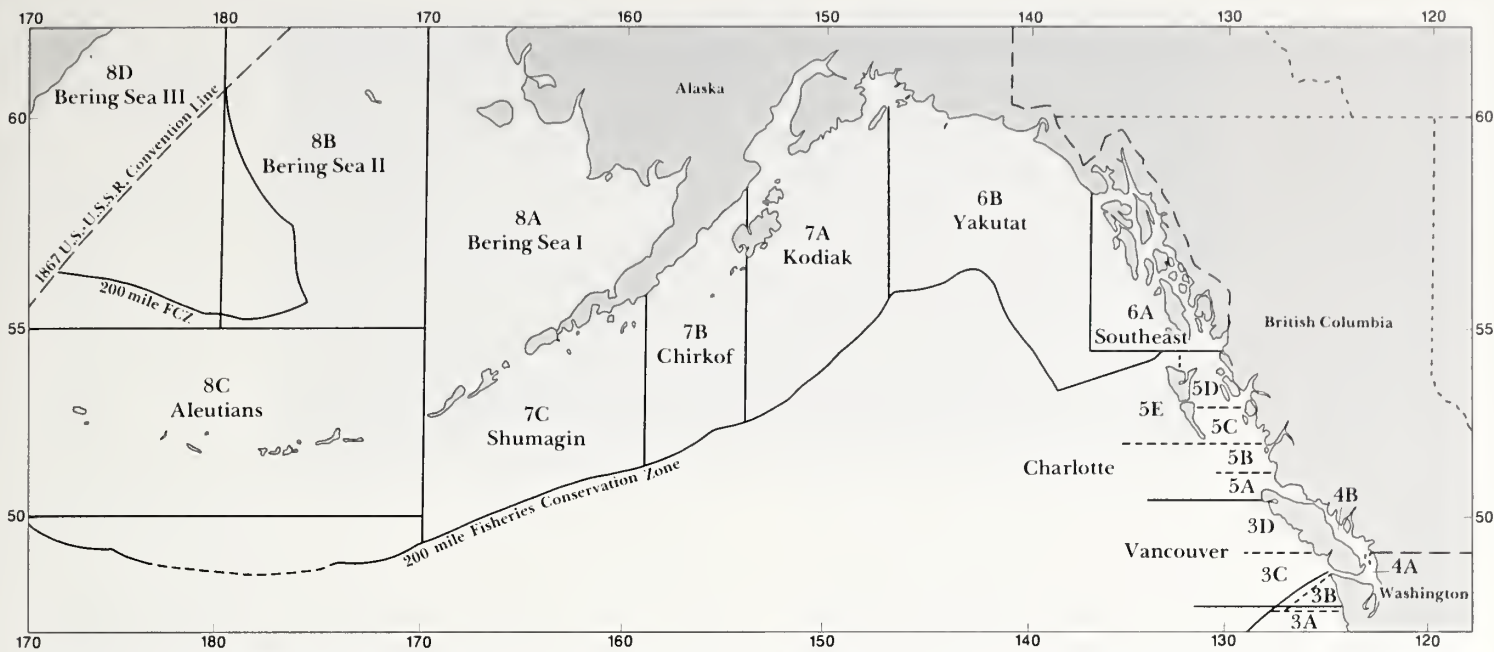


Figure 1-5. Pacific Marine Fisheries Commission and International North Pacific Fisheries Commission management areas for the Gulf of Alaska (from Forrester *et al.* 1983).

the present time. Vancouver continued to survey the west coast of America, reaching as far as Cook Inlet in 1794. As a result of Vancouver's work, this very complicated coast became so well documented that the notion of a passage through the continent was dispelled.

Early Human History

When Europeans first entered the coastal regions of the Gulf of Alaska, they found a diverse native population. Chugachimiut Eskimos inhabited Kodiak Island, the Alaska Peninsula, and northwestern Prince William Sound. The western Gulf region was occupied by Aleuts, who had settled as far east as the southwestern part of the central Gulf shores. Tanaina Indians were the principal inhabitants of Cook Inlet, and Athabascan-speaking Ahtna people were the principal inhabitants of the Copper River basin. The Eyak people were distributed from the Copper River Delta to the eastern part of Prince William Sound, which was also raided extensively by the Tlingits of southeastern Alaska.

Archaeological findings in Kachemak Bay (Yukon Island) indicate that this area was first occupied by Eskimos (from about 1500 B.C. to 1000 A.D.), and then by Athabascan Indians, who were probably ancestors of the Tanaina who moved into the coastal regions from Alaska's interior. The Eskimos of Kodiak Island subsisted primarily on salmon and marine mammals, but also consumed mollusks, cephalopods, and sea urchins when these species were available (Hrdlička 1941; Allen 1960; and Boucher 1960).

The great wave of European exploration and exploitation touched the Gulf of Alaska with the discovery voyage of Vitus Bering in 1741. Bering's discovery of Alaska was quickly followed by conquest and colonization of the entire area by Russia, which occupied the area for 126 years until its cession to the United States in 1867. The Russians generally

left the aboriginal Alaskans much as they had found them. An exception to this pattern was the Aleut inhabitants of the Aleutian Islands, the Alaska Peninsula, and some western offshore islands. Russian fur traders killed and enslaved many Aleuts in these areas, leaving the Eskimos along the Bering Sea and Arctic coasts, the Tanainas of Cook Inlet, the Athabascans of the central Gulf, and the Tlingits of Southeast Alaska relatively undisturbed.

Since the Russians were interested only in furs, they did not penetrate far inland and their principal settlements were along the Gulf of Alaska coast. In the spring of 1784 the first Russian colony was founded on Kodiak Island's Three Saints Bay. Hunting parties were dispatched to Prince William Sound and Cook Inlet the following year. In 1792

Table 1-1. Area of shelf regimes, expressed in square nautical miles, of the Gulf of Alaska INPFC fisheries management areas. Values in parentheses represent percent of total area within each INPFC management area (from Lynde 1986).

INPFC AREA	INSHORE Shore-50m	INNER SHELF 50-100m	MIDDLE SHELF 100-200m	OUTER SHELF 200-1,000m	TOTAL AREA
6A		9,823.4 ^a (58.02)	3,346.9 (19.77)	3,761.1 (22.21)	16,931.4
6B	2,465.9 (15.11)	1,457.4 (8.93)	9,143.8 (56.03)	3,252.3 (19.93)	16,319.4
7A		12,367.2 ^a (38.83)	15,483.6 (48.61)	4,000.3 (12.56)	31,851.4
7B	1,909.1 (10.87)	6,199.6 (35.30)	6,953.0 (39.59)	2,501.3 (14.22)	17,563.2
7C	2,871.2 (11.54)	8,894.6 (35.76)	10,325.5 (41.52)	2,779.7 (11.18)	24,871.0
All	7,246.2	38,742.2	45,352.8	16,294.7	107,536.4

^a Shore to 100 m all considered inner shelf.



Figure 1-6. Probably the first photograph of Mount Pavlof on the Alaska Peninsula (from Harriman Alaska Series of The Smithsonian Institution 1910, Vol. 4).

the settlement was moved to the present location of the city of Kodiak. A trading post established at Sitka by the Russian-American Company in 1799 was permanently settled five years later under the name of New Archangel. Other permanent Russian villages include Nikolski, Unalaska, Chernofski, and Belkofski in the Aleutians; and Kasilof, Ninilchik, and Kenai on the Kenai Peninsula. All that currently remains from the Russian period are some sturdy log cabins and a few Orthodox churches with their bulbous steeples and double-barred crosses.

Alexander A. Baranof, the first Governor of Russian America, was the most important and memorable individual in shaping early Alaskan history (Chevigny 1965). In 1799 he took possession of what is now called Baranof Island in the Alexander Archipelago. The present town of Sitka is located on the northwest corner of this Island. Here he began developing trade with natives, eventually extending his operations to such distant places as the Hawaiian Islands, Canton (China), Boston, and New York. Baranof died at sea in 1819 while returning to Russia. The Russian governors that followed were of lesser stature and left little mark on Alaska.

Under the congressional influence of William H. Seward, the United States Congress purchased Alaska from the Russians in 1867. Although Seward's purpose in promoting this acquisition was to enlarge the United States' strategic holdings in the Pacific arena, the congressional focus of interest at the time was on the area's vast resource wealth.

For nearly a third of a century following its purchase, Alaska was all but forgotten by the American people. The Russians had left nothing, and the Americans brought nothing other than a penchant for furs and whales. Then came the gold rush near the end of the nineteenth century, which marked the beginning of economic interest in Alaska. Discriminatory actions against Alaska as an 'incorporated territory', however, greatly limited self-government and were especially harmful to marine transportation interests. Until the beginning of commercial air service in 1940, maritime shipping was the only means of transportation between Alaska and the lower 48 states. The Merchant Marine Act of 1920 (also known as the Jones Act after its sponsor, Senator

Wesley Jones of the State of Washington) provided for the interchange of domestic or foreign carriers both on land and sea "except for Alaska." Passage of this strange law meant that all shipping in and out of Alaska had to be passed through Seattle before continuing to its destination. The resulting benefit to Seattle was at a very high cost to Alaska's development, because goods transported through Seattle then cost up to five times as much as they would have to or from other points in the Pacific (Gruening 1959).

Alaskan statehood in 1958 lifted many of the previous territorial restrictions, and significant progress began to occur in all areas of human services. Most significant in the marine field was the establishment (by an act of the Alaska Legislature) of the Institute of Marine Science at the University of

Table 1-2.

Scientific expeditions conducted between 1776 and 1876 in the North Pacific Ocean. Observers listed first are expedition leaders; those listed second are chief scientists.

DATE	OBSERVER	SHIP
1776-80	Cook, Burney	<i>Resolution, Discovery</i>
1785-88	La Perouse	<i>Boussole</i>
1791-92	Marchand, Fleurieu	<i>Solide</i>
1790-95	Vancouver	<i>Discovery</i>
1794	Malaspina	<i>Descubierta</i>
1803-06	Krusentern, Horner	<i>Nadiejeda, Neva</i>
1815-18	Kotzebue, Lentz	<i>Predpriatie</i>
1825-28	Beechey	<i>Blossom</i>
1826-28	Lutke, Erman	<i>Ssenjavin</i>
1826-29	D'Urville	<i>Astrolabe</i>
1831-36	Fitzroy, Darwin	<i>Beagle</i>
1836	Vaillant	<i>Bonite</i>
1836-39	Du Petit, Thouars	<i>Venus</i>
1837-42	Belcher	<i>Sulfur</i>
1839-42	Wilkes, Dana	<i>Vincennes, Peacock, Porpoise</i>
1843-46	Velcher	<i>Samarang</i>
1845-51	Kellett	<i>Herald</i>
1850-54	McClure, Armstrong	<i>Investigator</i>
1857-60	Wullerstorf	<i>Novara</i>
1873-75	Belknap	<i>Tuscarora</i>
1874-76	Hensen, Rottok	<i>Gazelle</i>
1872-76	Nares, Thomson	<i>Challenger</i>

Alaska in 1962. This brought together a skilled faculty, and prompted the development of modern facilities so that work on ocean sciences could be conducted from closer proximity than was previously possible.

Scientific History

General North Pacific Investigations

Aboard the *St. Peter* with Vitus Bering in command, Georg Wilhelm Steller spent the summer of 1741 as the first trained scientist to examine the flora and fauna of the Bering Sea, Aleutians Islands, and Alaska mainland (Kayak Island). The voyage of the *St. Peter* was dampened by clashes of temperament between an arrogant Steller and the crew, sickness due to scurvy and bad water, and general frustration with the foul weather found in the Gulf of Alaska. Nevertheless, Steller grasped his opportunity to describe many new findings, the most notable of which are the Steller's jay, Steller (northern) sea lion, and the Steller sea cow.

Steller's hard-won fame rests on his accurate descriptions of the sea cow and other marine mammals as published in his *De Bestiis Marinis* (Steller 1751). His dissection of a female sea cow in July 1742 represents the only scientific record of this northern manatee except for the few skeletons that were found years later. Twenty-seven years after its discovery by the Bering expedition, this magnificent species was extinct (see Dedication, this volume).

After the discovery voyage of Malaspina in 1794 (Table 1–2), greater emphasis was placed on determining oceanographic parameters—especially water depth and temperature. The first extensive oceanographic observations in the North Pacific were made by Krusenstern on the *Nadiejeda* from 1803 through 1806. His water temperature measurements down to 400 m and his observations of atmospheric pressure stimulated him (25 years later) to prepare an atlas on the northeast Pacific.

The Kotzebue–Lentz expedition on the *Predpriatie* (1815–1818) resulted in the first systematic measurements of water temperature, salinity, density, and oxygen content at depth using a device called the Lentz barometer. The observed decrease in temperature with depth in the low latitudes suggested to Lentz (1847) that the direction of flow was towards the equator for the low-temperature water below the surface and poleward in the high-temperature surface water.

Continuing these studies, Vaillant observed after many ocean temperature measurements and meteorological observations, that except for areas near the equator, sea surface temperatures in the Pacific were frequently higher than air temperatures (Prestwich 1876). It is now known that there is a long-term annual mean difference of about 20C in surface temperature between 20 and 60°N, as well as a maximum mean annual temperature range of about 10C at mid-latitude locations (Kenyon 1980).

Although the *Challenger* Expedition (1872–1876) never reached as far north in the Pacific as the Gulf of Alaska, its general contributions to the science of oceanography justify a brief discussion. As the first systematic interdisciplinary

study of the world's oceans, the *Challenger* project gathered data that were to set a standard for the oceanographic studies that followed. Of a total of 362 deep-water stations sampled on the expedition, seawater was analyzed for chemical constituents at 77 sites (more than half located in the Pacific Ocean). This procedure established the principle of constant relative proportion of the 11 major ions in seawater (independent of evaporation and precipitation) for all the seas, a principle of fundamental importance to modern chemical oceanography.

The comprehensive examination of bottom samples initiated on the *Challenger* Expedition began the science of marine geology and the formulation of a classification scheme for marine sediments. Large amounts of biological material were also collected, especially deep-water animal specimens. Nearshore biological communities were also first observed and catalogued on this expedition.

Measurements made by Makarov aboard the *Vityaz* (1886–1889), together with his organization of all temperature data obtained to that time, provided information for the first surface temperature maps of the Pacific Ocean to 45°N (U.S. Hydrographic Office 1878). Makarov (1894) documented the broad geographic distribution of surface water temperatures and densities in the Pacific Ocean.

Following the *Challenger*, several other large oceanographic vessels continued work in the North Pacific until the 1920s. The advent of trans-ocean cables provided a practical impetus for geological studies of the ocean bottom. Likewise, the rapid development of ocean shipping in international trade influenced the applied aspects of physical, biological, and chemical studies of the ocean. During this period, extensive biological studies were conducted aboard the U.S. Fish Commission's steamer *Albatross* in the North Pacific Ocean as far north as San Francisco Bay and also around the Hawaiian and Philippine Islands. From the work carried out over a period of nearly 40 years on the *Albatross*, extensive information was obtained about the composition of plankton, benthos, and nekton, including the description of many new species (*Albatross* 1902–1911).

Other expeditions were conducted on the English ship *Terra Nova* and German vessels *Eddy*, *Stephen*, and *Palanet*. Not only did expeditions of this period continue to develop the inventory of biological forms found in the ocean, but they established vertical and geographic distributions for the separate groups of organisms both in the open ocean and along the sea floor. They described the feeding habits of commercially important fishes and marine animals, together with many of the biological interactions between plankton, benthos, and nekton. Physical and chemical measurements often accompanied the collection of biological samples, and in this way, ecologically oriented data slowly accumulated.

Due to the remoteness of the area, the lack of established shipping zones, and the distance from marine research centers, few of the large oceanographic expeditions to the North Pacific Ocean reached as far north and east as the Gulf of Alaska. None of the major oceanographic expeditions reached the Gulf of Alaska (Wüst 1964). Special efforts to investigate this area began with the Northeast Pacific (NORPAC) Oceanographic Program in 1955; however,

many investigations conducted in other parts of the Pacific Ocean were important to future studies of more specific focus on the northeastern area.

The 1920s marked a period of detailed study of the world ocean. What had been separate, disjunct, and often incidental expeditions became well-planned, multidisciplinary, systematic investigations. Development of new methodologies and equipment played an important role in bringing about increased understandings in all areas of oceanography, as new underwater devices and methodologies were introduced. Prior to the 1920s measurement of such parameters as water depth required several hours using a winch and cable, and therefore only a few soundings could be made. The resulting paucity of data led to the erroneous concept of a flat ocean floor. When sonic devices that could make continuous measurements came into use, however, it was quickly determined that the ocean floor had canyons, ridges, trenches, and seamounts.

Important to our understanding of the oceanography of the North Pacific were the expeditions of the American ships *Carnegie* and *Ramapo*, the Dutch ship *Snellius*, the Danish ship *Dana*, the English *Discoverer II*, and the Japanese vessels *Shintoka Maru* and *Mansyu Maru*. Most of these ships did not reach the northernmost part of the eastern Pacific, nor were their efforts coordinated; but personnel on all ships participated in an interdisciplinary program during 1927 to 1929, which included the study of bottom topography and sediments, chemical and physical measurements from samples in the water column, and the collection of biological samples at horizontal and vertical intervals.

Important discoveries in the 1920s and 1930s included the observations that: 1) phytoplankton depend on nutrients in the euphotic zone for growth and development, and 2) the vertical distribution of plankton is closely related to temperature and salinity. Classical work in the ocean, especially that conducted by Cooper (1933) in the English Channel, showed that phytoplankton biomass depends on the amount of plant nutrients in the surface-water column. Geophysical methods such as pendulum gravitational and magnetic measurements were beginning to develop, and description of the hydrographic structure of the ocean was essentially completed (McEwen, Thompson, and Van Cleve 1930; Thompson, McEwen, and Van Cleve 1936; and Sverdrup *et al.* 1946).

During World War II, extensive oceanographic studies were undertaken in support of national defense. The vertical thermal structure of the surface ocean water, wave prediction, and bathymetric charting of vital areas of the ocean were emphasized. After the war came rapid development of complex data buoy stations and the development of devices that could measure temperature and salinity while the ship was moving, and other devices that could measure both surface and deep-water currents. In biological research, trawling techniques were perfected for use at specific depths and many new net systems appeared. The precision of chemical determinations reached 10 µg/l, both stable and radioactive isotopes found extensive use as tracers, and attention began to focus on trace components in seawater—particularly on dissolved organic matter and heavy metals.

Geologists began using echosounders, and magnetometers, as well as piston corers capable of obtaining sediment cores that reached up to 20 m in length. This period was capped with three around-the-world expeditions which passed through the Pacific Ocean: the Swedish *Albatross* (1947–1948), the English *Challenger II* (1950–1952), and the Danish *Galathea* (1950–1952). These expeditions determined the direction of geological investigations for subsequent expeditions by revealing that the relatively shallow depths of the sediments (only a few hundred meters) were many times less than had been theoretically estimated. Together with information provided by work aboard the American vessels *Midpacific* and *Capricorn*, these studies showed that the earth's crust beneath the Pacific Ocean is only 5 to 9 km thick as compared with the continental crust of between 30 and 40 kilometers. On these same expeditions, specimens of many bottom-dwelling and fossil fauna were obtained from submarine plateaus and trenches, giving heavy support to the field of paleontology.

Gulf of Alaska Investigations

Oceanographic work occurred in the northeast Pacific even though none of the classical large scientific expeditions reached as far North as the Gulf of Alaska (the *Carnegie* came closest, north of 50°N at 155°W). Many of the ships involved with research in the Gulf, the institutions that operated them, the period of investigation, the size of the vessel, and an indication of the kind of work accomplished are listed in Table 1–3. Despite these efforts, the number of oceanographic stations sampled north of 58°N and east of Kodiak Island between 1926 and 1969 was very sparse, as indicated in Figure 1–7 (Royer 1972). Activity has greatly increased since that period, largely as a result of the Outer Continental Shelf Environmental Assessment Program which began in 1974.

The most significant research effort in the Gulf during the late nineteenth century was undertaken by the Harriman Alaska Expedition (1910), which occurred during June and July 1899. Organized by E.H. Harriman of New York City and conducted at his expense, the expedition was planned originally as a holiday excursion for the Harriman family and a few friends interested in hunting. The plan was enlarged to include scientific work and later modified further to give the scientific group practical control of expedition details such as the route (Fig. 1–8) and other details affecting their work. Participants included 25 scientists representing a wide range of specialties such as ethnology, zoology, botany, geology, and geography. Among the scientific party were persons now well-known in Gulf of Alaska history: Dr. W.H. Dall, Mr. John Muir, Prof. B.K. Emerson, Dr. C. Palache, and Prof. W. Trelease.

Much of the cruise was spent near the coast, with almost daily landings of shore parties. From this expedition came much of the early marine-science literature on the coast and on the major island features of the Gulf of Alaska. Documentation of various scientific aspects, with an emphasis on biology and geology, was published in 13 volumes by the Smithsonian Institution (Harriman Alaska Expedition 1910).

From the time of the Harriman Expedition until 1955, the bulk of field research in the Gulf was undertaken by the Bureau of Commercial Fisheries (now the National Marine Fisheries Service) using the vessels *Albatross I* and *II* (Table 1–3); the Fisheries Research Board of Canada, Pacific Oceanographic Group using the vessels *Cedarwood* and *Ekhon*; the Faculty of Fisheries, Hokkaido University using the vessels *Ryofu Maru* and *Oshoro Maru II*; and the University of Washington using the vessels *Brown Bear* and *John Cobb*. Independently, the Soviets undertook a major oceanographic program in the western North Pacific aboard the *Vitiaz* (1949–1965). The results of biological studies conducted on the more than 40 cruises of the *Vitiaz* in the northern Pacific Ocean during this period constitute a major part of our knowledge of the area; both the quantity and the variety of data obtained during these surveys are probably unexcelled in the annals of oceanography (Moiseev 1955–1970).

In 1965, major oceanographic studies of the coastal Gulf of Alaska were undertaken by the University of Alaska using the *Acoma*. Among these studies were the first ever made in Cook Inlet, Prince William Sound, and the Alexander Archipelago. In 1971, the *Acoma* established the long, trans-Gulf of Alaska section line (GAK) south of Resurrection Bay. Information obtained with each succeeding oceanographic cruise along this transect has made the GAK line increasingly valuable to broad-scale Gulf studies.

The first documented physical oceanographic studies in the Gulf of Alaska were done for the International Fisheries Commission in 1927–1929 by McEwen *et al.* (1930). The station lines for the three cruises are given in Figure 1–9. In 1927, data were collected only at Stations 1 through 6 on the Ocean Cape section; in 1928 all lines were extended into the Gulf of Alaska. Salinity and temperature data obtained in January, during the halibut spawning season, delineated three water classifications: 1) coastal water having salinities of 32.5‰ or less and temperatures of less than 5°C, 2) intermediate water with salinities between 32.5 and 33.8‰ and a temperature maximum, and 3) ocean water with salinities greater than 33.8‰ and temperatures between those of coastal and intermediate water types.

This work was continued by Thompson *et al.* (1936), who deduced from dynamic-height computations that flow is generally westward in January with a maximum speed of one knot immediately off the continental shelf. Further current studies by Thompson and Van Cleve (1936) through drift-bottle experiments, elucidated the general directions of surface drift, but there was little information on flow rate because of the lag-time uncertainty connected with bottle recovery.

The next significant studies in the Gulf did not occur until 1954, the beginning of a surge of activity that continued until 1959 (Figure 1–7). This period included NORPAC studies and studies carried out during the International Geophysical Year (IGY). Research by University of Washington personnel aboard the *Brown Bear* and *John Cobb* in the northeast Pacific Ocean is summarized in Dodimead (1961), Favorite and Love (1957), and Bennett (1959). Unfortunately, except for a February 1957 cruise (Dodimead 1958), data were collected only during the summer months. Analyses of

these and other data collected during this period appeared regularly in the literature. A description of the dynamics of the halocline was reported by Fleming (1958). Oceanography of the region was reviewed by Fleming (1955) and Dodimead, Favorite, and Hirano (1963).

Using data from the *Oshoro Maru III* and other sources, Uda (1935, 1963) began extensive studies of the ocean as related to fisheries. Tully and Barber (1960) forwarded the far reaching concept of estuarine circulation—fresh water from the coast invades the deep ocean water much like rivers in an estuary—for the subarctic Pacific Ocean. Dodimead (1958) published some of the first data on surface concentrations of phosphate, nitrate, and silicate anionic nutrients.

Although another hiatus in Gulf cruise activity occurred during the 1960s, many important contributions to oceanographic understanding appeared in the literature. El Wardani (1960) described the organic/inorganic distribution of phosphorus; and Stephens (1964) reported on studies of primary productivity as related to chemical and physical parameters at Station P (50°N, 145°W). Studies of minor components of seawater also began to appear in the literature during the 1960s and 1970s. Bogdanov (1965) reported on Russian studies of suspended organic matter; Loder (1971) described extensive studies of both dissolved and particulate organic matter; and Natarajan (1968) discussed the distribution of thiamine, biotin, and niacin. Data on trace metals were published by Ali, Burrell, and Wood (1969), who examined the zinc distribution in fjords; Burrell and Hadley (1970), who described the partitioning of trace metals between solid and liquid phases; and Wood (1971), who reported on the chemical forms of gold in seawater.

Shellfish toxicity studies gained prominence with Schantz's (1965) research on the chemical structure of paralytic shellfish toxin and Chang's (1971) ecological study of the distribution of toxic butter clams. The first oceanographic studies of Cook Inlet (Hood, Natarajan, Rosenberg, and Wallen 1968) and of Prince William Sound (Hood 1969) also occurred during this period. Reid (1962) made one of the earliest analyses of the relationship of circulation, nutrients (phosphate), and biological populations (zooplankton); and Roden (1969) considered the wintertime circulation in the Gulf of Alaska.

In the mid-1970s, a new surge of oceanographic activity occurred in the Gulf—an involvement far more intense than any previous level of research. Pressure to develop potential oil and gas fields on the outer continental shelf, along with a strong mandate from the U.S. Government during the Nixon and Carter administrations to become energy independent, led to an oil and gas leasing program in the Alaskan outer continental shelf. Because it is the responsibility of the Department of Interior to protect the marine environment from adverse effects as a consequence of oil and gas development, the Bureau of Land Management (BLM), in May 1984, requested the National Oceanographic and Atmospheric Administration (NOAA) to initiate an environmental assessment program in the northeastern Gulf of Alaska. Later that year a major expansion of the program occurred in order to respond to additional sales on the Aleutian shelf, near Kodiak, and in lower Cook Inlet in the

Table 1-3.
Some vessels used in oceanographic research in the eastern North Pacific Ocean from 1880 to 1980.

NAME OF VESSEL	NATIONALITY OR INSTITUTION	PERIOD OF STUDY	TONNAGE OR (LENGTH)	SPECIALITY
<i>Jamestown</i>	U.S. Navy	1880	1,150	Surveyed Sitka Harbor
<i>Albatross</i>	U.S. Fish Commission	1882-1921	1,075	Marine biology
<i>Hassler</i> <i>Patterson</i> <i>McArthur</i> <i>Pathfinder</i>	Coast and Geodetic Survey	1872-1895	(159.5 ft)	Coastal survey of Alaska Fox Islands survey in Aleutians
<i>Concord</i>	U.S. Navy	1894-1920	1,710	Fur seal studies and protection
<i>Elder</i>	Individual E.H. Harriman	1899		Biology and geology of the coast of Alaska
<i>Carnegie</i>	U.S.A.	1928-1929	568	Physics, biology, sediments Trans-Pacific north of 40°N
<i>Catalyst</i>	University of Washington	1928-1938	(75 ft)	Oceanography of Puget Sound
<i>Ekhon</i> <i>Cedarwood</i>	Fisheries Research Board of Canada	1936-? 1950-1952		Fisheries Assessment Oceanography
<i>E.W. Scripps</i>	Scripps Institute of Oceanography	1937-1955	140	Oceanography of Puget Sound
<i>Ryofu Maru</i>	Japanese	1937-1955	1,206	Physics
<i>Albatross II</i>	U.S. Bureau of Fisheries	1926-1934	(150 ft)	Hydrography and chemistry Gulf of Alaska
<i>Garnet</i>	U.S. Navy	Summers 1926-1935	950	Areal survey support Gulf of Alaska
<i>Oceanographer</i> (formally <i>Corsair II</i>)	Coast and Geodetic Survey	1938-1944	1,600 (304 ft)	Surveys and Survey charting off Alaska
<i>Hydrographer</i>	Coast and Geodetic Survey	1931-1966	1,044	Hydrographic surveys Aleutian Islands
<i>Explorer</i>	Coast and Geodetic Survey	1939-1944	1,900	Hydrographic surveys in Aleutian Islands
<i>George B. Kelez</i>	NMFS	1944-1966	760 (176 ft)	Fisheries oceanography
<i>Oregon</i>	NMFS	1946-1984	219 (100 ft)	Fisheries assessment
<i>Horizon</i>	Scripps Institute of Oceanography	1948-1969	900	Oceanography of North Pacific Ocean
<i>Spencer Baird</i>	Scripps Institute of Oceanography	1952-1965	997	Oceanography of North Pacific Ocean
<i>Stranger</i>	Scripps Institute of Oceanography	1955-1962	405	Oceanography of North Pacific Ocean
<i>Commando</i>	University of Washington/ Bureau of Commercial Fisheries	1950-	(65 ft)	Coastal biology
<i>Brown Bear</i>	University of Washington	1950-1965	270	Oceanography of Gulf of Alaska
<i>John N. Cobb</i>	Bureau of Commercial Fisheries	1950-	(~ 90 ft)	Fisheries research
<i>Vitiaz</i>	U.S.S.R.	1957-1967	5,700	Detailed oceanographic cruises in North Pacific Ocean
<i>Oshoro Maru III</i>	Japanese	1962-1983	1,180	Fisheries oceanography
<i>Oshoro Maru IV</i>	Japanese	1983-		Fisheries oceanography
<i>Acona</i>	University of Alaska	1963-1980	(85 ft)	Coastal oceanography
<i>Cayuse</i>	Oregon State University	1967	(80 ft)	Coastal oceanography

NAME OF VESSEL	NATIONALITY OR INSTITUTION	PERIOD OF STUDY	TONNAGE OR (LENGTH)	SPECIALTY
<i>Alpha Helix</i>	University of Alaska	1965–	(125 ft)	Coastal oceanography
<i>Miller Freeman</i>	NMFS	1967–	1,920	Fisheries research
<i>Surveyor</i>	NOAA	1960–	3,440	Survey and support of OCSEAP
<i>Oceanographer</i>	NOAA	1966–	3,959 (303 ft)	Oceanography and support of OCSEAP
<i>Murre</i>	NMFS	1965–	(78 ft)	Coastal fisheries
<i>Thomas G. Thompson</i>	University of Washington	1965–	1,362 (208 ft)	Oceanography of North Pacific Ocean
<i>Hakuro Maru</i>	University of Tokyo	1969–	3,200	Some cruises to North Pacific Ocean and Bering Sea
<i>Melville</i>	Scripps Institute of Oceanography	1969–	1,806	GEOSECS cruise

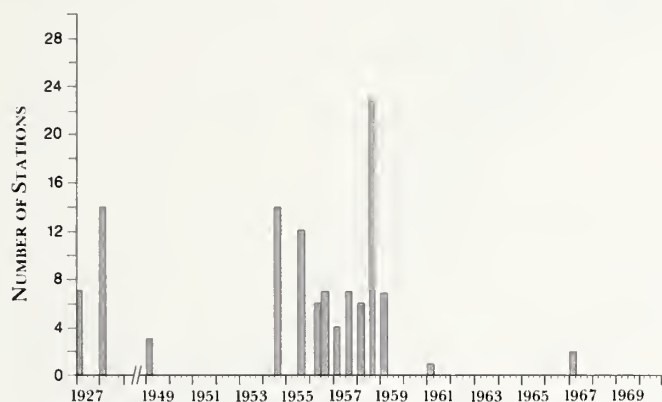


Figure 1-7. Oceanographic stations sampled per year, by quarters, north of 58°N and between 130° and 150°W (from Royer 1972).

Gulf of Alaska. It was out of this joint BLM/NOAA research initiative that the Outer Continental Shelf Environmental Assessment Program (OCSEAP) was created.

The pattern of leasing in the Gulf dictated the location and timing of OCSEAP studies. The disciplinary content and geographical intensity of the study program was heavily influenced by the 'need to know' as determined by local issues. As a result, a large data base was obtained in the NEGOA sale area, Kodiak area, and in lower Cook Inlet. Relatively little work was done, however, in areas of low interest, such as Shelikof Strait, the southern Aleutian shelf, Yakutat, or in the southeastern Gulf of Alaska. OCSEAP studies provide much of the subject matter for this book and will be treated in detail in the disciplinary chapters that follow. The abundance of data which resulted, though uneven in both geographic and disciplinary coverage, contains a wealth of information that is useful in building an understanding of the oceanography of the Gulf of Alaska. In each of the chapters which follow, the authors have drawn heavily upon OCSEAP data as well as other sources in an attempt to synthesize all of the available information into a single, coherent document which describes our present level of knowledge of the Gulf of Alaska.

The Status of Science in The Gulf of Alaska

Far out of the usual path of oceanographic ships and remote to shore-based laboratories, the Gulf is rendered even more inaccessible by persistent heavy seas and fog cover. As a result, it has received relatively little scientific attention in comparison with other parts of the world ocean that are similar in size and importance. Even the neighboring Bering Sea, also inhospitable to man, has fared better in terms of documentation of scholarly findings; the eastern continental shelf of the Bering Sea is probably as well understood as any in the world. A serious lack of such basic Gulf of Alaska data as nutrient levels and cycling rates limits the effectiveness of modern modeling procedures in this area.

With insufficient information it is not possible, for example, to adequately develop trophic-level simulation models, particularly for the apex consumers. Our inability to understand more fully the processes that control the productivity of commercially exploited Gulf species has led to 'boom and bust' fisheries throughout history. Perhaps the most baffling scientific uncertainties at this time surround the recent sharp declines of the king crab and shrimp populations (OCSEAP Staff, Ch. 14, this volume).

The recent development of an Alaskan pollock fishery in the central and western Gulf has resulted in the ongoing Fishery Oceanography Experiment (FOX), which focuses on interdisciplinary studies of the biotic and abiotic environment as they relate to year-class variations (Wilson, Inze, Macklin, and Schumacher 1986). Perhaps this kind of research program can eventually be applied broadly enough to provide the level of understanding necessary to manage the many environmental uses to which the Gulf is inextricably subjected.

Multiple use demands on the ocean and its resources are ever increasing. A thorough understanding of ocean processes and the natural variability which occurs in them is fundamental to the development of satisfactory policies for wise ocean use. The value of any studies proposed for the Gulf of Alaska (or any ocean) should be weighed in terms of what they can contribute to the basic understanding of



Figure 1-8. Cruise tracks of the Harriman Alaska Expedition of 1899 (from Harriman Alaska Series of The Smithsonian Institution 1910. Vol. 4).

ocean processes. Although much superficial descriptive knowledge is available, we are presently poorly prepared to respond to larger ocean-use questions.

Although now pristine in a practical sense, the Gulf of Alaska will probably come under increasing human demands in the future. Because of its remoteness to population centers, the Gulf is unlikely to be called upon to bear an immediate burden of waste disposal for the escalating human population; however, adequately feeding the global population will require fuller use of all ocean resources. Enhancement of the ocean's productivity appears to be a definite development for the future, and some mariculture (aquaculture) is inevitable.

Other than disease prevention and structural containment, the most limiting factor in mariculture development is a reliable, low-cost, high-quality supply of feed that does not compete with livestock feeds. Careful examination of the coastal areas of the Gulf of Alaska reveals an unusual

oceanographic situation. High nutrient levels reach nearer to the surface than in any other part of the world ocean. Annually, the surface waters are enriched by vertical mixing in the winter, leading to the annual vernal primary productivity. In regions where vertical mixing continues through the summer, such as in lower Cook Inlet and on the Kenai shelf, exceedingly high levels of primary productivity (≥ 300 g C/m²y) occur naturally. Could similar levels of productivity be reached in other regions, such as inlets and fjords, by some artificial means? Here the opportunity clearly exists.

In the development of scientific understanding there are three steps in progress that mark levels of achievement. First, the discovery phase which finds and identifies the problem. Then, the data collecting and experimental phase which describes and characterizes the system and, finally, the analytical phase which brings all data and experiment into focus to describe and predict the processes which control the system. Only in a few oceanographic systems has the

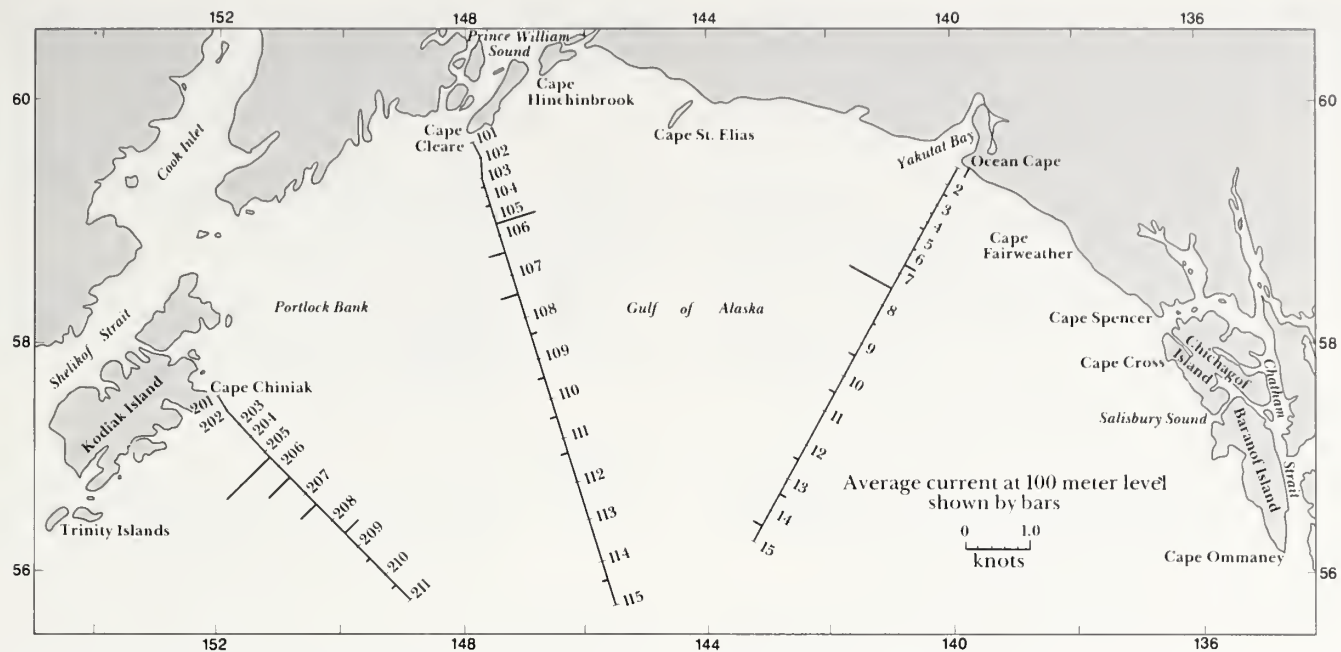


Figure 1-9. Surface currents (at 100-m depth) at stations along three 1929 cruise transects in the Gulf of Alaska (from Thompson *et al.* 1936).

level of achievement reached the final phase, but like all science, movement occurs on a broad front and success in one area is often generic and of value to other areas. While broad progress in oceanography will contribute heavily to a better understanding of the Gulf of Alaska, there are priority areas of research which should be addressed in order to attain the level of understanding needed for the analytical phase indicated above. Briefly, these are:

- data acquisition for development of simulation models for all trophic levels
- data acquisition concerning the natural history and population levels of apex consumers
- an integration of the dynamics of biology, chemistry, and physics into a systems understanding that includes natural variability
- increased application of known methods, and development of new ones, to enhance resource enhancement and utilization.

The Gulf of Alaska has many features, as discussed earlier, that make it a highly significant part of the world's oceans. Our level of understanding of the Gulf is probably less than for most other ocean areas. Therefore, if—in the words of Francis Bacon—we are to command it wisely for man's use, we must better understand its natural processes and learn to obey and abide by the natural phenomena which occur there.

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^a Bacon's *Novum Organum* (1620) has done more perhaps than any other work to inculcate into science unbiased, accurate, and careful observation and experimentation.

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Section 2

Physical Environment

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ABSTRACT

The Gulf of Alaska is one of the most active meteorological regions on earth. The types of weather found there are primarily caused by the passage of storm systems along the Aleutian storm track. Many of these storms are stalled by the high coastal mountains that ring the Gulf and are subsequently dissipated. Variability in the weather of the Gulf of Alaska is largely determined by planetary-scale motions, in particular by the presence of a high-pressure system that blocks the normal passage of storms. Large interannual variations are the norm.

Throughout the year, offshore winds are predominantly from the south in the eastern Gulf, from the east in the northcentral region, and from the west, but highly variable, near the Aleutian Islands. Wind intensity is the greatest in the winter months of October through April. The nearshore wind field can be quite variable due to the presence of the high mountain barrier to onshore flow. Examples of nearshore wind phenomena include coastal wind jets, gap winds, and katabatic winds.

Winter air temperatures over the ocean are generally warmer than at continental stations at the same latitude due to relatively warm ocean-water temperatures. Frequently during the winter cold, continental air will stream over the region, bringing a dramatic drop in air temperature. The Gulf of Alaska is almost always cloud covered and the precipitation away from the coast is on the order of 100 cm/y. Storms that cross the Gulf drop as much as 800 cm/y of precipitation in the form of rain and snow in the high coastal mountains. These mountains provide substantial storage for runoff.

The weather in the Gulf of Alaska affects the regional oceanography by means of both wind-induced currents and coastal currents driven by differences in water density from the large runoff of fresh water along the coast of southeast Alaska. Because the weather influences the Gulf current systems and ocean stability, it has a major impact on the variability of the oceanic biological community.

Introduction

The Gulf of Alaska is one of the most active meteorological regions on earth. Winter storms create 15-m seas, cause devastating coastal winds, and produce enough rain to classify some coastal areas as extratropical rain forests. The Gulf of Alaska is also a graveyard for storms: weather systems propagating eastward and northward across the North Pacific Ocean encounter a wide, continuous belt of mountains with peaks as high as 3,000 to 6,000 meters. In this chapter we describe the meteorology of the Gulf by considering dominant weather patterns, storm tracks, winds, precipitation, air temperature, and other secondary variables. We also discuss regional features such as coastal winds

and give an introduction on the influence of the atmosphere on the ocean.

The meteorology of the Gulf of Alaska is dominated by the passage of storms that are characterized by low sea-level pressure and associated cold fronts. There are basically two seasons: winter extends from October through April and summer from May through September. During the winter, an average of one storm every four or five days (Hartmann 1974) crosses the Gulf, generally from west to east.

With these storms come winds of up to 40 m/s and nearly continuous cloud cover. In addition, warm, moist air moving ahead of the various cold fronts drops as much as 800 cm of precipitation annually in the high coastal mountains. Behind the cold fronts, cold, dry continental air streams

southward, enhancing cloud convection on scales of 2 to 100 km and producing gusty winds. A region of high sea-level pressure (a ridge) can often develop over the region in the winter and deflect storms to the north or south. The summer pattern in the Gulf of Alaska is typified by light winds and the fog or low stratus clouds commonly associated with oceanic high-pressure systems.

Along the coast, the high mountains modify and impede the onshore passage of storms. This condition sets up local wind fields such as strong gap winds in low-level channels, alongshore wind jets, and the outflow of continental air over the ocean. Outflows are greatest during the large-scale, winter pressure pattern, which features low pressure over the ocean and cold air over the interior continental plateaus.

The meteorology of the Gulf of Alaska has a dramatic effect on the regional oceanography. Precipitation rates between 40 and 800 cm/y produce an annual-mean-runoff rate of $\sim 23 \times 10^3 \text{ m}^3/\text{s}$ from Southeast Alaska. The runoff is confined in a narrow current jet that is held against the coast by the wind-induced, onshore Ekman transport typical of storm systems in the eastern Gulf. Current speeds reach 100 cm/s during peak runoff in the autumn. Wind and density gradients induce an alongshore current that transports nutrients and biota counterclockwise around the Gulf. Year-to-year ocean variability depends largely on inter-annual changes in storminess.

Large-Scale Meteorology

Semi-Permanent Atmospheric Systems

The meteorology of the Gulf of Alaska is influenced by the relative positions of three semi-permanent atmospheric features: the Aleutian low-pressure region and the east Pacific and Siberian high-pressure regions (Fig. 2-1).

The Aleutian low-pressure region is caused by intense storms (low-pressure systems) that pass through this area at a higher frequency than almost any other place on earth. This low is a statistical low-pressure area in the sense that the monthly average sea-level pressure along the Aleutian Island chain is lower than surrounding areas. The statistical low has an elliptical shape with the long axis oriented west to east. The shape indicates the west-to-east passage of individual low-pressure centers (Grubbs and McCollum 1968). The elliptical shape is also due to low-pressure systems reaching their maximum intensity (lowest pressure) in the western and central Gulf.

The Aleutian low occurs 25% of the time, making it the dominant influence on Gulf of Alaska weather throughout the year (Overland and Heister 1980). By averaging 80 years of monthly-mean data on a 5° latitude-longitude grid, Angell and Korshover (1982) found the average position of the Aleutian low at 56°N , 168°W with an average central pressure of 1,002 millibars. Its position is described by Favorite, Dodimead, and Nasu (1976) as moving southeastward

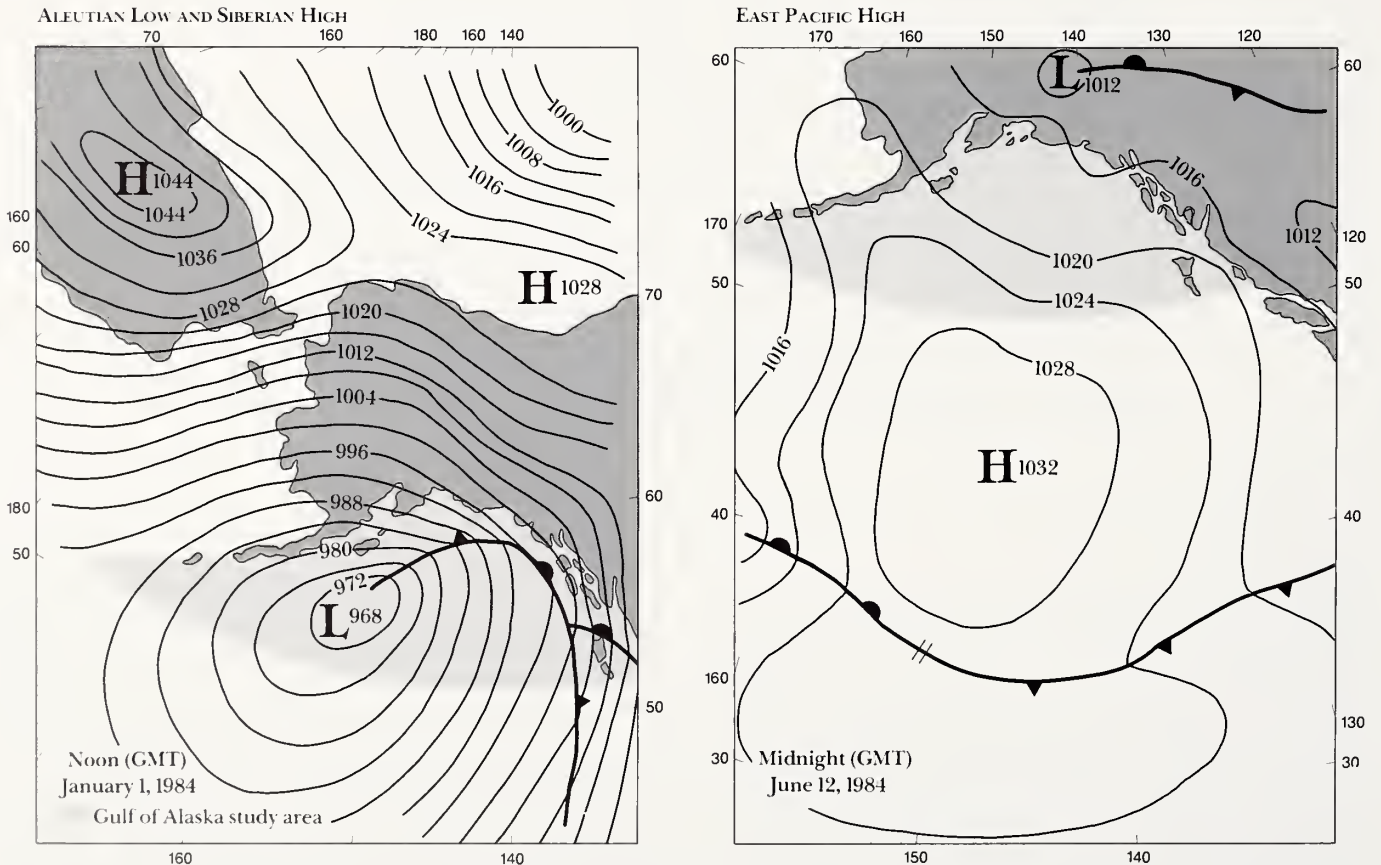


Figure 2-1. Examples of the Aleutian low, Siberian high, and east Pacific high-pressure systems. These three semi-permanent atmospheric features influence the weather over the Gulf of Alaska. Contours refer to sea-level pressure in millibars (mb).

from the Bering Sea into the Gulf between August and December. In January, the low-pressure center moves to the western Aleutians where it slowly weakens through July.

During summer, cyclonic low-pressure systems are weaker and tend to migrate further north due to the decreased difference in temperature between the Equator and the pole. The oceanic region is cooler than the adjacent land masses and a large high-pressure system is established over the Gulf of Alaska. This east Pacific high-pressure system is present throughout the year off the California and Baja California coasts. It reaches maximum intensity and northward position in June through August, when it dominates almost the entire North Pacific including the Gulf of Alaska (Favorite *et al.* 1976). Its 80-year average position is 35°N, 143°W with an average central pressure of 1,024 mb (Angell and Korshover 1982).

The Siberian high-pressure system influences the Gulf of Alaska from October through March. The high, which reaches its maximum intensity in January, is associated with the huge pool of very cold winter air over eastern Asia and northern Alaska. Although rarely present in the Gulf, its influence is felt through a southward shift in the location of the Aleutian storm track and an increase in cold winds blowing from the north over the western Gulf.

Cyclonic Weather Systems

Because of its importance to all aspects of Gulf of Alaska weather, we provide a brief description of the meteorology associated with individual storms. An idealized surface low-pressure system and a frontal structure in a mature stage of storm growth are shown in Figure 2-2. Storm systems in the northern hemisphere are cyclonic, with the winds flowing counterclockwise around a low-pressure center. Surface geostrophic winds are caused by a balance between the force of the sea-level pressure gradient and the Coriolis force. Surface winds over the ocean are typically 80% of the magnitude of the geostrophic wind and are oriented ~20° to the left of the geostrophic wind direction (toward a low-pressure center, out of a high-pressure center) due to the influence of surface friction.

As shown in the idealized view of a low-pressure area, the winds in the eastern sector ahead of the cold front are southerly. The winds behind the cold front are northwesterly, and the winds north of the low and ahead of the warm front are northeasterly and easterly. East of the cold front, moist warm air is advected northward by surface winds. Behind the cold front, cold air moves southwest into warmer regions. There is a net transport of heat and moisture northward near the surface due to a storm passage. Inclement weather is associated both with the north and east sector of a low-pressure system and with the cold front.

This idealized view is accurate for an area over the ocean away from the coast. Near the coast (< 100 km offshore) the picture is complicated because the geostrophic balance is blocked by high coastal mountains (Overland 1984), and special wind and precipitation phenomena are induced by the topography of the coast.

Fronts are regions of air temperature contrast. As storms cross the North Pacific, the air flowing from the east in the

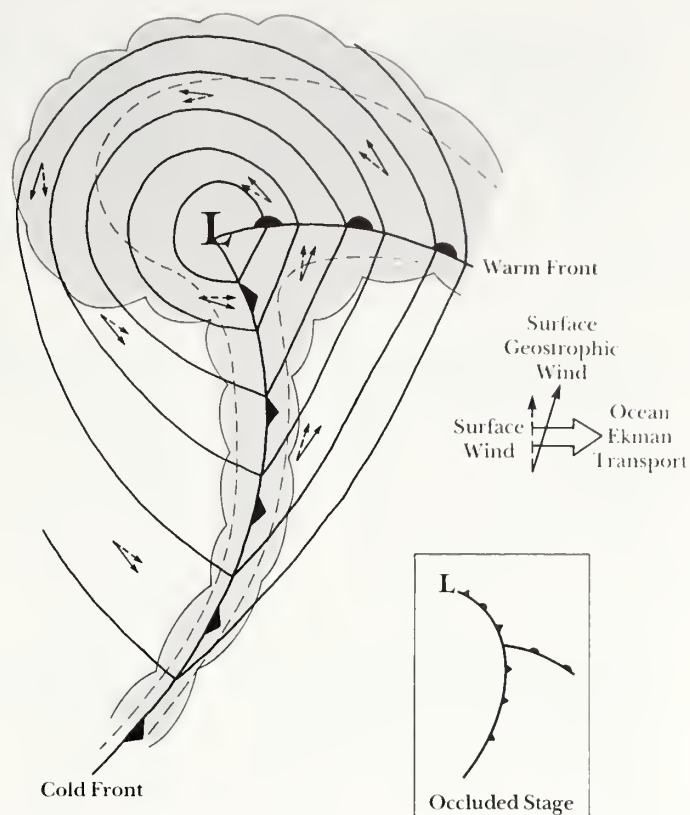


Figure 2-2. Idealized view of a low-pressure system. The heavy solid lines that encircle the low pressure center (L) are isobars (lines of constant pressure) decreasing in magnitude towards the center. Shaded area is approximate cloud cover, and the dashed line encloses the area where rain is expected along the fronts and near the low center. Winds blow counterclockwise (Northern Hemisphere; cyclonic) around the low. The last stage before a low-pressure system dissipates is the occluded stage where the low center moves deep into the cold air sector.

northeast sector of the storm (north of the warm front in Fig. 2-2) is similar to the air flowing from the south (south of the warm front in Fig. 2-2). This similarity occurs because air on both sides of the warm front is modified when it flows over areas of similar ocean temperature. Under these conditions, when there is relatively little temperature contrast between the northeast and eastern sectors, storms entering the Gulf do not usually have pronounced warm fronts. The cold front tends to maintain its identity.

As wind blows over the ocean surface, momentum is transferred to ocean waves and currents. Another term for momentum transfer is stress, which is defined as the vertical flux of momentum per unit area. Since there are few locations where stress has been measured directly over the ocean, most oceanic estimates are computed from measured or geostrophically derived surface winds.

Momentum transfer is related to the square of the wind speed adjacent to the ocean surface (Businger 1973) by a drag (or transfer) coefficient (CD) that increases slowly with increasing wind speed (Han and Lee 1983). The transfer of sensible heat and moisture (latent heat) between the ocean and atmosphere is important to the energetics of a cyclonic weather system. These transfers depend on 1) the tem-

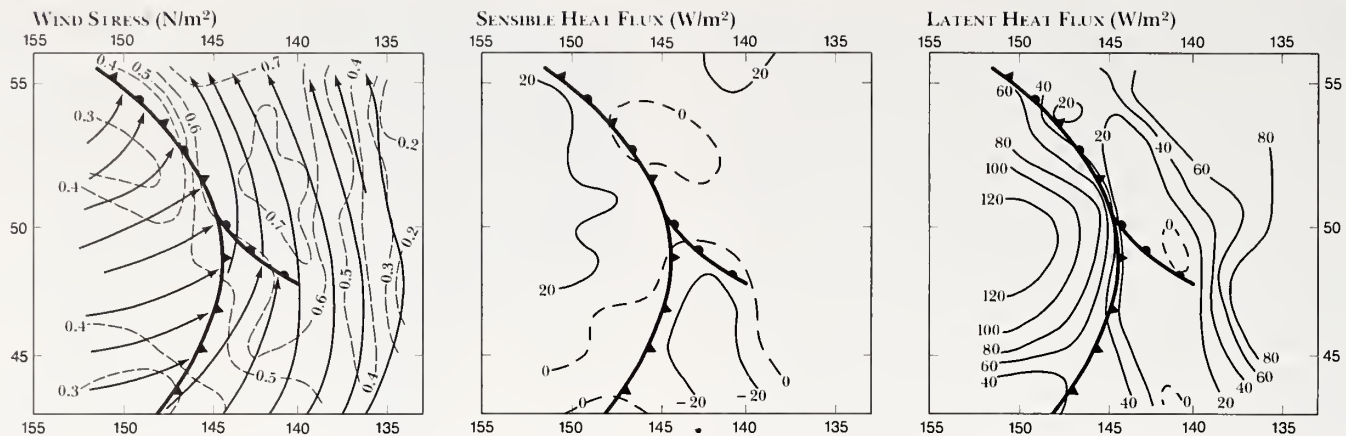


Figure 2-3. Six-storm composite in the vicinity of Station P (50°N , 145°W) showing wind stress, sensible heat flux, and latent heat flux. Arrows indicate direction of air flow and dashed lines are contours of the magnitude of the wind stress. (Modified from Fleagle and Nuss 1985.)

perature and moisture differences between the air and the sea, 2) the wind speed, and 3) transfer coefficients.

Fleagle and Nuss (1985) present composite patterns of streamlines (lines of constant wind direction), wind stress, sensible heat flux, and latent heat flux derived from observations of six winter storms in the Gulf (Fig. 2-3). The maximum wind stress occurs in the region of highest wind speeds; in the Gulf this is frequently in the warm sector to the east of the low-pressure center. In the warm sector east of the cold front, where warm air is flowing from the south over the ocean, the flux of sensible heat (Fig. 2-3) is from the air to the sea. In the cold air sector to the west and north of the cold front, the heat flux is from the sea to the air. In the warm sector, latent heat transfer is at a minimum where the air is warm and moist (Fig. 2-3). To the west of the cold front, the air originating over more northerly latitudes is cold and dry, which produces a maximum of transfer of moisture and heat from the ocean to the atmosphere.

Just as there are low-pressure areas in the atmosphere, there are also regions of high pressure. A high-pressure area (also called a ridge or anticyclone) has clockwise flow (in the Northern Hemisphere) and tends to be an area where high-level air is warmed through compression as it sinks toward the surface. This warm, dry air from above diverges near the surface, bringing warmer-than-normal temperatures to the region under the ridge. A low-level temperature inversion may keep the air from above away from the surface (Treidl, Birch, and Sajecki 1981). When the center or axis of the ridge is over the North Pacific Ocean, northerly winds east of the ridge bring cold, continental air over the Gulf. In addition, anomalously strong, southerly winds west of the ridge produce conditions that are warmer and wetter than average. The surface weather associated with high-pressure ridges in the Gulf of Alaska is frequently fog or low clouds.

Annual Cycle of Pressure and Storm Tracks

Storms tend to form in specific regions in the Pacific, most notably along the east coast of Asia where warm ocean currents pass southeast of cold land masses. Additional storm formation regions are in the central Pacific along the

oceanic front located near 35°N (Roden 1970). These are regions of strong horizontal temperature gradients and unstable air masses. Once formed, storms can either intensify or weaken as they move generally eastward. Storms crossing the North Pacific usually intensify as they slowly gather heat and moisture from the ocean surface. A storm may, however, undergo rapid development in conditions where deep vertical mixing is fueled by cloud processes (Gyakum 1983; Mullen 1983). Almost all rapid-development events occur in early winter, with the largest number occurring in October (Murty, McBean, and McKee 1983). Early winter is a likely time for conditions of unstable atmosphere and deep convection to occur since the sea surface remains warm and transfers its heat to the adjacent atmosphere underneath a region of southward flowing cold air in the upper atmosphere.

Low-pressure systems that move into the Gulf of Alaska during early and late winter often stall and dissipate. A quasi-stationary low-pressure center is maintained in the Gulf by the presence of coastal mountains. Transient, low-pressure systems entering the Gulf often lose their separate identity to this persistent feature. Figure 2-4 shows the

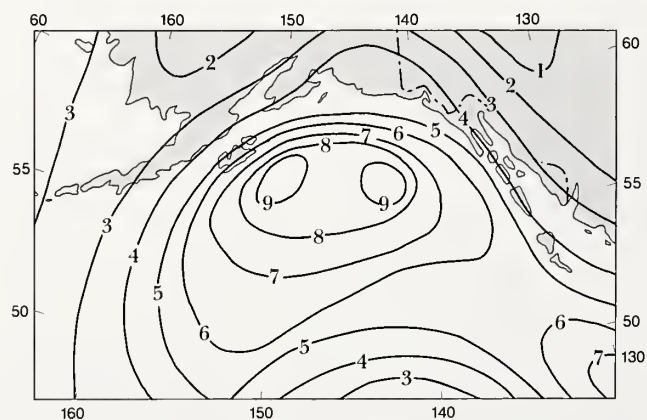


Figure 2-4. Annual distribution of cyclone dissipation positions. Contours show the number of cyclone dissipations for the period February 1980 to January 1981. (Modified from Roebber 1984.)

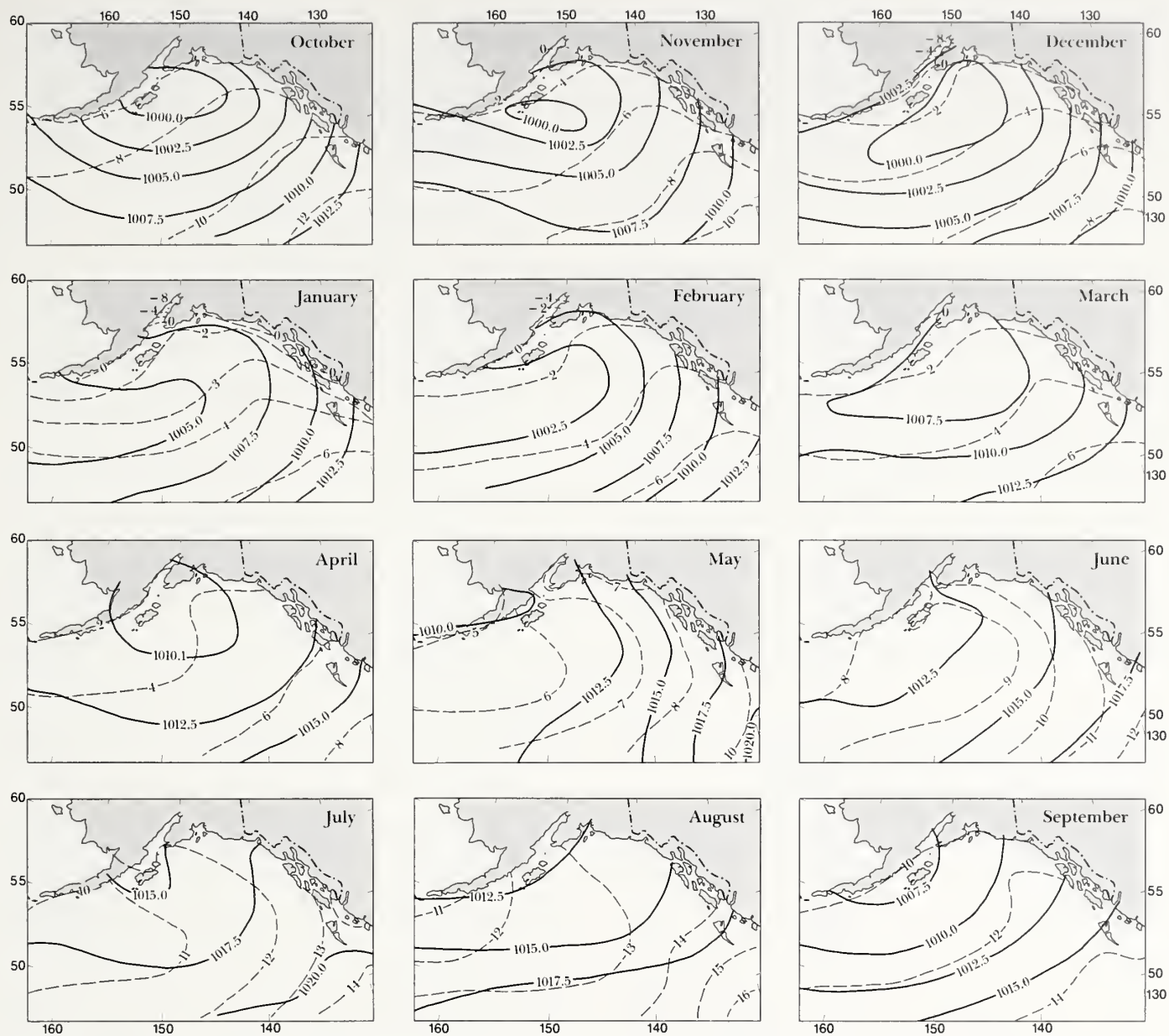


Figure 2-5. Monthly mean sea-level pressure (mb; solid contours) and surface-air temperature (C; dashed contours) maps over the Gulf of Alaska. The time period of observations varies at each station. (Modified from Brower *et al.* 1977.)

Gulf of Alaska as a major storm-dissipation area in the Northern Hemisphere for the period February 1980 to January 1981 (Roebber 1984).

Monthly-mean pressure and temperature patterns over the Gulf of Alaska are presented in Figure 2-5 (Brower, Diaz, Prechtel, Searby, and Wise 1977). The winter presence of the Aleutian low is clearly seen in the pressure field from October through December. Higher pressures in January than in either December or February are associated with the frequent development of a high-pressure area over the Gulf in January. Pressure rises from a low in late winter to a maximum in July—corresponding to the influence of the east Pacific high as the Aleutian low retreats into the northwestern Bering Sea. The pressure gradient increases in August and September as the Aleutian low moves southeastward once again to dominate the region in the winter.

Cyclones that originate in the same area usually follow similar paths called storm tracks. Storm tracks are characterized by poleward fluxes of heat, moisture, and angular momentum. Monthly cyclone frequencies and storm tracks are shown in Figure 2-6 (Whittaker and Horn 1982). Cyclone frequency was determined by counting the number of low-pressure centers in 5° latitude-longitude boxes for a 15-year period between 1958 and 1977. Primary tracks are defined as those tracks showing the highest occurrence of minimum-pressure systems along the track. Lesser counts are considered as secondary tracks. Few cyclones actually follow these tracks from beginning to end, but statistically, cyclones are most likely to appear along these trajectories. Tracks from Whittaker and Horn (1982) for 1958 to 1977 can be compared to tracks from Klein (1957) for the years 1909 to 1914 and 1924 to 1937.

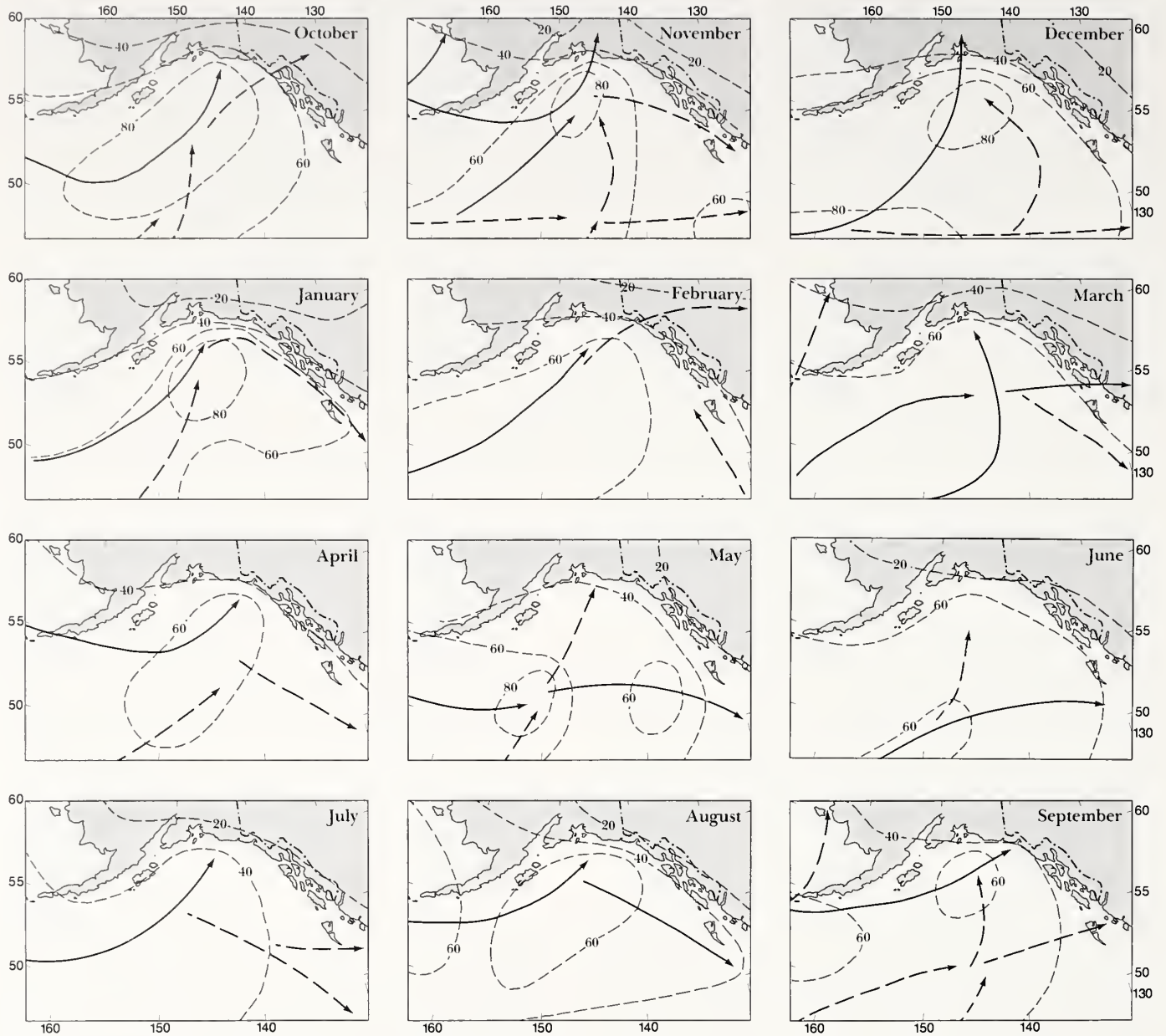


Figure 2-6. Monthly cyclone frequency (dashed contours are the number of storms counted on a 5° latitude–longitude grid over a 15-year period, 1958–1977) and storm tracks. The solid arrows are primary storm tracks and dashed arrows are secondary tracks. (Modified from Whittaker and Horn 1982.)

Winter months from October through March are characterized by high storm frequencies in the central Gulf (over 80 storms in the 15-year period of the study) (Whittaker and Horn 1982). Main storm tracks originate off the east coast of Asia with trajectories northeast to the south coast of Alaska. The main track is south of the Aleutian Islands throughout the winter, except in November when it is in the southern Bering Sea. Lows that form in the mid-Pacific follow a more northerly track and strike the coast in approximately the same location.

During many months, secondary storm tracks curve from the Gulf southward toward Washington or Oregon along the west coast of North America. Low-pressure centers tend either to move inland over the southeast Alaska coastal

mountain range into northern Canada, or to stagnate in the Gulf. Klein (1957) shows a similar pattern except that his primary storm tracks are over the Aleutian Islands throughout the winter months.

The cyclone frequency pattern weakens progressively from January to July. An exception to this pattern is a period of maximum frequency for the middle of the Gulf in May, when the track from the western Gulf crosses the secondary track of the northward-propagating mid-Pacific cyclones. The main track is still south of the Aleutians, except in April when it enters the Gulf from the southern Bering Sea. Again, Klein's (1957) main track is farther north over the Aleutian Islands. In August and September the storm frequency in the Gulf begins to increase. Main tracks from both

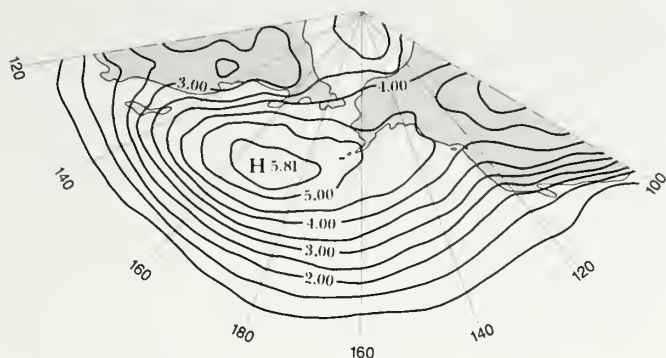


Figure 2-7. Standard deviation from winter mean (15 Nov.–14 Mar.) sea-level pressure pattern (contours of 0.5 mb) of 2.5- to 6-day filtered data for the period 1963–1964 and 1971–1972. (Modified from Blackmon *et al.* 1977.) The region of high variability corresponds to their definition of a storm track.

Whittaker and Horn (1982) and Klein (1957) are similar. Storms originating off the Asian coast move along the Aleutians, either to the Bering Sea or to the northcentral Gulf of Alaska.

The storm tracks discussed here were determined using various techniques based on counting low-pressure centers. Other approaches provide further insight. Blackmon, Wallace, Lau, and Mullen (1977) (Fig. 2-7) and Lau (1981) use the variability of atmospheric parameters (sea-level pressure, 500-mb height, and relative vorticity) to locate storm tracks. They assume that the maxima in variability correspond to regions through which cyclones frequently pass. Holopainen (1984) took readings from regions where there was maximum conversion of both potential and kinetic energy contributing to the mean flow, and compared those readings with the amount of both potential and kinetic energy normally available to high- and low-pressure systems.

The patterns that result from using these other techniques are all more zonal (east-west orientation) than patterns that result from using the low-pressure-center counting technique. One possible reason for the difference (cyclone counts vs. meteorological variability) is that much of the atmospheric variability occurs in association with cold fronts that yield a broader storm track region.

The storm-to-storm variation in track position is caused by two factors: 1) changes in the position of upper-level steering winds, and 2) the point of origin of the storms. The variability of inclement weather in the Gulf of Alaska, including clouds, precipitation, and winds, is directly related to the variability in time and space of storm tracks, storm intensity, and the frequency of storm passage.

Interannual Variability, Blocking Ridges, and Long-Term Trends

It is important to understand the large interannual variability of both winter-storm frequency and storm tracks in order to study the physical and biological environments of the Gulf of Alaska region. This variability is largely influenced by blocking high-pressure ridges in the winter atmospheric pressure field in the Gulf of Alaska. Blocking ridges are large-scale anticyclones extending vertically through-

out the atmosphere that block the passage of low-pressure systems for periods lasting up to several weeks. During this time, winter low-pressure systems that normally progress eastward across the Gulf are either deflected to the north over the Bering Sea and central Alaska or to the south towards the Oregon or California coast. This variability can be quantified by comparing either monthly pressure or temperature differences between two widely separated locations near the North Pacific, or by examining shifts in the Aleutian storm track.

Blocking ridges are not random occurrences around the globe, but tend to develop in particular locations. These locations, including the North Pacific (Fig. 2-8), may be determined by orography and/or land-sea thermal contrast (Kikuchi 1969, 1971; Egger 1978; Tung and Lindzen 1979; and Hartmann and Ghan 1980). Blocking events in the North Pacific may take one to two weeks to become established over the region (Rex 1950) and rarely last for more than two months. These events have a duration distribution heavily skewed toward 5 to 10 days with a mean of 12.1 days (Fig. 2-9) (Treidl *et al.* 1981). They occur almost exclusively in mid-winter, with a secondary maximum in the summer, (White and Clark 1975; Treidl *et al.* 1981; and Lejenäs and Økland 1983) and tend to form between 56 and 60°N (Treidl *et al.* 1981) with a longitudinal extent possibly as wide as the North Pacific (White and Clark 1975). Lejenäs and Økland (1983) found that a 30° longitudinal extent is most frequent but

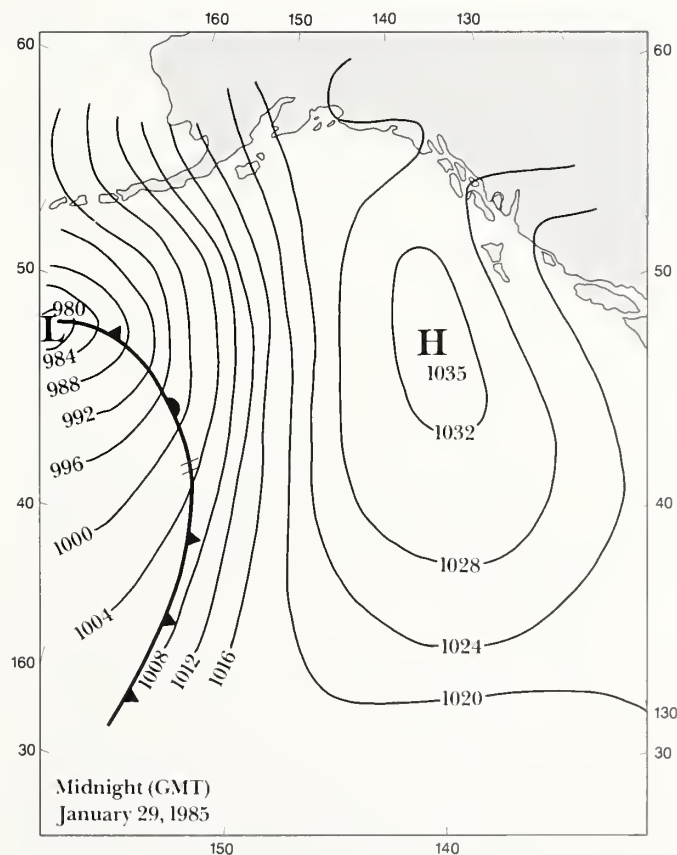


Figure 2-8. Blocking high pressure in the Gulf of Alaska deflects cyclones to the north or south away from the Gulf. Contours refer to sea-level pressure in millibars.

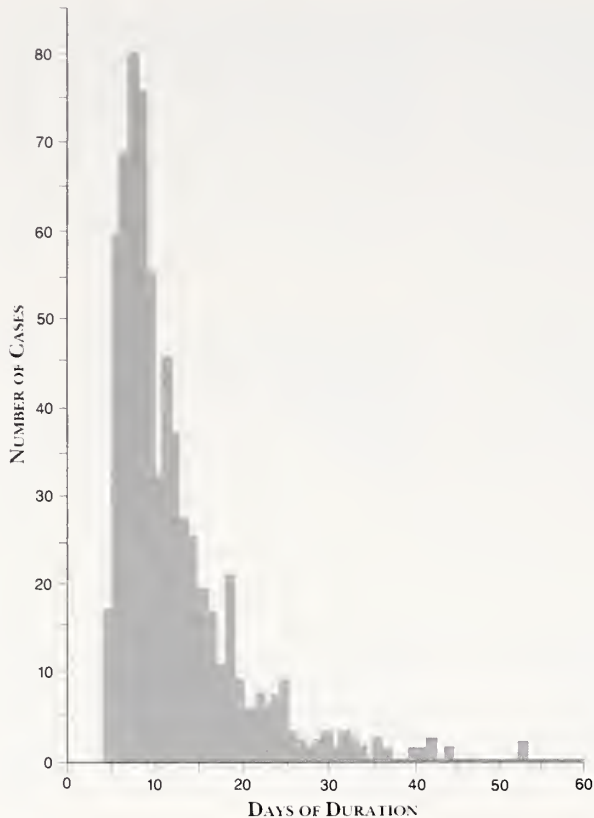


Figure 2-9. Duration of blocking events over the northern hemisphere for the period 1945 to 1977. (Modified from Treidl *et al.* 1981.)

that 40 to 60° extends together account for almost half the cases. Most blocking ridges in the Gulf of Alaska move slowly eastward, although Lejenäs and Økland (1983) found that long-lasting events move to the west.

The interannual variability of blocking ridges is depicted in Figure 2-10, taken from White and Clark (1975), and shows no discernible pattern. January has the highest number of blocking incidents. Tung and Lindzen (1979) attribute the interannual variability of blocking events both to the contrast between land and sea temperatures and to resonance in the long-wave pattern of the upper atmosphere. Additional evidence of the importance of land-sea temperature differences is the noticeable maximum in the number of blocking events that occur in the North Pacific in January, when the maximum temperature difference occurs between the land and sea (Lejenäs and Økland 1983; White and Clark 1975).

Two indices of note, the North Pacific Oscillation (NPO) index (Walker and Bliss 1932; Rogers 1981) and the Emery and Hamilton (1985) pressure index, are used to quantify the variability in the positions of the semi-permanent atmospheric systems. The NPO index is a measure of the difference in mean winter air-temperature anomalies between St. Paul Island in the southern Bering Sea and Edmonton, Canada (Rogers 1981). During those years when there is a cold anomaly in winter temperatures at St. Paul and a warm anomaly at Edmonton, there is usually an intensified Aleutian low in the eastern North Pacific. Conversely, years fea-

turing a warm anomaly at St. Paul and a cold anomaly at Edmonton are associated with a weak Aleutian low that is centered in the western North Pacific (Fig. 2-11). The NPO is related to the relative positions of the Siberian high-pressure air mass (cold and dry) and the Aleutian low (warm and moist) and has been correlated with variabilities in both air temperature and precipitation over North America, with variabilities in sea-surface temperatures in the Gulf of Alaska, and with variations in the extent of Bering Sea ice.

When the mean winter sea-level pressure pattern in the Gulf of Alaska deviates from the long-term average, it does so in two ways (Emery and Hamilton 1985): 1) an intensification of the pressure pattern of the Aleutian low, and 2) a weakening of the pressure pattern when the Aleutian low is displaced to the west and a relatively weak, secondary low is present (in a statistical sense) in the central Gulf. The Emery and Hamilton (1985) pressure index compares the winter (December, January, and February) mean pressure south of the Aleutian Islands with the mean pressure over coastal California (pressure at 40°N, 120°W minus the pressure at 50°N, 170°W). This index is shown in Figure 2-11. High index values correspond to low relative pressures near the Aleutians, both of which relate to more intense and/or frequent cyclone activity.

For a given year, the Emery and Hamilton (1985) winter mean-pressure index correlates well with sea-surface temperature anomalies along the west coast of North America. Because sea water temperatures change slowly compared with atmospheric temperatures, Emery and Hamilton (1985) believe the winter season is the most important in establishing the large interannual variability of the atmosphere over the Gulf of Alaska.

The weather responds to a high- or low-pressure index differently in the eastern Gulf of Alaska than in the western Gulf. In the eastern Gulf, high- or low-pressure indices are manifested by high or low southerly wind speeds. An intense Aleutian low (high index) with high southerly wind stress is associated with relatively warm sea-surface temperatures and high sea levels in coastal areas (Emery and

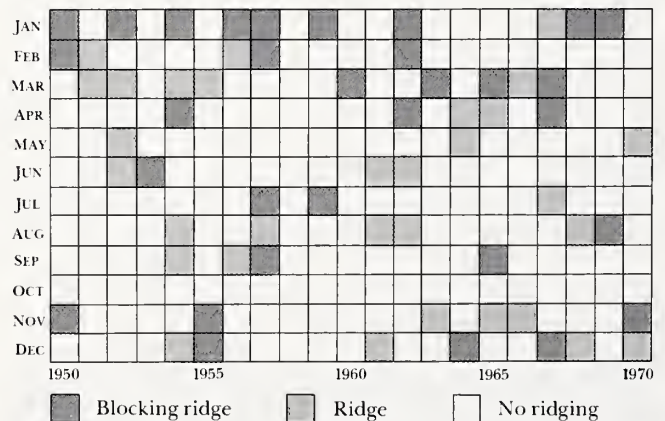


Figure 2-10. Interannual variability of blocking events over the North Pacific for the period 1950 to 1970. Note the large number of occurrences in January. Ridge implies some high-pressure activity during the month. (Modified from White and Clark 1975.)

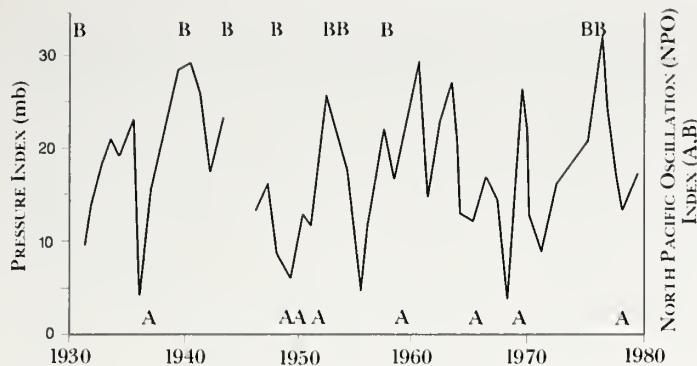


Figure 2-11. North Pacific Oscillation (NPO) index with 'A' indicating weak Aleutian low and 'B' indicating strong Aleutian low (Rogers 1981), and the Emery and Hamilton (1985) pressure index (pressures at 40°N, 120°W minus pressures at 50°N, 170°W) averaged over December, January, and February for the years 1931 to 1979. High index values indicate low Aleutian pressure relative to pressure near the California coast.

Hamilton 1985). In the western Gulf, a high index is characteristic of cold northerly winds and a deepening of the oceanic thermocline. The interannual variability of the pressure pattern is indicated by directional variability in the mean wind.

A shift in the position of major storm tracks is an indicator of a long-term trend. The winter storm tracks of Whittaker and Horn (1982) are about 5° of latitude south of the Klein (1957) positions over the Aleutian Island chain. Storm frequency counts for the period 1923 to 1932 for November/December and January/February (Richardson 1936) confirm Klein's (1957) maps and show that the main track was farther north earlier in this century. More recent storm-frequency data (1951-1970) by Reitan (1974) for the middle month of each of the four seasons generally agree with Whittaker and Horn (1982). However, an exception occurs in January when Reitan's (1974) only track originates off the Washington coast and moves inland.

Overland and Pease (1982) provide additional evidence that the main storm tracks from eastern Asia into the Gulf of Alaska shifted south of the Aleutians after the mid-part of this century. They counted low-pressure centers in the Bering Sea and over the Aleutians for the winter months (October-March) for 23 years (1957-1958 to 1979-1980). It must be noted that the apparent shift in the route for main storm tracks could be an artifact of the increase in ship reports in the latter half of this century.

A trend of higher air temperatures in the eastern Gulf since 1976 is associated with 1) anomalous sea-surface temperatures in the North Pacific, 2) below-normal temperatures north of Hawaii, and 3) above-normal sea-surface temperatures off the coast of North America (including the Gulf of Alaska) (McClain 1983). The monthly-mean-pressure pattern at 500 mb (the approximate level in the atmosphere of the winds that steer surface storms) during this time period shows a general eastward shift of the axis of a high-pressure ridge to a location over western North America. Such trends, however, are much smaller than the interannual variability. One must keep in mind that apparent trends in atmospheric data may be actual trends, may be

very long period fluctuations, or can be a persistent run expected from the statistics of a normal distribution of events. More research is necessary in this area.

Means and Variability

Wind and Wind Stress

The movement of low-pressure systems across the Gulf of Alaska is the main determinant of surface winds in the winter. A deep low (950 mb) can bring winds of devastating magnitude (>25 m/s), although winds average 8 to 11 m/s from October through February (Fig. 2-12). We have chosen to connect all the monthly-mean data in Figure 2-12 with lines to accentuate the annual cycle, although this is not strictly correct. Summer winds result mainly from the east Pacific high-pressure system or weak low-pressure systems in the Gulf. Figure 2-12 shows how mean winds decrease through the spring to a low of from 6 to 7 m/s in June, and also shows large standard deviations for all months.

Schumacher and Reed (1983) note a marked difference between the mean winds in the northcentral Gulf and those along the Alaska Peninsula, especially in the winter storm season. This difference is attributed to the location of the storm track along the Alaska Peninsula and south of the Alaska coast. In the vicinity of the storm track across the western Gulf, the wind direction is highly variable, depending on whether the low center is north, south, east, or west of a specific location. The mean-vector winds in this region have a westerly component in all months (Fig. 2-13). In the northcentral Gulf the wind is almost always from the south or east, because lows cross the Gulf to the south. The southerly component is especially pronounced in the months of transition between the two seasons (October and April). The eastern Gulf winds are predominantly southeasterly in the winter. In the summer, the mean-vector winds are smaller

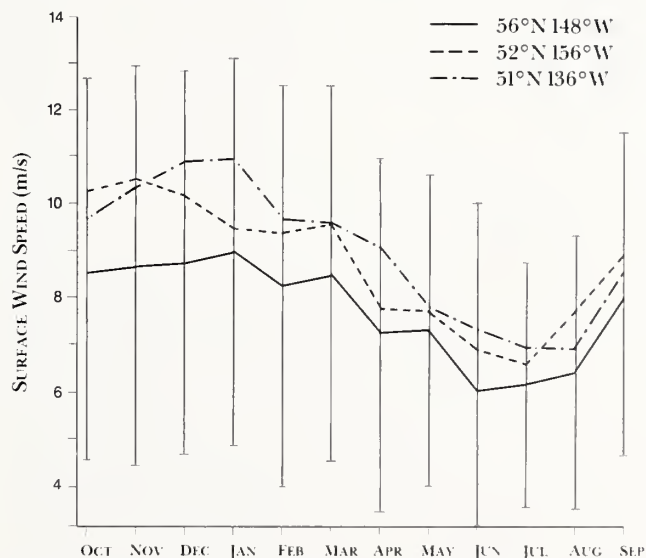


Figure 2-12. Monthly-mean surface wind speed at three Gulf of Alaska offshore NDBO buoys for the period 1972 to 1981. The vertical bars are the monthly standard deviations at the 56°N, 148°W buoy and have similar magnitudes at the other two stations. (Modified from Gilhousen *et al.* 1983.)

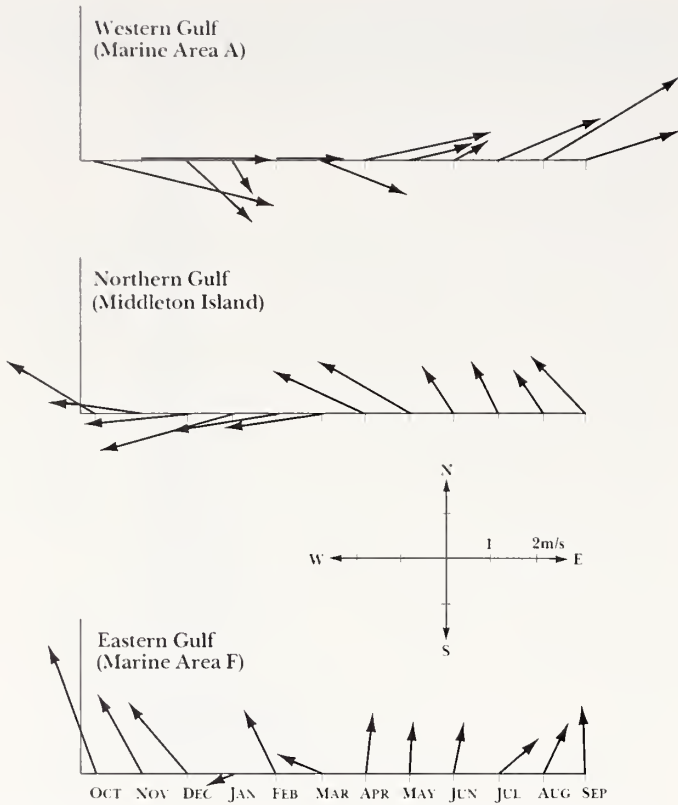


Figure 2-13. Monthly-mean vector winds (m/s) for the western, northern, and eastern Gulf. Marine area A is an average of observations (mostly by ships) in the area bounded by 157°W to 165°W and 52°N to the Alaska Peninsula. Similarly, marine area F is bounded by 54°N and 138°W to the southeast Alaska coast. The central northern Gulf is represented by observations at Middleton Island (59.4°N, 146.3°W). (Modified from Brower *et al.* 1977.)

and more south to southwesterly. In addition to the passage of storms, the nearshore wind field is also influenced by topography as discussed in the following section on local meteorology.

The annual cycle of monthly-mean wind stress based upon monthly averaged winds observed from ships over the 15-year period from 1961 to 1975 is shown in Figure 2-14 (Kutsuwada and Sakurai 1982). Momentum transferred from the atmosphere to the ocean is directed toward the east in the western Gulf. This is a region of high winds both ahead of (southwesterlies) and behind (northwesterlies) the cold fronts that cross the region. In the southeastern Gulf, the stress is directed toward the northeast through the year. Note that this subregion is shifted to the west relative to marine area F in Figure 2-13. The stress pattern in the central Gulf has high variability from month to month. The stress estimates from Han and Lee (1983) and Hellerman and Rosenstein (1983) qualitatively agree with Figure 2-14.

Radiation, Air Temperature, Sea-Surface Temperature, and Heat Fluxes

The balance of thermal energy flux at the sea surface depends on several factors, including the amount of solar

radiation that reaches the surface (minus the radiation that is reflected), as well as sensible and latent heat transferred from the sea to the adjacent atmosphere. Talley (1984) discusses the many problems associated with computing the energy balance over such a data-sparse region as the Gulf of Alaska. Budyko (1974) has mapped the terms of the energy balance equation over the earth. Many subsequent authors believe that Budyko (1974) underestimated the cloud correction factor by between 17 and 25%, thereby producing a 6 to 23% underestimate of the amount of incoming solar radiation. Given the uncertainties, Budyko's (1974) estimates of 80 to 105 W/m² for incoming solar radiation, 40 to 50 W/m² for long wave radiation, 25 to 55 W/m² for latent heat, and 6 to 16 W/m² for sensible heat transfer over a year indicate the relative importance of these processes in the Gulf of Alaska. The temperatures of the lower atmosphere and adjacent ocean are important in describing the climatology of the Gulf region and are related to the passage of storms across the region through their influence on modifying the balance of energy at the sea surface.

The monthly average spatial distributions of surface-air temperatures are shown in Figure 2-5 (Brower *et al.* 1977). A fairly steady winter temperature distribution lasts from November through April. The summer patterns show a warming through August of the region centered near the Alaska Peninsula. May and October are the two transition months that encompass most of the changes in temperature between the two seasons. The prevailing southerly winds in

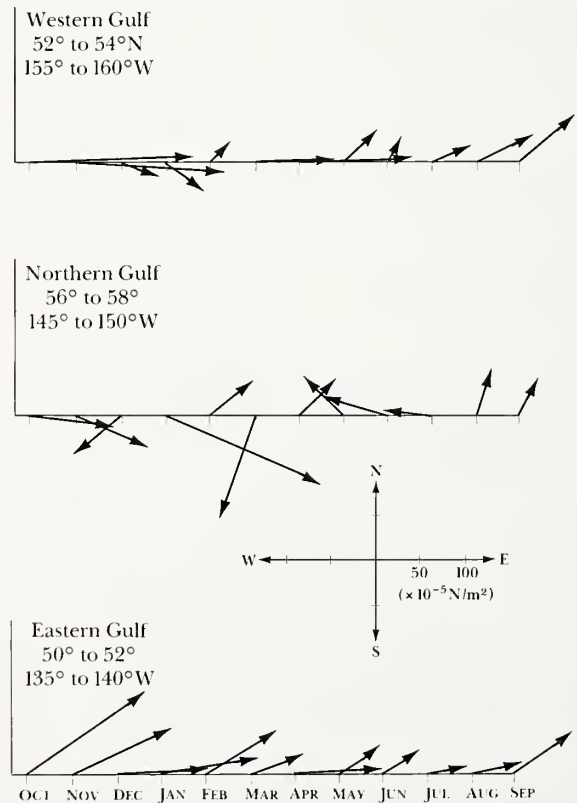


Figure 2-14. Monthly-mean wind stress ($\times 10^{-5}$ N/m²) for the western, northern (central), and eastern Gulf of Alaska for the period 1961 to 1975. (Modified from Kutsuwada and Sakurai 1982.)

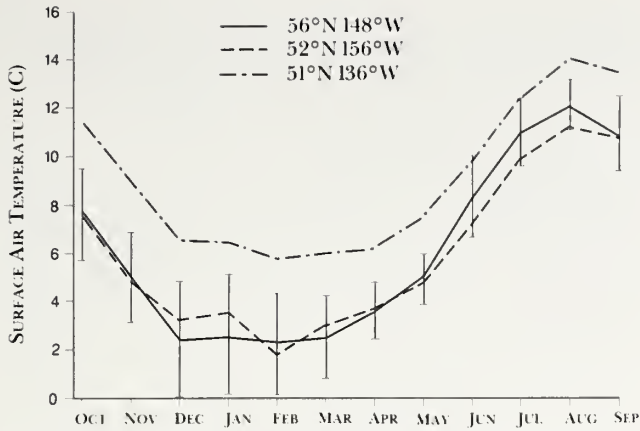


Figure 2-15. Monthly-mean surface air temperature at three Gulf of Alaska offshore NDBO buoys for the period 1972 to 1981. The vertical bars are the monthly standard deviation at 56°N, 148°W. (Modified from Gilhousen *et al.* 1983.)

the eastern Gulf produce a tongue of warmer air along the west coast of North America throughout the year. The annual cycle of air temperature at three open-ocean buoys (Gilhousen, Quayle, Baldwin, Karl, and Brines 1983) is depicted in Figure 2-15. The stations in the central and western Gulf are very similar, and they are colder than the eastern station throughout the year.

High summer temperatures for the area correspond with a minimum in variability compared with winter temperatures due to the decrease in the number and the intensity of passing storms. The air temperature over the Gulf is moderated by the ocean and is considerably warmer than continental stations at the same latitude during the winter months. Frequently throughout the winter, cold continental air will stream over the Gulf and bring a dramatic drop in temperature over the region. The rise in temperature at all three stations in January may be associated with the frequent occurrence of a blocking ridge over the Gulf during this month.

Annual-mean air temperatures show no long-term trend along the northcentral Gulf coast and southeast Alaska coast (Fig. 2-16). The annual-mean temperature of 6.3C for the period 1828 to 1876 is the same as the annual mean for the mid-1970s (Ingraham, Bakun, and Favorite 1976). The mean of the three ocean stations in Figure 2-15 is 7.1C for the years 1972 to 1981. The annual-mean air temperature was found by Ingraham *et al.* (1976) to have short fluctuations of from one to four years, such as the dramatic cooling episode from 1934 to 1936 along the south coast of Alaska and longer trends such as the cooling event that lasted from 1944 to 1955.

We have chosen to present the air-sea temperature difference instead of sea-surface temperature, because the transfer of sensible heat between the atmosphere and the ocean is directly proportional to this quantity (Businger 1973). The monthly-mean air-sea temperature differences at three ocean buoys (Fig. 2-17) (Gilhousen *et al.* 1983) are fairly constant from March through September, before decreasing through early winter to a minimum in December when cold, continental air flows over water that still retains some heat from the summer. The ocean continues to cool

throughout the winter. The small air-sea temperature differences in January are a reflection of the warmer air temperatures at the buoys (Fig. 2-15) and the cooler water temperatures of mid-winter. The difference may be the result of the frequent occurrence of blocking highs over the Gulf in that month.

The February values drop to a level between the December minimum and the summer values. Note the large variability (standard deviation) of air-sea temperature difference associated with the passage of different storm sectors during the winter months. As with air temperature (Fig. 2-15), the mean values contain individual events when cold, continental air flows over the warmer ocean. These outbreaks induce fluxes of heat that are additive with respect to the total transfer of heat from the ocean to the atmosphere over the winter season.

Latent-heat transfer depends on the difference in specific humidity between the ocean surface and the adjacent atmosphere. There are very few measurements available from over the open ocean. The composite latent heat flux shown in Figure 2-3 (Fleagle and Nuss 1985) emphasizes how important latent heat is (relative to sensible heat) to the total heat flux associated with individual storms: 120 W/m² behind the cold front compared with 20 W/m² for the sensible heat flux (Fig. 2-3). At present, there are major difficulties in estimating the monthly, regional heat transfer over the North Pacific, and there are no agreed-upon parameters (R.K. Reed, PMEL/NOAA, pers. comm.).

Cloud Cover, Fog, and Coastal Visibility

The Gulf of Alaska is almost always what meteorologists refer to as 'mostly cloudy'. Figure 2-18 shows monthly cloud cover estimates at three locations taken from Favorite *et al.* (1976) that are based on shipboard observations taken from 1948 to 1967 on a 5° latitude-longitude grid. The cloud cover is a minimum in the winter increasing through the spring to a maximum in July, then decreasing in late summer and early winter. Over the main body of the Gulf there is a cold, low-level stratus deck in mid- and late-winter (Grubbs and McCollum 1968).

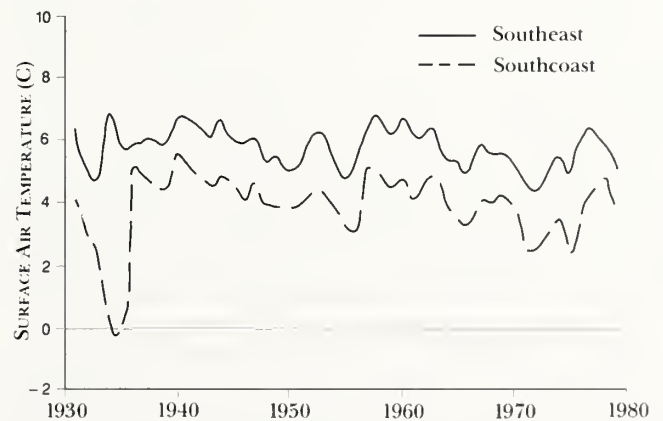


Figure 2-16. Annual-mean surface air temperatures along Southeast Alaska (defined as the Canadian border to south of Yakutat) and southcoast Alaska (defined as Yakutat to 155°W) for the period 1931 to 1979. (Modified from Royer 1982.)

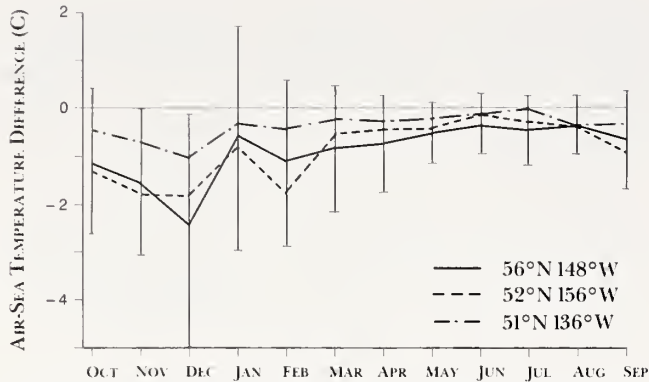


Figure 2-17. Monthly-mean air-sea temperature difference at three Gulf of Alaska offshore NDBO buoys for the period 1972 to 1981. The vertical bars are the monthly standard deviations at 56°N, 148°W. (Modified from Gillhousen *et al.* 1983.)

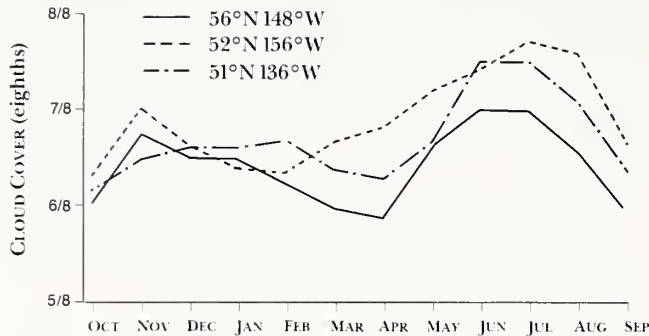


Figure 2-18. Monthly-mean cloud cover estimates in eighths at three Gulf of Alaska offshore NDBO buoys for the period 1948 to 1967. (Modified from Favorite *et al.* 1976; Fig. 31, data drawn from 5° latitude-longitude grid.)

Winter cloudiness is associated with the passage of cyclonic systems and with the flow of cold, continental (relatively dry) air off the Alaskan continent over the relatively warm Gulf waters. The winds that originate over the continent or over the Bering Sea seasonal ice field are associated with cloud streets and cumulus convective cells over much of the Gulf (Walter 1980; Overland and Wilson 1984). Cumulus convection is typical after the passage of a cold front. The north and northeastern sectors of a storm are typified by solid overcast (Fig. 2-2). Under the east-Pacific high-pressure system in summer, moist air near the surface is trapped by a low-level temperature inversion resulting in persistent fog and low stratus clouds over the Gulf.

The average number of clear days (less than one-eighth cloud cover) along the Gulf of Alaska coast is four to seven per month (Grubbs and McCollum 1968). In the summer, Grubbs and McCollum (1968) found that some cloudiness along the coast was present throughout most of the day and increased in the evening.

Fog occurs over the Gulf of Alaska in every month of the year. It is most prevalent in the summer and the early winter months (Grubbs and McCollum 1968; Guttman 1975). During the winter, supercooled fog occurs in the vicinity of ice-covered Cook Inlet.

Visibility in the coastal regions is often restricted by fog, rain, or snow. The increased shower activity both in early

winter and in late winter (a secondary maximum) brings low visibility (Grubbs and McCollum 1968). In general, early summer is the time of year with the greatest visibility.

Precipitation and Runoff

The precipitation over the Gulf of Alaska varies between 0.8 and 100 cm/yr, except along the Southeast Alaska coast where oceanic precipitation exceeds 100 cm/yr (Reed and Elliott 1979). The maximum monthly mean precipitation occurs during the winter, in association with the maximum in cyclone activity, with 8 to 10 cm/mo during December, January, and February and greater than 10 cm/mo falling near Southeast Alaska. The precipitation amount is reduced to 7 to 8 cm/mo in March, April, and May, less than 5 cm/mo in the summer, and rises to 7 to 8 cm/mo in September, October, and November. These averages are based on sparse temporal and spatial precipitation-frequency data from almost a century of observations. The Reed and Elliott (1979) and the Elliott and Reed (1984) annual estimates of 100 cm/yr near the Southeast Alaska coast contrast with the Dorman and Bourke (1978) estimate of 180 cm/yr. The latter, however, was corrected with coastal data that showed higher precipitation rates due to the proximity of the mountains. This is a persistent problem in making open-ocean precipitation estimates.

The annual precipitation distribution over Alaska is shown in Figure 2-19 (Reed and Elliott 1979; Royer 1983). Near the coast, the onshore flow of moist, marine air is forced up the slope of coastal mountains. As the air cools, precipitation is enhanced. Air cooling over glaciers also enhances precipitation. There is a large variation in precipitation in mountainous regions where the amount is determined both by the height to which air is lifted and by the presence of glaciers. A maximum of over 800 cm/yr of precipitation occurs in the mountains of Southeast Alaska (Fig. 2-19). Grubbs and McCollum (1968) report that the precipitation in coastal regions generally occurs from 14 to 16

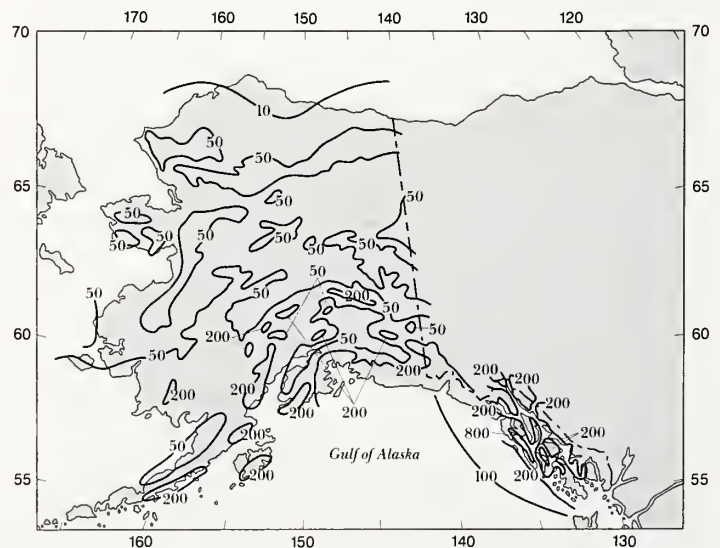


Figure 2-19. Annual-mean precipitation (cm) for the Gulf of Alaska (after Reed and Elliott 1979), and over Alaska (after Royer 1983, courtesy of Larry Mayo).

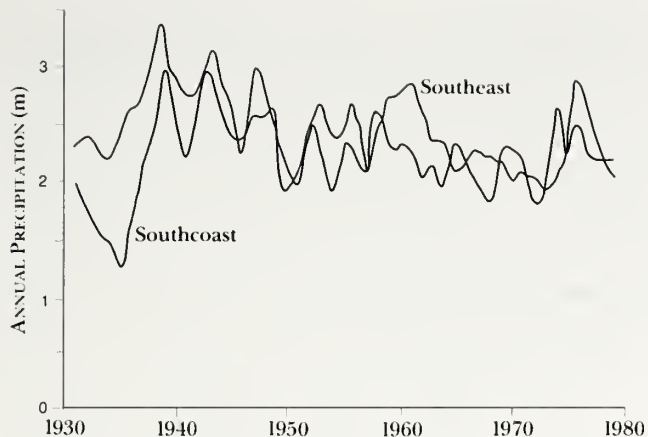


Figure 2-20. Annual-mean precipitation along Southeast Alaska (defined as the Canadian border to south of Yakutat) and southcoast Alaska (defined as Yakutat to 155°W) for the period 1931 to 1979. (Modified from Royer 1982.)

d/mo in the mid-winter and from 18 to 22 d/mo in the late summer and early winter. The annual mean precipitation for a 49-year period at stations along the south and southeast coast of Alaska is shown in Figure 2-20 (Royer 1982).

A result of the high precipitation rates along the Alaskan coast is a high rate of freshwater runoff into the Gulf of Alaska. Precipitation that falls in the coastal mountains either runs off or is stored in the mountains in the form of snow and ice. Glaciers that cover ~20% of the coastal drainage area (Royer 1982) retain the precipitation that falls there for periods ranging from months to years.

It is impossible to measure all or even most of the freshwater discharge into the Gulf because of the large number of rivers and streams along the Alaskan coast. However, Royer (1982) uses monthly mean precipitation rates, air temperatures, area of the drainage regions, and the interannual growth and ablation rates of glaciers to compute runoff. Maximum runoff occurs in late summer and early winter due to a combination of meltwater runoff and the increased precipitation that occur during winter (Royer 1982) (Fig. 2-21). The runoff rates decrease quickly after November when the air temperature drops below the freezing level and precipitation is stored as snow. Royer (1982) found that the discharge is at a minimum in February and March, then increases to the maximum in October with a secondary maximum occurring in May. This secondary maximum is due to summer snow melt in the mountains and is more pronounced south of the Gulf region where less precipitation is retained in glaciers.

Royer's (1982) annual discharge rates for 49 years along the Alaska coast are shown in Figure 2-22. The mean discharge rate for the period is $2.3 \times 10^4 \text{ m}^3/\text{s}$. These estimates exclude the Copper River ($1.05 \times 10^3 \text{ m}^3/\text{s}$) and the runoff that enters the Gulf of Alaska from British Columbia (Fraser River rate is $2.69 \times 10^3 \text{ m}^3/\text{s}$) or the northwest United States. The Copper River was found to be less than 5% of the total discharge for the region, which is well within the error estimates. Royer (1982) believes, however, that the freshwater input from British Columbia and the northwest United States is probably significant. Also plotted in Figure 2-22 is the pressure index from Emery and Hamilton (1985) and the

NPO years from Rogers (1981). The correlation coefficient is 0.43 for the discharge and pressure-index time series. Of special interest are years when a high-pressure index and/or a 'B' NPO index (intensified Aleutian low) are coincident with high runoff (1940, 1944, 1953, 1960, 1975, and 1976).

Other Means and Variabilities

In addition to means and variabilities in the categories of wind, radiation, cloud cover, and other topics we have covered in this section, there are three additional categories to address: 1) superstructure icing, 2) sea ice, and 3) waves.

Superstructure Icing. When the air temperature is below the freezing temperature of seawater (-1.7C at a sal-

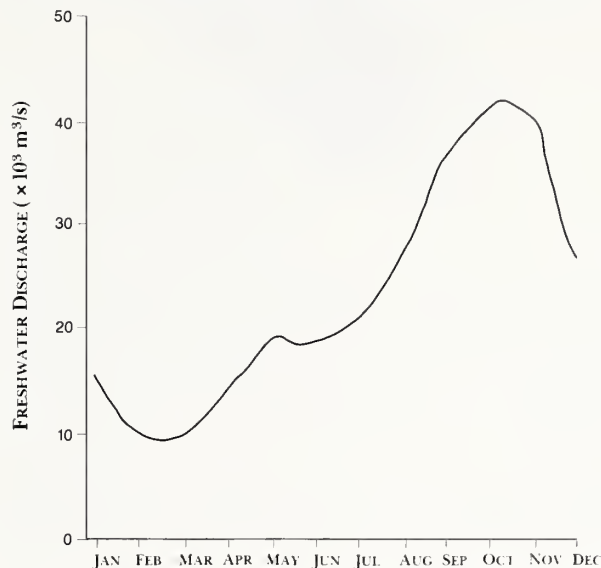


Figure 2-21. Monthly-mean discharge of freshwater into the Gulf of Alaska for the period 1931 to 1979. (Modified from Royer 1982.)

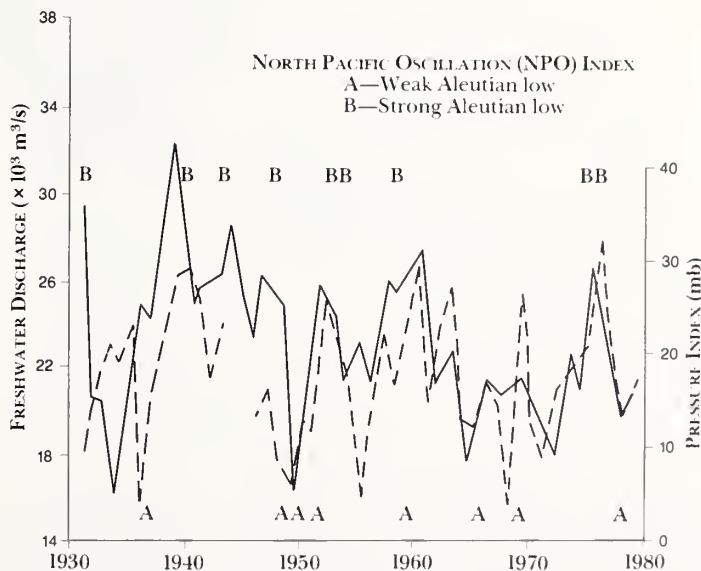
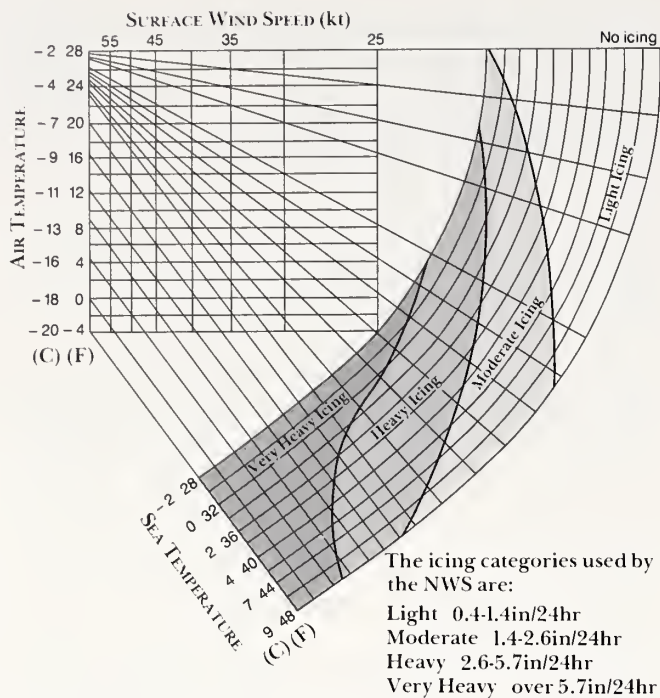


Figure 2-22. Annual-mean discharge of freshwater into the Gulf of Alaska for the period 1931 to 1979 (solid line). (Modified from Royer 1982.) Superimposed is the Emery and Hamilton (1985) pressure index and the Rogers (1981) North Pacific Oscillation (NPO) index.



Instructions: Say that you estimate that the air temperature is 14°F, wind velocity is 30 knots, and the sea temperature is 32°F. Enter the nomograph on the 14°F line. Follow this line to the 30 knot wind velocity line. From the intersection of the two lines, follow the diagonal line to the 32°F sea temperature line. At the intersection read off the icing category, in this case, heavy icing.

Figure 2-23. Superstructure icing nomogram uses wind speed and air and sea temperatures to predict ice accumulation on ships and other structures. (Modified from Comiskey 1976.)

nity of 35‰), any water in the air (e.g., fog, rain, and sea spray) will freeze to structures on ships, platforms, and low-flying aircraft. The accumulation of ice on structures due to sea spray is a complicated process depending on air and sea temperatures, wind speed, wave direction relative to the structure, and structure configuration. Comiskey (1976) developed an icing nomogram using wind speed along with air and water temperatures for forecasting ice accumulation from sea spray (Fig. 2-23). A more recent algorithm (Overland, Pease, Preisendorfer, and Comiskey 1986) predicts icing rates of more than three times those predicted by the Comiskey nomogram.

Although the water temperature in the southern reaches of the Gulf is generally warm enough to avoid icing problems, near Kodiak Island and along the Alaska Peninsula during the winter a ship can accumulate ice on its superstructure that makes it top-heavy and susceptible to sinking. Locations where superstructure-icing have occurred, as reported by Wise and Comiskey (1980), are shown in Figure 2-24. The actual area where conditions favor icing may be broader, but other data are not available. The lack of data is especially important north of the Alaska Peninsula where there has been little winter shipping traffic. Recent evaluations suggest that values shown in Figure 2-23 may underestimate icing rates.

Sea Ice. Cold temperatures and freshwater runoff combine to cause many inlets and embayments to be frozen over in the winter. The onset of ice at the head of Cook Inlet is most highly correlated with the meteorological parameter, adjusted-frost-degree-days (Poole and Hufford 1982). The southern extent of the ice in Cook Inlet was determined to be dependent on the rate of freshwater inflow, the tem-

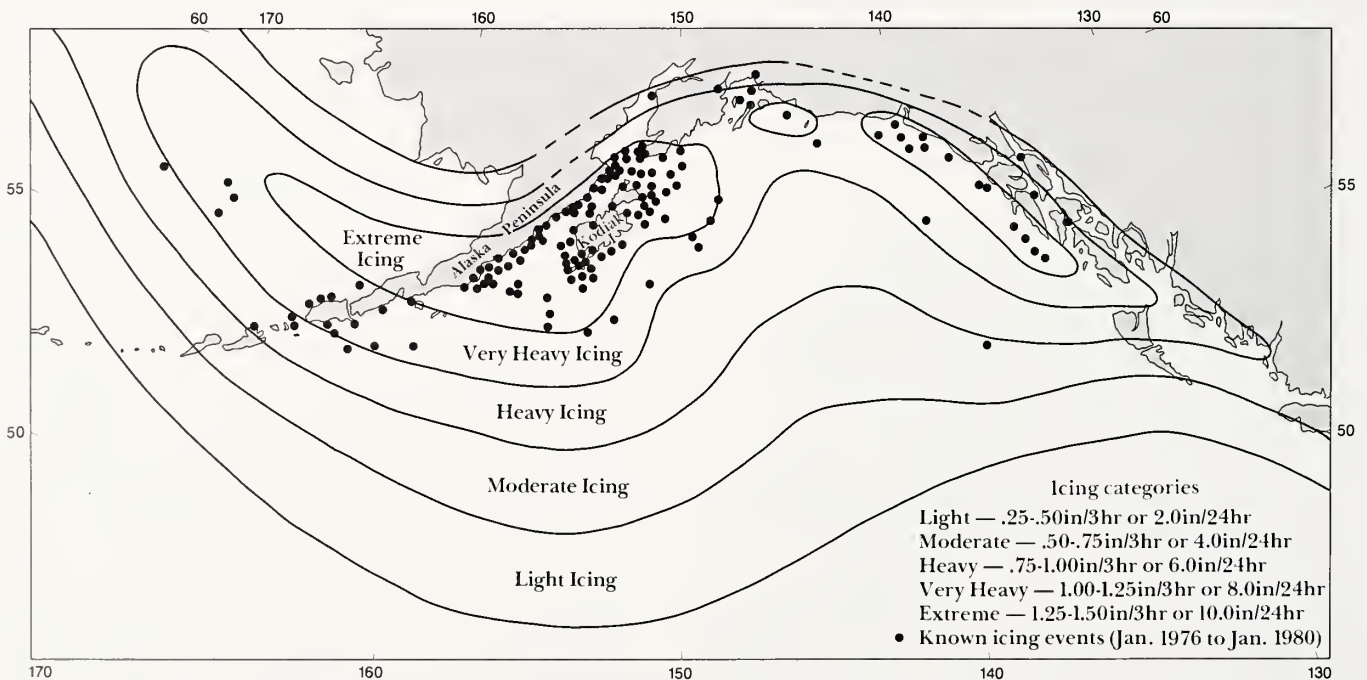


Figure 2-24. Estimated zones of icing categories under the most extreme conditions in the Gulf of Alaska. Black dots are locations of known icing events from January 1976 to January 1980. (Modified from Wise and Comiskey 1980.)

perature of Gulf of Alaska water, and the local winds that advect the ice. Maximum ice extent usually occurs in February. In the period of the Poole and Hufford study (1969–1980), the ice edge during minimal-ice years was in the vicinity of Kalgin Island in Cook Inlet. In abundant-ice years, the ice edge extended from north of Anchor Point on the Kenai Peninsula to Cape Douglas on the Alaska Peninsula.

Occasionally, pieces of ice break away either from glaciers or from the seasonal ice pack in one of the many ice-filled inlets along the coast (*e.g.*, Prince William Sound and Yakutat Bay) and drift into the warm Gulf of Alaska water.

Waves. Wave size is determined by the wind speed, wind duration, and the distance that the waves have traveled over the surface (fetch). Waves generated locally are called 'seas', and waves that continue with no relation to the local wind are termed 'swell'. Swell travels on great circular courses.

Waves are reported by significant wave height, defined as the mean height of the highest 1/3 of the waves observed over a 20-minute period (Shepard 1973). The annual cycle of significant wave height at three buoys in the Gulf of Alaska is shown in Figure 2–25 (Gilhousen *et al.* 1983). The pattern is very similar to that of the surface wind speed (Fig. 2–12), with a broad maximum occurring in the winter months and a minimum occurring in June and July. Maximum-significant-wave heights (Fig. 2–26; the 99th percentile) at these same buoys show a similar pattern. The low maximum-wave heights in January and February are related to the lighter winds associated with blocking highs that can develop during these months (Fig. 2–10).

The Aleutian Islands block the propagation of swell from the west into the Gulf and limit the fetch for westerly winds. Maximum wave heights occur when a storm moves into the Gulf from the south and when the winds have a south or southwesterly fetch associated with a slow-moving, intense cold front (Cardone 1980).

In the Gulf of Alaska, it is important to consider the interaction of waves with tidal and other currents. Wind opposing water movement alters the shape and speed of waves. Coastal inlets of the Gulf are typified by large tidal-height ranges with associated tidal current speeds of up to 150 cm/s (Cook Inlet; Muench and Schumacher 1980). The waves steepen when incoming seas or swell is opposed by the ebb flow from inlets and straits. The predominant surface current is westward around the perimeter of the Gulf in response to the cyclones that dominate the region. Locally generated seas opposing this flow may steepen from their interaction with the current and may become an important hazard to navigation.

Local Meteorology

The mountain arc that bounds three sides of the Gulf of Alaska has a dominant influence upon the meteorology of the coastal zone. Topography modifies wind fields, precipitation, and visibility associated with a particular storm

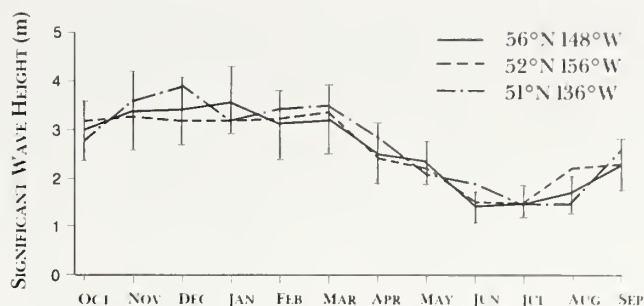


Figure 2–25. Monthly-mean significant wave height (including seas and swell) at three Gulf of Alaska NDBO buoys for the period 1972 to 1981. The vertical bars are the monthly standard deviations at 56°N, 148°W. (Modified from Gilhousen *et al.* 1983.)

structure; the storm structure itself is modified by the presence of the mountain arc.

Over the open ocean, low-pressure cyclones have horizontal scales of from 500 to 1,000 km (Fig. 2–2). On these scales there is a very strong balance between the pressure-gradient force (the field of mass) and the Coriolis force (the field of motion). This results in the geostrophic balance. When imbalances occur due to variations in sea-surface temperatures, small-scale radiation, or latent-heat release in clouds, the wind field and the mass field will return to a geostrophically balanced state. This occurs within about 12 hours through a process called geostrophic adjustment. If, however, a high coastal mountain arc is present, the wind field near the surface cannot flow through the mountain barrier. Therefore, a geostrophic balance cannot be maintained with a pressure gradient oriented parallel to the mountain chain. This imbalance has major consequences both for the modification of storm systems as they approach the coast and for the resulting coastal wind fields.

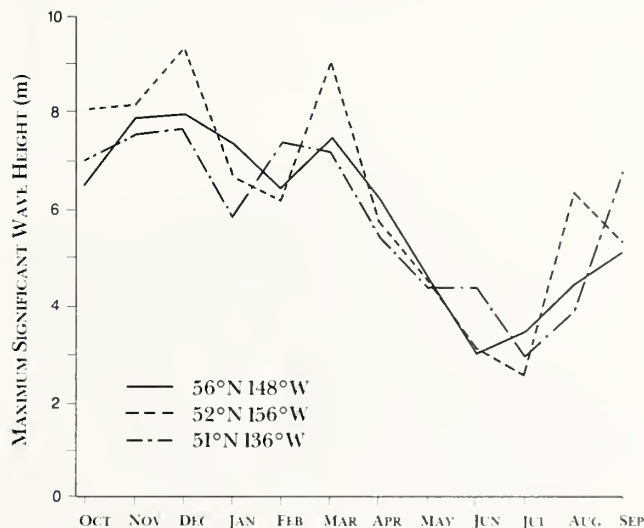


Figure 2–26. Maximum significant wave heights (including seas and swell) at the same three Gulf of Alaska offshore NDBO buoys as shown in Figure 2–25. The 99 percentile values for each month were used because they had an average of 16 occurrences (vs. 1 for the 100 percentile) in the period from 1972 to 1981. (Modified from Gilhousen *et al.* 1983.)

Nearshore Winds

Analysis of the equations of atmospheric motion (Overland 1984) shows that wind fields within a distance of 80 km of a 1,500- to 2,000-m high coastal mountain range are systematically modified by the presence of the topography. Beyond this distance (technically known as the Rossby radius of deformation), air flow is cyclonic around a low-pressure system as shown in Figure 2-2.

Within the Rossby radius, the response of the wind depends upon the orientation of the lines of constant sea-level pressure (isobars) to the coastline. If the isobars are aligned parallel to the coastline, the winds can continue to flow parallel to the isobars in a near-geostrophic momentum balance. If, however, the isobars are perpendicular to the coastline, the winds cannot blow through the mountain wall. They will tend to flow, instead, from regions of high atmospheric pressure to regions of low pressure. A special case is marine straits whose widths are the same or smaller than the Rossby radius (Fig. 2-27). Here winds tend to accelerate from regions of high pressure to regions of low pressure when the pressure gradient is parallel to the axis of the strait (*i.e.*, the isobars are perpendicular to the strait).

For example, in the vicinity of Kodiak Island, on 4 March 1983, the NOAA WP-3D research aircraft rapidly mapped the spatial variation of the surface wind field and sea-level pressure field (Fig. 2-28) (Macklin, Overland, and Walker 1984). The wind field to the east (seaward) of the Kennedy and Stevenson entrances to Cook Inlet showed winds roughly parallel to the isobars over the open ocean. The winds in Cook Inlet flowed from high pressure in the north to low pressure further south. In Shelikof Strait there was some turning of the winds at the northeast entrance, but in the Strait proper, winds increased in magnitude toward the southwest as they accelerated down the pressure gradient, the so-called gap wind (Overland and Walter 1981). There are abrupt changes in the wind field at the exits to straits, such as the southern end of Shelikof. Such rapid changes in the wind field produce very confused wave fields and must

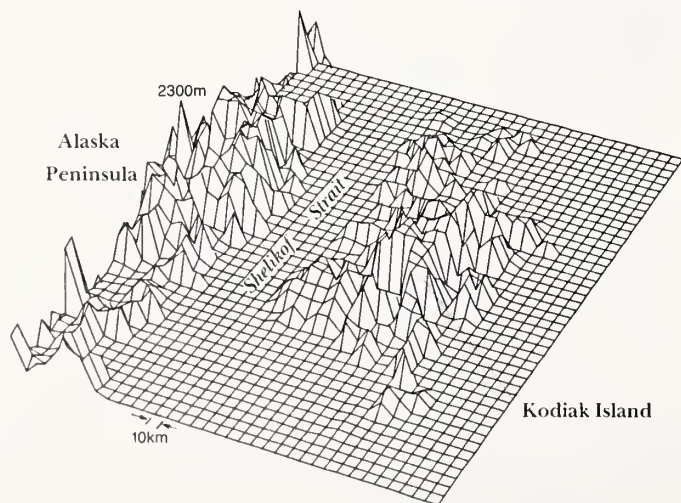


Figure 2-27. Topography of Kodiak Island and the Alaska Peninsula that bound Shelikof Strait (on a 10-km grid). Vertical exaggeration $\times 40$.

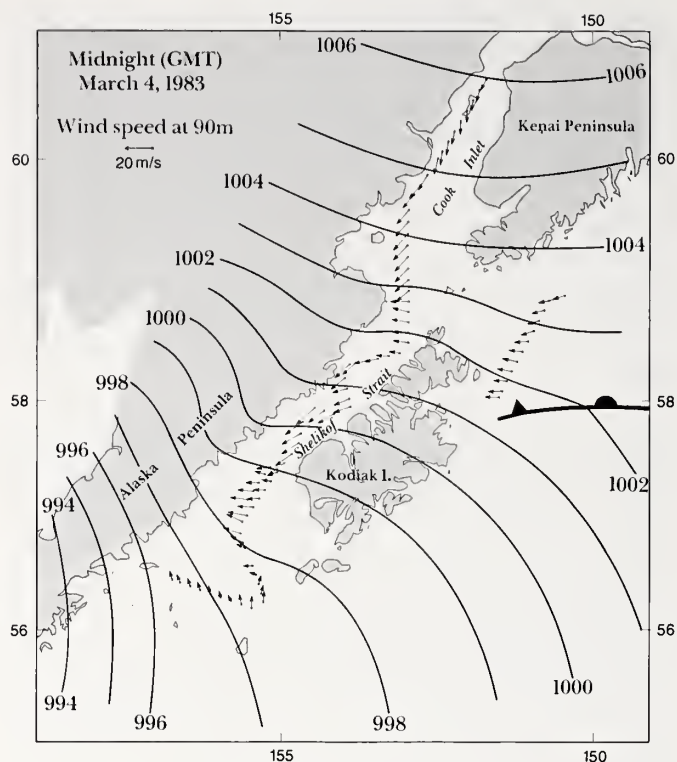


Figure 2-28. Sea-level pressures (mb) and 90-m wind measurements (m/s) from the NOAA WP-3D aircraft (additional pressures from large-scale analysis). Winds in Shelikof Strait turn toward the pressure gradient parallel to the axis of the Strait with rapid readjustment to geostrophic conditions at the southern exit region. The offshore wind field is seen on the right side of the figure. (Modified from Macklin *et al.* 1984.)

certainly have an influence on local ocean upwelling patterns.

Katabatic Winds

A second class of coastal winds is katabatic flow, characterized by cold air masses at higher elevations that accelerate down slope as a result of gravity and a large-scale pressure gradient. These flows funnel through straits and fjords and influence coastal regions (Reynolds, Macklin, and Heister 1981). Historically, katabatic flow is divided by length scale into fall (also called bora or Taku) winds and gravity winds.

Fall winds are a large-scale phenomenon driven by the large-scale pressure gradient and a reservoir of cold air in an elevated interior of the coastal mountains. The air in the interior is cold enough to remain cold relative to the surrounding air mass as it descends, despite the tendency of descending air to warm due to higher pressure at lower altitudes. As the cold air flows down to the sea, it accelerates and becomes highly turbulent (Defant 1951). A typical winter weather situation is shown in Figure 2-29 (Reynolds *et al.* 1981), where high pressure and cold temperatures exist inland with a low-pressure center offshore. This situation where the cold air is accelerated down slope by gravity reinforced by the pressure-gradient forces is favorable for wide-spread katabatic flow throughout Southeast Alaska (Kilday 1970). In Figure 2-29, the wind barb northeast of 'A' and lines of clouds at 'B' are both perpendicular to the lines

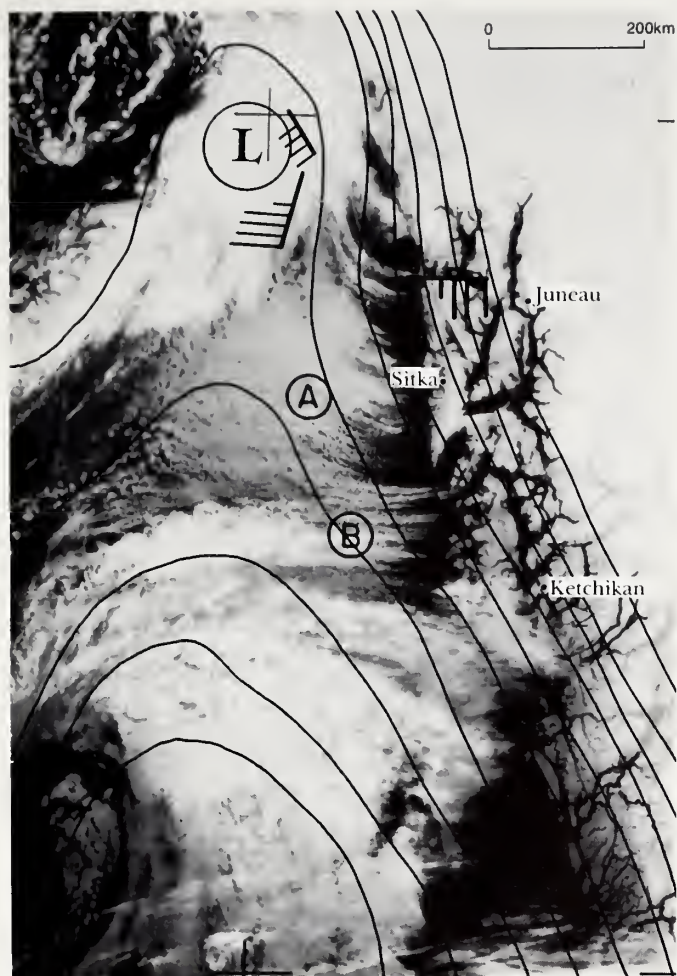


Figure 2-29. Satellite photograph of the Gulf of Alaska showing winds blowing away from the coast and their modification into the synoptic scale pattern. (Modified from Reynolds *et al.* 1981.) On the wind barb, short crossbars indicate 5-kt wind speed increment; long bars indicate 10 knots.

of constant pressure, indicating katabatic winds. Observations show that wind onset times and maximum velocities are both independent of time of day.

Often, large land/sea temperature differences are sufficient to produce near-continuous offshore flow. A cold continental air mass maintains the interior pressure higher than the warmer ocean regions. Often, these winds flow down large river valleys such as the Susitna Valley at the head of Cook Inlet. In the vicinity of Anchorage, the winds are channeled down Cook Inlet and dominate the winter wind field as far south as Augustine Island (Macklin, Lindsay, and Reynolds 1980). When the pressure gradient is increased by an approaching oceanic cyclone, the winds can become quite intense.

The gravity wind is a local katabatic flow. Interchangeably called 'drainage wind', 'mountain wind', or 'katabatic wind', it is caused by greater air density next to a mountain slope than at the same elevation away from the slope. Highly dependent on net radiation at the surface, the air flows downhill in balance with frictional drag, the Coriolis force, and the large-scale pressure field. Because of the earth's

rotation, the flow is inclined away from the line of steepest descent (Ball 1960), but is still focused into valleys and estuaries where violent winds can occur.

In many locations, katabatic winds are highly intense and short-lived. One particular type of gravity wind is the glacier wind, which is a continuous flow down the surface of the glacier. Glacier winds are relatively independent of solar heating (Defant 1951). Its thermal gradient is due to the temperature difference between the ice surface and free air at the same elevation. In general, these winds are relatively light, but there are dramatic exceptions.

Virtually every Alaskan estuary along the mountainous coastline is dominated by outflow resulting from katabatic drainage. Winds at the mouths of estuaries such as Icy Bay on the southeast coast of Alaska often exhibit up to 50-m/s velocities (Searby 1969). When the estuary is the terminus of one or more glaciers, outflow winds show little diurnal variation and are relatively persistent, especially in the winter months. Estuaries without glaciers exhibit more diurnal katabatic winds, called nocturnal winds. At the coast, an offshore wind often flows under the prevailing maritime air mass.

An example of the offshore persistence of katabatic flow off of Malaspina Glacier is shown in Figure 2-30 (Reynolds *et al.* 1981). Data for this example were measured on a transect completed by the NOAA Ship *Discoverer*. A transition to a marine air mass occurred between 19 and 29 km offshore. One can only speculate that the abrupt transition to a nearly geostrophic flow occurs at a distance where the coastal mountain influence on geostrophic adjustment is diminished.

There is onshore flow when high pressure exists over the Gulf and a low-pressure center is present over Alaska. This is one of the few situations when there is flow inland through the gaps in the mountains (Overland and Heister 1978).

Storm/Mountain Interaction

The lack of geostrophic adjustment in the surface layers of the atmosphere adjacent to a mountainous coastline must not only modify the surface wind but modify the storm structure as well. When a storm such as the one shown in Figure 2-31 (top) (Reynolds 1983) strikes the coast, a secondary low-pressure feature can often be observed later to the north of the original low-pressure center (Fig. 2-31, middle and bottom). As the parent storm is impeded by the Alaskan coastline, two phenomena result: 1) the low is distorted due to a tightening of the low-level pressure gradient normal to the shore, and 2) the distorted low then combines with favorable conditions for offshore-katabatic winds to create an intense, shallow front, which generally resides within 60 km of the coast.

The presence of a secondary low (Fig. 2-31) can be the result of several conditions, including: 1) northward propagation of energy from the parent low along the mountainous coast, 2) local storm development due to the low-level convergence of the wind field, and 3) instability associated with extreme horizontal-temperature gradients at the front. Clearly, this area requires more research.

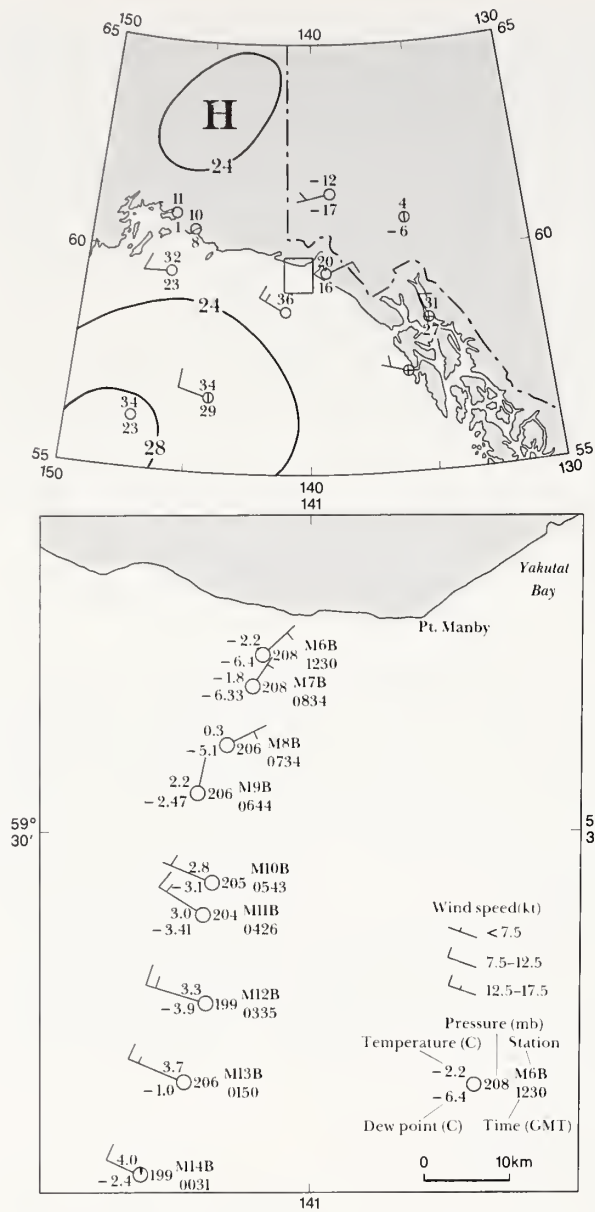


Figure 2-30. Weather map for the northeast Gulf of Alaska, 1200 GMT, 9 March 1976 (top). Temperatures (above circles) and dewpoints (below circles) are in F, pressure contours in mb - 1000. Surface observations for the NOAA ship *Discoverer 9* March 1976 trackline (bottom). Open circles indicate clear skies; atmospheric pressure coded as (mb - 1000) × 10. (Modified from Reynolds *et al.* 1981.)

Conclusions

Effect of Weather on Ocean Circulation

One of the most obvious effects the weather has on the ocean is in the generation of wind-induced currents. Research has established that weather in the Gulf is dominated by the presence of low-pressure atmospheric systems in winter and that cyclone activity exists throughout the year. A low-pressure center in the Gulf of Alaska along with its associated counter-clockwise winds induce divergent flow at the ocean surface. Because the Gulf is ringed by land to the east, north, and west, the divergence of surface flow is

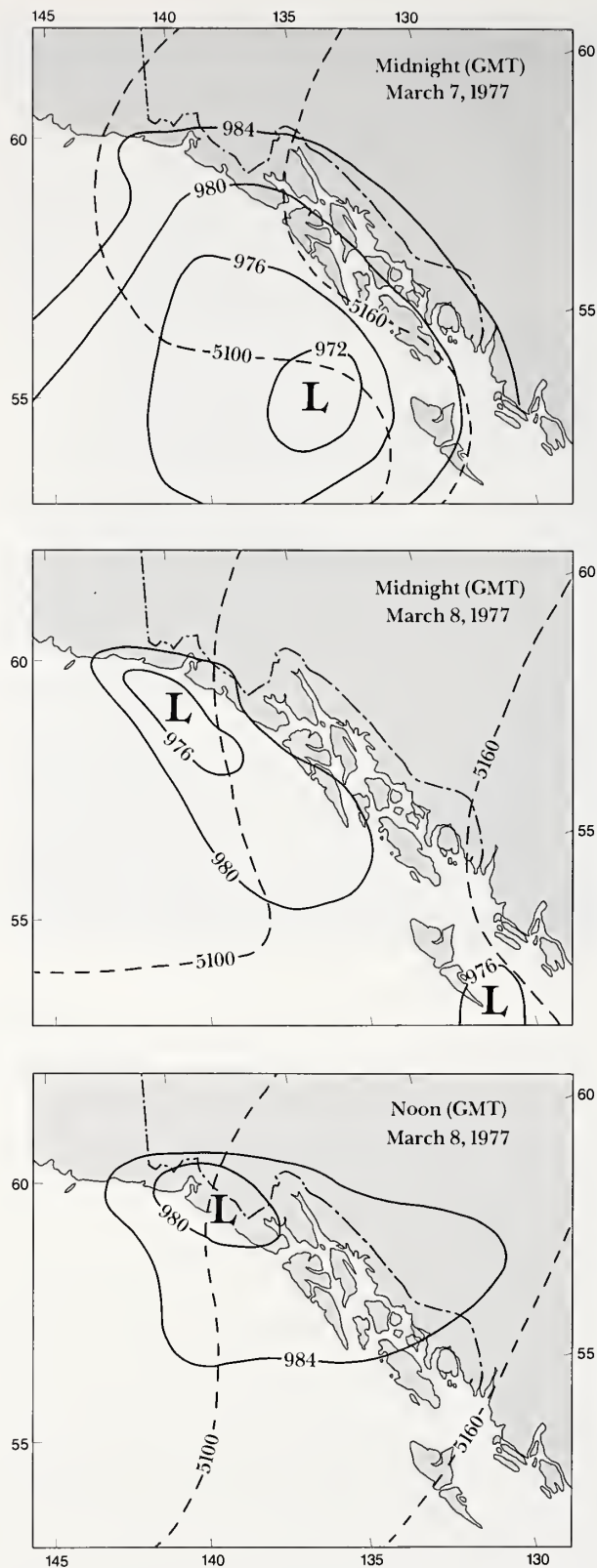


Figure 2-31. Three weather maps showing the northwestward shift of a surface low-pressure center as the system impacts the coast. There is an associated northward propagation of a wave in the 500-mb height field. The solid lines are contours of sea-level pressure (mb); the dashed lines are heights (m) of the 500-mb pressure surface. (Modified from Reynolds 1983.)

trapped by the coast. As water piles up along the coast, sea-level height increases. A barotropic pressure gradient develops perpendicular to the coast and generates a westward-flowing alongshore current called the Alaska Coastal Current (Royer 1983; Schumacher and Reed 1983).

Along the Aleutian Islands, the picture changes because the coastal area is no longer persistently to the north or east of passing low-pressure centers. Averaged over a winter season, the coastal current along the Aleutians is not as narrowly confined to the coast as the Alaska Coastal Current (Royer 1983) and mean transport is small. However, individual storms induce strong transport on- or offshore (J.D. Schumacher, PMEL/NOAA, pers. comm.).

In the summer months, anticyclonic winds associated with the east Pacific high-pressure system and the cyclonic winds of weak low-pressure systems are much less intense than those produced by winter cyclones. For this reason, surface currents driven by summer winds in the northern and eastern Gulf are much weaker (Reed and Schumacher, Ch. 3, this volume).

Downwelling and upwelling in the ocean are related to the component of the surface wind that runs parallel to the shoreline. The mean alongshore wind component is southerly in the eastern Gulf and easterly along the Kenai Peninsula and northcentral Gulf coast, favoring coastal convergence and downwelling in the ocean. It is westerly at Unimak Pass, favoring upwelling and offshore transport of water (J.D. Schumacher, PMEL/NOAA, pers. comm.) (Fig. 2-32). Strickland and Sibley (1984) used the upwelling index in Ingraham *et al.* (1976) to produce Figure 2-33. Downwelling is clearly indicated east of Kodiak Island throughout the winter, with weak upwelling from May through September. Upwelling, albeit weak, dominates the pattern in the vicinity of Unimak Pass.

In addition to wind-driven currents, cyclones in the Gulf of Alaska influence the coastal currents through the runoff of precipitation (Fig. 2-21). Freshwater runoff is added to the coastal waters, thereby inducing a salinity (density) gradient that enhances the density-driven component of the coastal current (Royer 1982; Schumacher and Reed 1983). The swift current extends from Southeast Alaska to Kodiak Island. The current is maintained as a narrow jet along the coast by the onshore Ekman transport associated with winds over the northcentral and eastern Gulf. The seasonal cycle and anomalies of sea level and transport are well correlated with precipitation and runoff rates (Royer 1979). Precipitation runoff along the coast of the Gulf of Alaska is one of the major contributors to the seasonal variability of the Alaskan Stream and Alaska Coastal Current.

In the eastern Gulf, sea-surface temperature anomalies may be caused by a wave-like coastal propagation of warm water northward from the tropical Pacific. However, the anomalies are more likely caused by increased southeasterly winds. Such winds are associated with an intensified Aleutian low that induces a northward transport of relatively warm water (Emery and Hamilton 1985). Anomalies in the western and central Gulf are the result of local air-sea transfer.

During episodes of cold-air outflow through river valleys like the Copper River, the water column is quickly cooled.

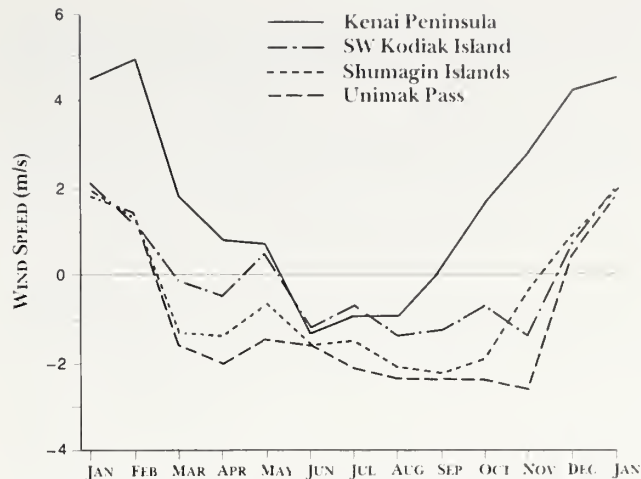


Figure 2-32. Monthly-mean along-shelf (240°) wind component of the geostrophic wind for the period from 1973 to 1980 (from J.D. Schumacher, PMEL/NOAA, pers. comm.). Winds are derived from hemispheric gridded pressure data. Positive values favor coastal convergence and downwelling in the ocean.

The cold, fresh water contains a huge volume of suspended sediments and may become unstable and sink toward the sea floor. This process may be an important consideration in understanding the distribution of suspended sediments in coastal areas (Feely, Baker, Schumacher, Massoth, and Landing 1979).

Effect of Weather on Regional Biology

The Gulf of Alaska is a very important world fishery (OCSEAP Staff, Ch. 14, this volume; Rogers, Ch. 15, this volume). Understanding the physical environment of the Gulf is important to fishery management.

One important factor in determining the reproductive success for many species of fish is the transport by water motion of eggs and larvae in nursery regions. The dominant

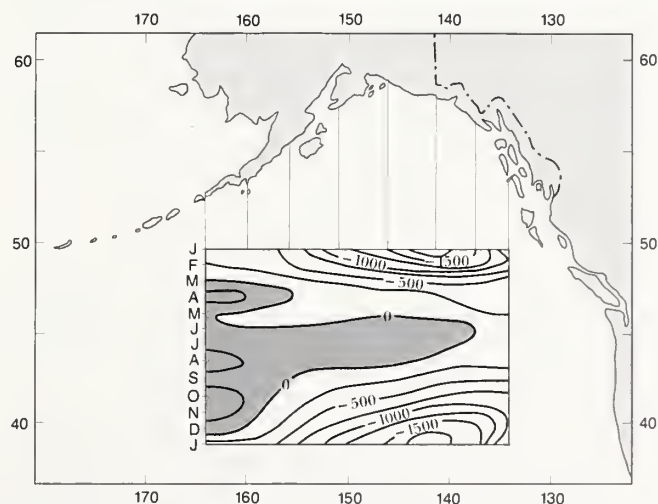


Figure 2-33. Monthly distribution of coastal upwelling and downwelling (m^3/s per kilometer of coast) in the Gulf of Alaska. (Modified from Strickland and Sibley 1984; Fig. 21.) Positive values (shaded) denote upwelling. (Modified after Ingraham *et al.* 1976.)

winds associated with lows crossing the Gulf generally favor coastal convergence, so that fish eggs and larvae remain in their coastal nursery areas over the continental shelf. Bailey (1981) studied the Pacific whiting and found that the distance of larvae from shore was positively correlated with the wind-driven Ekman transport. Since the juvenile nurseries are inshore, offshore Ekman transport is negatively correlated with year-class strength (a measure of the number of adult fish available to the fishery in any one year).

Strong winds associated with storms that induce offshore transport in the coastal regions of the Gulf of Alaska may be catastrophic for pelagic fish eggs and larvae. This is because they will be transported away from their nutrient-rich nurseries over the shelf into either the swift Alaskan Stream or Alaska Coastal Current.

Wind-driven coastal convergence also affects sea level, where high sea levels correspond both to onshore convergence and to reduced offshore transport. Mysak, Hsieh, and Parsons (1982) found a high positive correlation between the year-class strength of herring and the sea level in northern British Columbia. High sea level is also well correlated with the survival of herring larvae in inshore nurseries (Stevenson 1962).

Storm winds mix the upper layers of the ocean. In shallow regions, this mixing may extend to the sea floor. In years when storms are frequent, Sambrotto and Goering (1983) found high biological production levels and an increase in total organic matter that reached the benthos (ocean bottom community). During annual phytoplankton blooms, the upper ocean stratification (which is roughly inversely proportional to mixing) is important to the rate of nitrate uptake by the plankton (Sambrotto and Goering 1983). Stratification increases under calm conditions, thus shortening the period of high nitrate uptake and limiting the period of the phytoplankton bloom.

While it is important to consider both mean quantities and any significant deviations from these means, one must not forget that a single storm of sufficient magnitude can alter ocean stratification, water properties, and transport. It is the sum of these individual events that affect the survival of living organisms. An understanding of the atmospheric environment provides valuable explanations for variability in the biological populations of the ocean.

General Weather Review

Statistically, the movement of low-pressure systems across the Gulf of Alaska is determined by two factors: 1) the relative position of the Siberian high-pressure system in the winter, and 2) the east Pacific high in the summer. At any one time, the track of an individual low-pressure center is controlled by upper-level flow. Many of the cyclones that enter the Gulf are stalled by the high mountains that encircle the region, causing them to dissipate. The weather in the western Gulf in winter is determined by frequent storm passage (Aleutian low) and is highly variable. The eastern Gulf is characterized by steady conditions associated with dissipating lows. Weather changes are mainly due to the presence or absence of a high-pressure ridge over the Gulf or North Pacific that blocks the normal progression of storms

across the region. This phenomenon is most common in January and is associated with higher air temperatures, lower wind speeds, and reduced heat fluxes from the ocean.

Winter winds in the western Gulf are highly variable depending on where the low-pressure center of a storm is located. The central and eastern portions of the Gulf (dominated by dissipating low-pressure systems) are characterized by winds that are southwesterly to southeasterly along Southeast Alaska and easterly in the northcentral Gulf. These winds vary in magnitude with the storm system. In the summer, winds are generally light.

Acknowledgments

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ABSTRACT

We review the state of both the circulation and the physical property knowledge for the Gulf of Alaska. The largest-scale feature we cover is the offshore boundary current. This current is relatively wide (~ 400 km) and slow (~ 30 cm/s) on the east side of the Gulf, but it narrows to less than 100 km from Kodiak Island westward, with peak speeds of ~ 100 cm/s. Although occasional large changes occur in the path, transport, and properties of the Alaskan Stream, high-frequency variability is not typical. The Stream may transfer heat and momentum into coastal waters, although the relative importance of this process has not been established.

Other features covered by our review include a continental shelf circulation system which is generally separate from the Alaskan Stream. On the outer shelf, there is weak net flow, but circulation seems to be steered by the bathymetry in large troughs which transect the shelf. On the east side of the Gulf, the flow tends to be variable but is probably stronger in winter than in summer as a result of local wind forcing. Along the Kenai Peninsula there is a distinct narrow current flowing westward with typical speeds of 20 cm/s, but which can range as high as 100 cm/s in the fall. This rapid fall spin-up results from a maximum freshwater discharge in September–October, and is accompanied by surface salinities as low as 25 parts per thousand.

Winds may constrain the relatively dilute flow along the coast. This geostrophic coastal flow first enters Shelikof Strait where the barotropic mode may be important, then continues west along the Alaska Peninsula. These features of coastal circulation are clearly seen in seasonal sea level cycles at various tide stations. Large interannual changes also occur in the Gulf of Alaska. In general, the wind regime along the coast produces downwelling at the coast rather than upwelling.

Introduction

This chapter both reviews previous investigations and synthesizes the results obtained from recent measurements in the northern Gulf of Alaska. The focus of this work is a description of 1) the large-scale features of flow and circulation, and 2) the distribution of physical properties. We feel that this description is central to any effort to integrate our knowledge and that the results presented here will be of value to researchers in other fields. In addition, certain facets of physical oceanography such as the determination of eddy fluxes of momentum and properties, analysis of the tidal regime, and development of heat and moisture budgets are not dealt with in detail. In the chapter, we stress

observational rather than theoretical aspects of physical oceanography.

The term 'Gulf of Alaska' is here taken as the area north of 52°N and east of 176°W . We discuss offshore circulation and properties, but emphasize coastal oceanography because of the comprehensive Outer Continental Shelf Environmental Assessment Program (OCSEAP) on the continental shelf. Readers should note that this shelf (shoreward of the 200-m isobath; see Fig. 3-1) is a vast area in the Gulf of Alaska and is not the narrow feature typical of much of western North America.

Investigations before the OCSEAP work, which started in 1974, were summarized by Dodimead, Favorite, and Hirano (1963) and by Favorite, Dodimead, and Nasu (1976). Prior to

the 1950s, work in the Gulf was carried out by the International Fisheries Commission. For example, McEwen, Thompson, and Van Cleve (1930) inferred the existence of a counterclockwise gyre; Goodman and Thompson (1940) investigated conditions in the area; Sverdrup, Johnson, and Fleming (1942) discussed circulation and water properties; and Robinson (1957) analyzed bathythermograph data collected in the region through 1952.

Dodimead *et al.* (1963) examined the extensive observations from 1955 through 1959. A considerable amount of observational and analytical work was done in connection with a hydrographic time series at Ocean Station 'P' at 50°N, 145°W (Tabata 1961; Fofonoff and Tabata 1966) (Fig. 3-1). Uda (1963) summarized information on the subarctic Pacific, including the Gulf of Alaska. An interesting aspect of most of this earlier work is that few observations were made in the coastal waters of the Gulf, and conditions on the shelf were virtually ignored. It is tempting to speculate that this omission may have partially resulted from the belief that the geostrophic relation for computing flow was only valid in deep water (Dodimead *et al.* 1963). However, we now use the relation in water depths of 100 m or less.

Favorite *et al.* (1976) compiled information on the entire subarctic Pacific, including the Gulf of Alaska, and they give numerous data presentations, analyses, and references to earlier studies. Of special interest is a map showing the distribution of hydrocasts as of December 1972, because few observations were available as of that late date in coastal waters of the Gulf. Bogdanov (1961) examined water circula-

tion in the Gulf, and Roden (1969) presented results from a synoptic survey conducted in the winter of 1967. In addition, Favorite *et al.* (1976) list a number of atlases that have treated some aspects of the oceanography of the Gulf of Alaska.

An especially useful compilation on the Gulf's marine climate is that of Brower, Diaz, Prechtel, Searby, and Wise (1977). A recent atlas of worldwide subsurface oceanographic data was presented by Levitus (1982). *Oceanographic Monthly Summary* (produced by NOAA's National Weather Service and National Environmental Satellite, Data, and Information Service) is an ongoing publication that contains monthly maps of sea surface temperatures and temperature anomalies for the world's oceans. Sea level information has recently been published by Hicks, Debaugh, and Hickman (1983). The great majority of available data consists of temperature and salinity observations; direct current measurements and water chemistry data are relatively rare. Satellite sensors are steadily being improved, and a considerable increase in observational capability seems imminent.

In this review, we will first discuss the offshore circulation and water properties. This offshore system is a major oceanic feature, and understanding it is crucial to understanding the coastal processes. Next, we examine hydrographic data in the coastal waters. As part of this examination, we review the results from direct current measurements on the shelf, as well as analyses of sea level data. Finally, we explore certain aspects of the coastal circulation system.

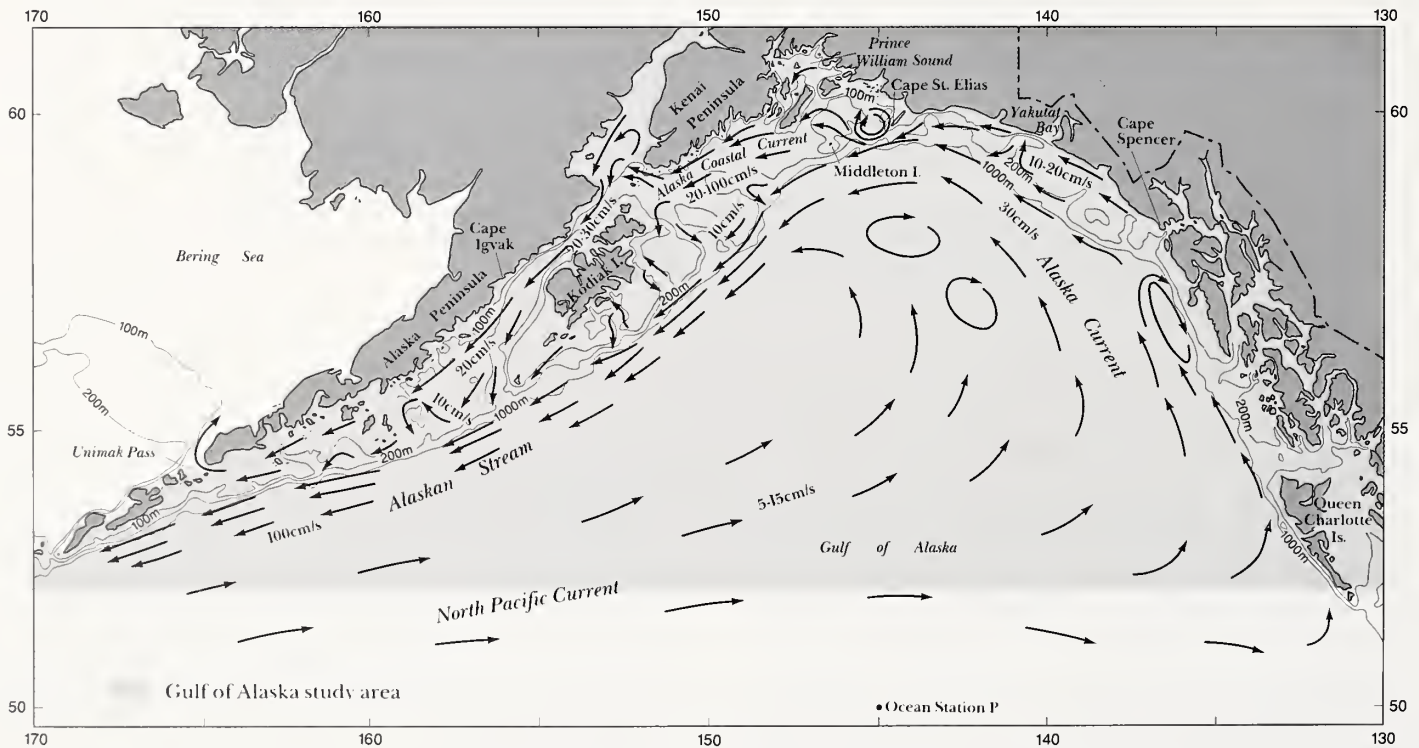


Figure 3-1. Schematic representation of the major currents in the Gulf of Alaska. The depth contours are from International Hydrographic Office Chart 5.03.

Offshore Circulation and Properties

Offshore water circulation in the Gulf of Alaska is dominated by the Alaska Current/Alaskan Stream (e.g., Favorite *et al.* 1976). This feature is the eastern and poleward boundary of the large-scale, counterclockwise rotating subarctic gyre (see Fig. 3-1). The flow generally parallels the continental slope, taking first a northward and then a westward direction. The flow varies in width from perhaps 300 km near the head of the Gulf to less than 100 km from Kodiak Island westward. The waters flowing into the Gulf often exhibit a large clockwise eddy off Sitka, with large eddies or bends also occurring in other areas nearby (Tabata 1982). Reed (1980a) showed the existence of a large eddy near Pratt Seamount (~56° 30'N, 143°W). On the eastern side of the Gulf, we use the term Alaska Current, but we prefer Alaskan Stream (Dodimead *et al.* 1963; Favorite 1967) west of about 150°W, because this term seems more descriptive of this high-speed, narrow, deep boundary flow. In general, the Alaskan Stream does not have large velocities in water depths less than 300 m (Reed, Muench, and Schumacher 1980). Although the Stream may affect the inshore circulation, coastal features often seem to be separate, or at least different, from those offshore. South of the Alaskan Stream is the North Pacific Current, a weak eastward flow.

Although recent work has been more concerned with circulation and conditions near the coast, rather than offshore, an appreciable amount of data on the Alaskan Stream was collected in the vicinity of Kodiak Island (Reed *et al.* 1980; Royer 1981a). Furthermore, two surveys of virtually the entire Stream system (Reed 1984) helped redress the limited spatial coverage in much of the work near Kodiak Island. Finally, long-term current measurements in the Stream have increased our understanding of the major characteristics of this system (Reed and Schumacher 1984).

Property Distributions and Geostrophic Flow

Some typical distributions of the physical properties in the Alaskan Stream are shown in Figures 3-2 and 3-3; Figure 3-2 is based on data taken in February 1980 near 164°W (just south of Unimak Pass) (Wright 1981), and Figure 3-3 shows conditions off Kodiak Island in September 1981 (Reed 1984). The winter section shows a zone of cold (<4C), low-salinity (<33‰) water near the surface which forms as a result of winter cooling and convection (Dodimead *et al.* 1963). A zone of relatively warm (>5C) water underlies the cold, near-surface water. In general, winter surface temperatures decrease from 5 to 6C in the head of the Gulf to less than 3C near the Aleutian Islands. Surface salinity typically decreases toward shore, with values less than 32‰ on the shelf in winter. The marked similarity of salinity and sigma-t or density slopes in Figure 3-2 shows the strong influence of salinity on the density structure in this region. Isolines of all properties slope downward sharply near the continental slope, a fact that is reflected by the maximum computed geostrophic flow of over 80 cm/s. Values in excess of 100 cm/s are often found, especially near the Aleutian Islands (Reed 1984).

The summer section (Fig. 3-3) shows sea-surface temperatures in excess of 12C and surface salinity generally less than 32.2‰; both values are typical for late summer. Note also the temperature minimum near 100 m depths, which results from failure of near-surface warming to remove all

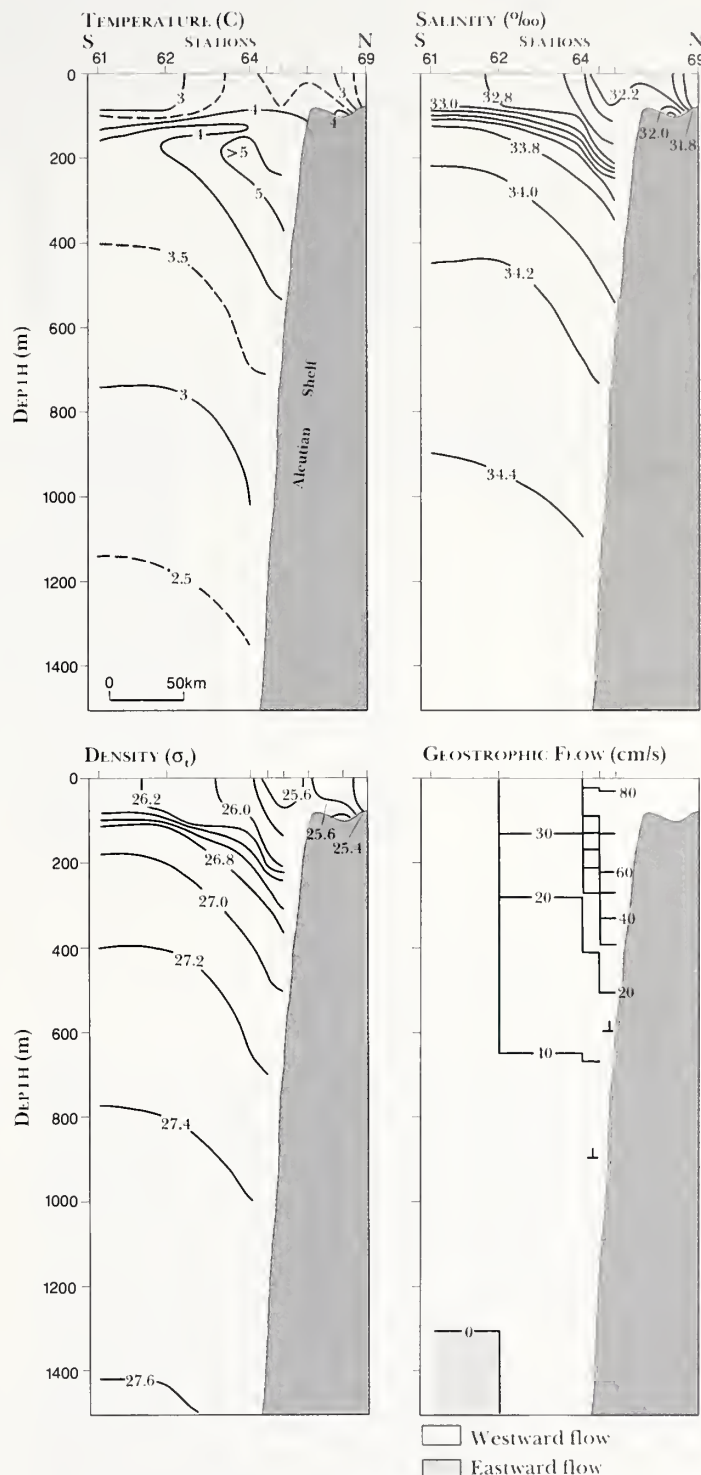


Figure 3-2. Vertical sections of temperature, salinity, density, and geostrophic flow (referred to 1,500 db = 0/1,500 db) across the Alaskan Stream at approximately 164°W, 24-25 February 1980.

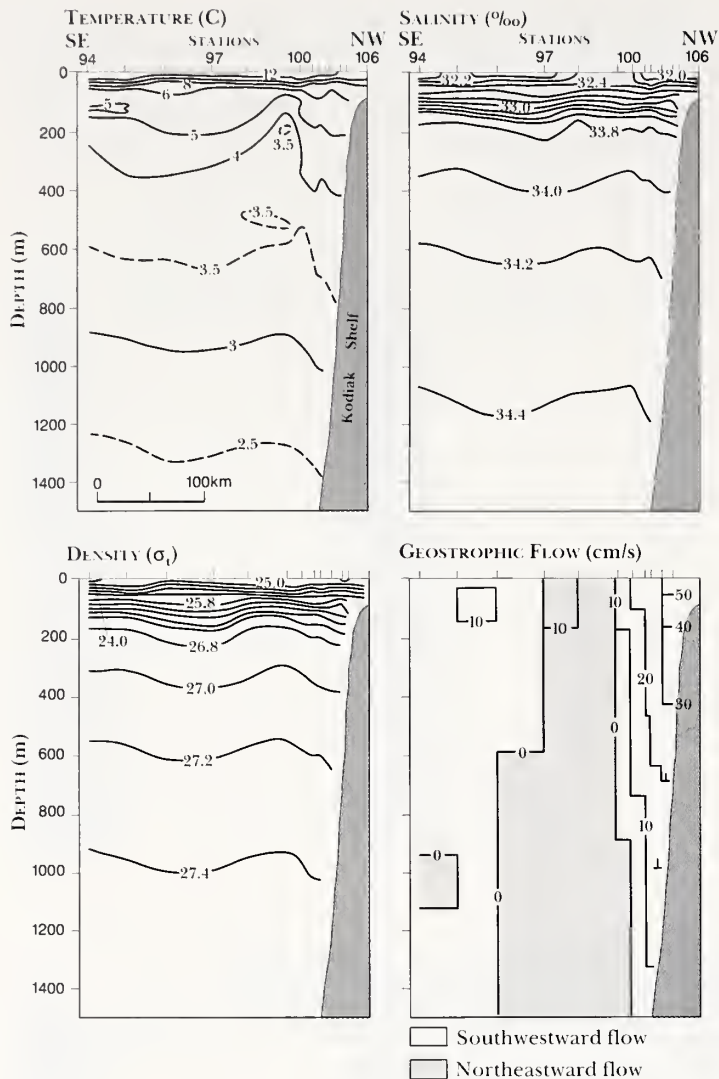


Figure 3-3. Vertical sections of temperature, salinity, density, and geostrophic flow (0/1,500 db) across the Alaskan Stream off Kodiak Island, 6-7 September 1981.

vestiges of the cool layer from the previous winter. Two features of this section are not typical of summer conditions, however: 1) the maximum velocities were relatively weak (~ 50 cm/s), and 2) the deep water (even to depths of 1,000 m) was warmer and less saline than the water shown in Figure 3-2. These conditions resulted from the large-scale change in circulation (Reed 1984) that is discussed below.

The distribution of surface salinity in the Gulf of Alaska and along the Aleutian Islands in winter 1980 and summer 1981 is shown in Figure 3-4. The large-scale patterns are influenced by factors such as variations in freshwater runoff and precipitation, the structure and intensity of the Alaskan Stream and coastal currents, and the exchange of water through passes between the Aleutian Islands. In offshore waters, the values in summer 1981 were generally about 0.5‰ less than in winter 1980. This appears to be a typical seasonal difference (Royer 1981a) resulting from increased freshwater discharge in late summer or fall. The most striking difference in these maps is the very dilute water ($< 26\text{‰}$)

that was present along the Kenai Peninsula in September 1981 compared with that in February 1980. While these huge differences clearly reflect the seasonal differences in freshwater discharge (Schumacher and Reed 1980; Royer 1981b), they will be discussed later in connection with coastal processes.

Reed *et al.* (1980) examined the volume transport of the Stream near Kodiak Island. They attempted to adjust the computations for the existence of density slopes near the bottom in depths less than the reference level (1,500 db). On that basis, a mean adjusted transport of 12×10^6 m^3/s was determined for 17 sections. Although temporal variations in transport were present, they were not correlated with the large seasonal variations in integrated wind-stress transport. Hence, Reed *et al.* (1980) drew the conclusion that there were no significant seasonal variations in transport of the Alaskan Stream.

Royer (1981a) used these and other data, but he did not adjust the computations for near-bottom density slopes. He inferred that transport does vary seasonally by about 13% of the mean, with a maximum occurring in March. The existence of such a signal is difficult to confirm; the number of hydrocast sections is still quite limited, and the estimates are influenced by spatial as well as temporal variations of the Stream. Some recent results, however, show that seasonal differences are considerably smaller than interannual or year-to-year changes.

Geopotential topography of the sea surface (referred to 1,500 db) from cruises in February-March 1980 and August-September 1981 is shown in Figure 3-5. Both maps show westward flow from the head of the Gulf to the western Aleutian Islands, but the relief across the flow (and hence speeds and transports) east of 160°W on the second cruise was only about half of the relief recorded on the first cruise. (This difference in flow also explains the relatively warm, fresh subsurface water noted earlier in Figure 3-3; the normal cold, saline subarctic water was not present just offshore from the Stream.) Normally, the inflowing source waters of the Stream (Alaska Current) flow northward along the east side of the Gulf so that transport is relatively constant from the head of the Gulf westward (as on the upper map). Water flowing into the Stream as far west as 165°W is quite rare (Reed 1984). Thus, the Stream in August-September 1981 had a transport in the Gulf of only about 6×10^6 m^3/s , but typical transport of 12×10^6 m^3/s occurred along the Aleutian Islands (west of 165°W). This disrupted or split inflow is not a normal seasonal occurrence (Dodimead *et al.* 1963; Favorite *et al.* 1976; and Ingraham, Bakun, and Favorite 1976). If it does occur preferentially, even though rarely, in summer, it could account for the seasonal signal inferred by Royer (1981a).

This change, which is believed to be a sporadic or inter-annual one, was suggested by Reed (1984) to result from an unusual tilt of the pycnocline brought about by the effects of differential Ekman pumping in the region of the inflowing source waters. That is, in summer 1981, wind stress over the east side of the Gulf essentially collapsed, but at the same time, wind stress increased greatly to the west. This created a tendency to divert the inflow northwestward rather than along the eastern boundary. Although the frequency of such

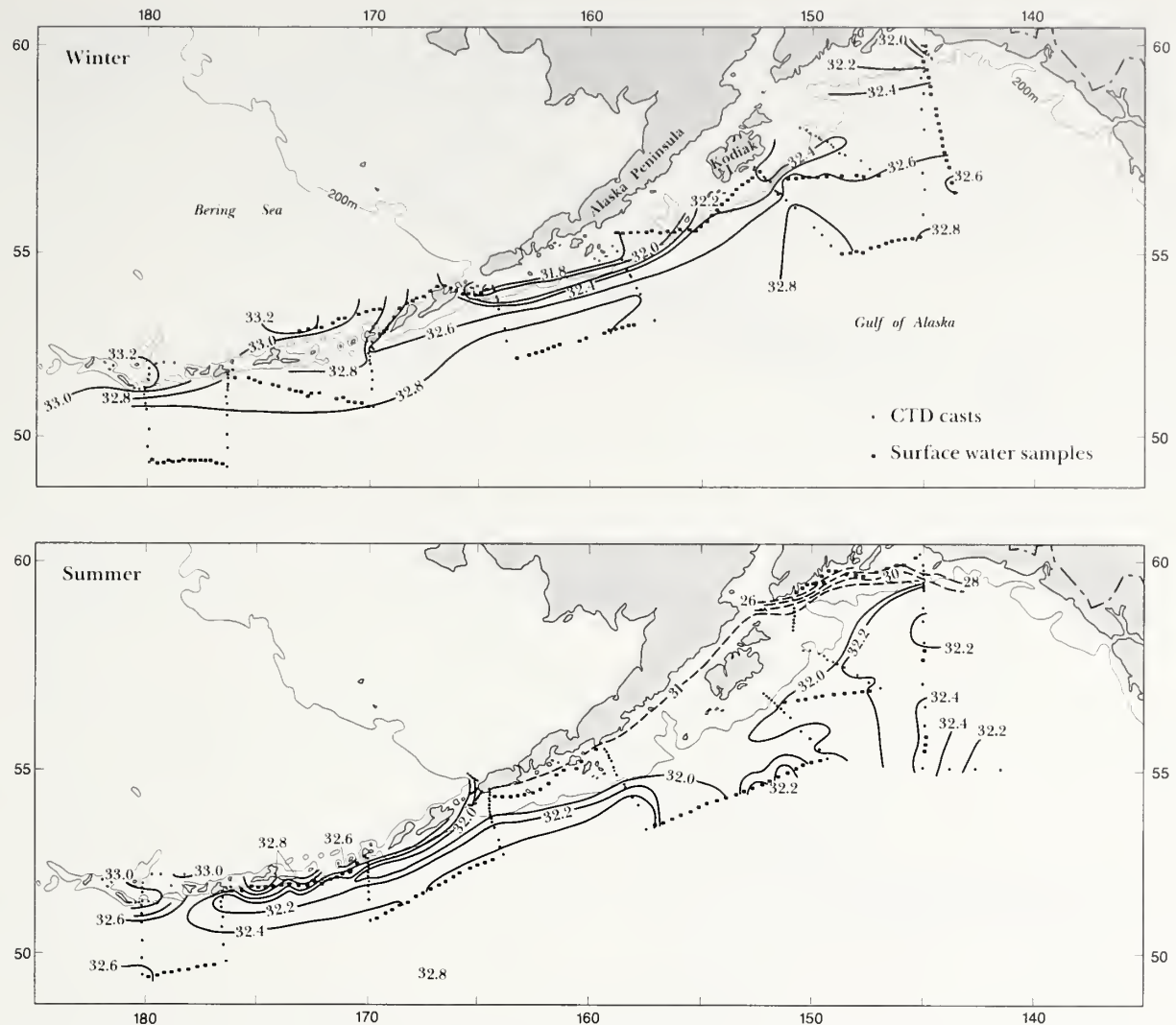


Figure 3-4. Distribution of surface salinity (‰) during winter (9 February to 9 March 1980) and summer (25 August to 16 September 1981).

events is not known, the resulting weak flows and relatively warm, fresh waters in the Gulf may affect biota in the region.

We have not presented data on dissolved oxygen and nutrients; however, this information is included in the chapter on chemical oceanography (Reeburgh and Kipphut, Ch. 4, this volume). We have not shown traditional water-mass analyses (temperature–salinity diagrams and other methods) either, but these are presented in considerable detail in Dodimead *et al.* (1963), Favorite *et al.* (1976), Emery and Dewar (1982), and other studies.

Direct Current Measurements

A number of direct current measurements have been made in the Alaskan Stream. Most of the observations were made using drogued drifting devices and were of very short duration (see Figs. 14–15 and 14–16, OCSEAP Staff, Ch. 14, this volume). Although much of the information obtained was not highly definitive, investigators found relatively high

velocities that were in agreement with geostrophic flow computations (for example, Reed and Taylor 1965). Some drifters were tracked by satellite for longer periods, and they provided conclusive evidence of recirculation around the Gulf of Alaska gyre (Reed 1980b). During February through August 1980, Reed, Schumacher, and Blaha (1981) obtained a current record at 1,000 m in a depth of about 1,700 m off Kodiak Island. Ten-month records at this site, plus records at an inshore location, were later obtained at four levels; these data have been analyzed (Reed and Schumacher 1984) and are examined here in some detail.

Information on these records is presented in Table 3-1. As expected, the data indicate flow to the southwest that decreases with depth. The measured shear was in excellent agreement with the computed geostrophic shear (Reed and Schumacher 1984), but the results imply that the baroclinic flow does not vanish until a depth of about 3,000 meters. On this basis, true transport of the Alaskan Stream in the Gulf of Alaska is about $15 \times 10^6 \text{ m}^3/\text{s}$ rather than $12 \times 10^6 \text{ m}^3/\text{s}$ (referred to 1,500 db) (Reed 1984). Thus the subarctic gyre

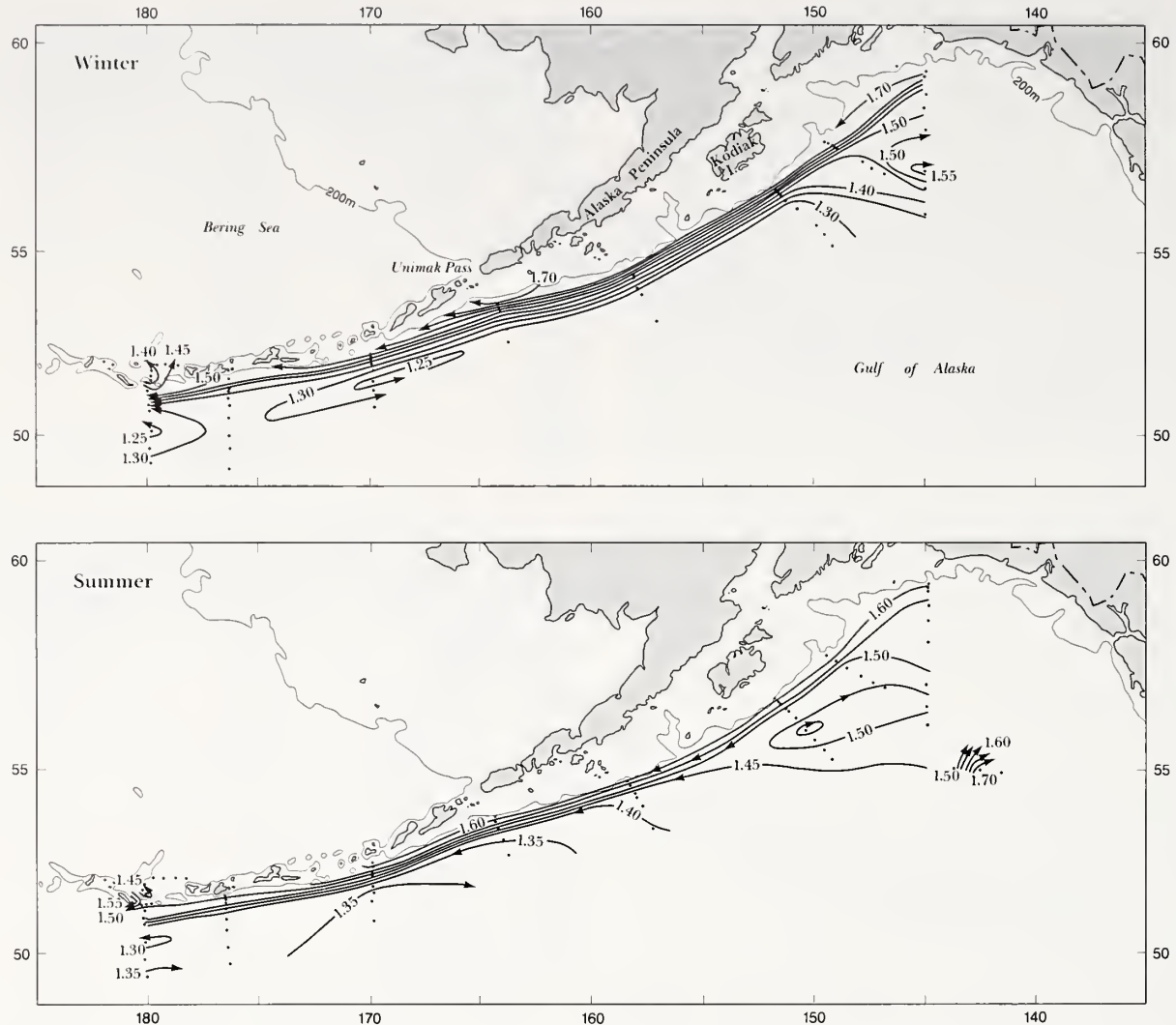


Figure 3-5. Geopotential topography (ΔD , dyn m) of the sea surface (0/1,500 db) during winter (11 February to 3 March 1980) and summer (25 August to 16 September 1981).

appears to have a transport about one-third that of the Pacific subtropical gyre.

Vector plots of the data from these moorings (Fig. 3-6) indicate remarkable flow stability, especially at the deep

Table 3-1.
Information on current meter moorings near Kodiak Island (from Reed and Schumacher 1984).

STATION	LOCATION	METER DEPTH (m)	WATER DEPTH (m)	DATES	NET FLOW (cm/s, deg)	VARIANCE (cm^2/s^2)
1	56°39'N 151°46'W	230	700	13 Sep 81- 11 July 82	28,207	312
2	56°31'N 151°40'W	305	1,730	13 Sep 81- 22 July 82	24,219	166
		520		13 Sep 81- 19 Feb 82	19,230	158
		1,020		13 Sep 81- 22 July 82	8,224	54

mooring. Furthermore, the features were extremely coherent vertically, and even small ones tend to be present at all levels. (This similarity of flow in the vertical does not imply a barotropic flow, however; speeds clearly decreased with depth and were in good agreement with computed geostrophic or baroclinic flow.) Although the flow was relatively stable with time, some low-frequency variations were present. For example, records from the first two months reveal relatively weak flow, which appears to agree with the time of disrupted inflow to the Stream (Reed 1984). Spectral analysis of these data indicates that the variations were predominantly at the lower frequencies (typically $< 0.02/\text{d}$), whereas a record at 300 m depth on the edge of the Stream (Niebauer, Roberts, and Royer 1981) showed relatively more high-frequency energy. In general, the Stream appears to be considerably more stable (and have lower levels of eddy energy or variance) than typical western boundary currents such as the Gulf Stream and the Kuroshio Current (Reed and Schumacher 1984). We concluded that this probably results from relatively little planetary wave activity in most of the Stream.

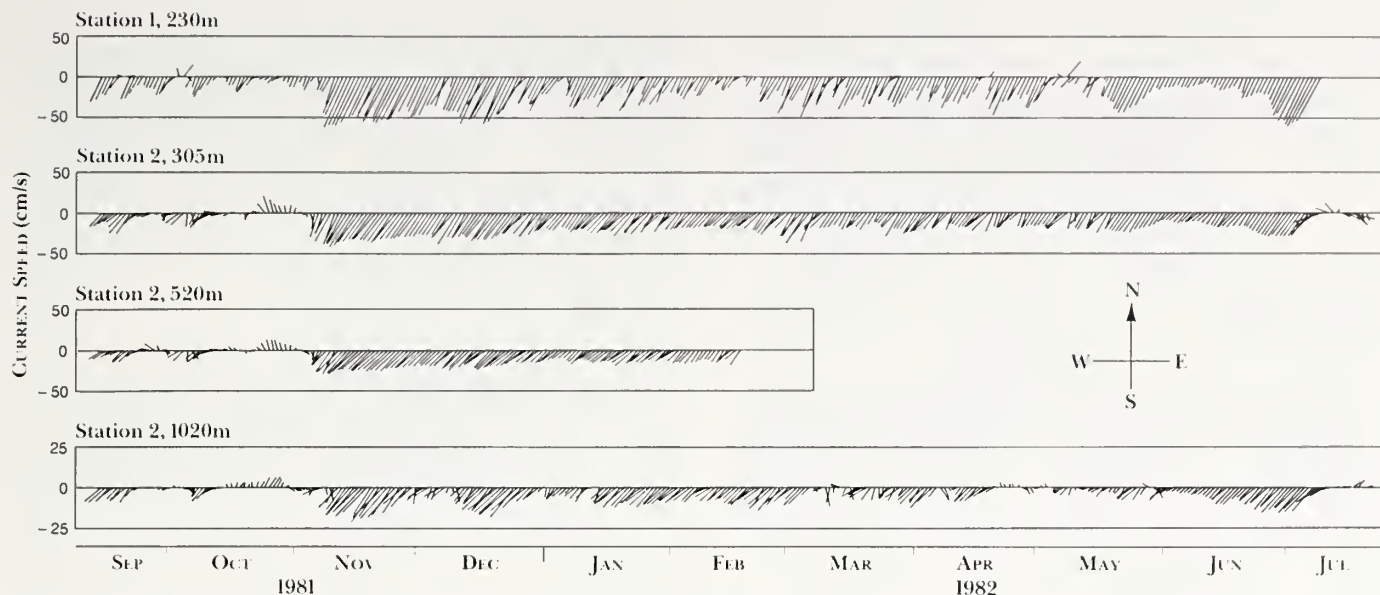


Figure 3-6. Daily net current vectors (after use of a 35-h filter) at Stations 1 and 2 (Table 3-1), 15 September 1981 to 21 July 1982. Note scale change for the 1,020-m depth at Station 2.

The data at these sites were further used to examine the eddy fluxes of momentum, heat, and salt. The fluxes were generally much smaller than those on the inshore edge of western boundary currents (Reed and Schumacher 1984). Momentum was being transferred from the mean flow to smaller scales, unlike in the Gulf Stream, but our estimate of eddy viscosity was only about $10^6 \text{ cm}^2/\text{s}$. As expected, eddy heat flux was onshore; since we did not have data in the upper 200 m, it was not possible to quantify the likely impact of this flux on the shelf waters.

In summary, the Alaskan Stream is a high-speed, off-shore boundary for the coastal circulation systems in the Gulf of Alaska. The Stream seems to be quite stable but does occasionally undergo large changes. On the east side of the Gulf, the flow is usually about 400 km wide with peak speeds of about 30 cm/s; near Kodiak Island and westward, the Stream is typically less than 100 km wide and has peak speeds of 100 cm/s.

Coastal Circulation and Properties

As we noted earlier, a very limited amount of data had been obtained in coastal waters of the Gulf of Alaska prior to 1974, and few detailed analyses had appeared. Sea level data as well as temperature and density observations at tide stations existed, of course, but only limited efforts (Reid and Mantyla 1976) had been made to interpret them in terms of oceanographic conditions on the shelf. While there was a large increase in the number of hydrocasts as a result of OCSEAP-sponsored field studies in the Gulf, an even more striking change took place in the availability of direct current measurements. We will attempt to summarize and extend these results.

Property Distributions and Geostrophic Flow

Distribution of surface salinity in both the Alaskan Stream and over a sizable portion of the shelf is shown in Figure 3-4. This figure shows that the salinity of coastal waters may change seasonally as much as seven parts per thousand. Although the surface temperature of coastal waters varies by about 7C from winter to summer, this only alters density by about one sigma-t unit, whereas the change in salinity affects density four to five times as much. Thus, variations in salinity generally have the largest effects on density distribution and baroclinic flow in this region (Royer 1981a). The distribution of surface salinity has long been used as an index of the offshore circulation (Dodimead *et al.* 1963), and it appears to be equally useful for inferring coastal flow. In fact, Royer (1979, 1981b, and 1982) concluded that the nearshore, westward coastal current around the Gulf is the result of salinity gradients that are controlled by freshwater discharge from land. Furthermore, this coastal flow or Alaska Coastal Current (Royer 1981b) has a strong seasonal signal with maximum flow in fall during the maximum discharge. The salinity (density) gradients attenuate rapidly with depth, however, so that surface geostrophic flow (referred to 50 or 100 db) appears to be a good approximation of actual circulation (Royer, Hansen, and Pashinski 1979; Reed and Schumacher 1981).

Large amounts of data were not collected in the north-east Gulf, but Reed, Schumacher, and Wright (1981) found enough limited information to prepare maps over areas of varying size near Yakutat. Salinity at 10 m and geostrophic flow of the sea surface (referred to 90 db) are shown in Figure 3-7. In March, June, and November the range of salinity inshore of the 915-m isobath, excluding values inside Yakutat Bay, was only 1‰ or less. In September, there were much lower salinities in a narrow zone nearshore. The geopotential topography for all periods indicates a weak,

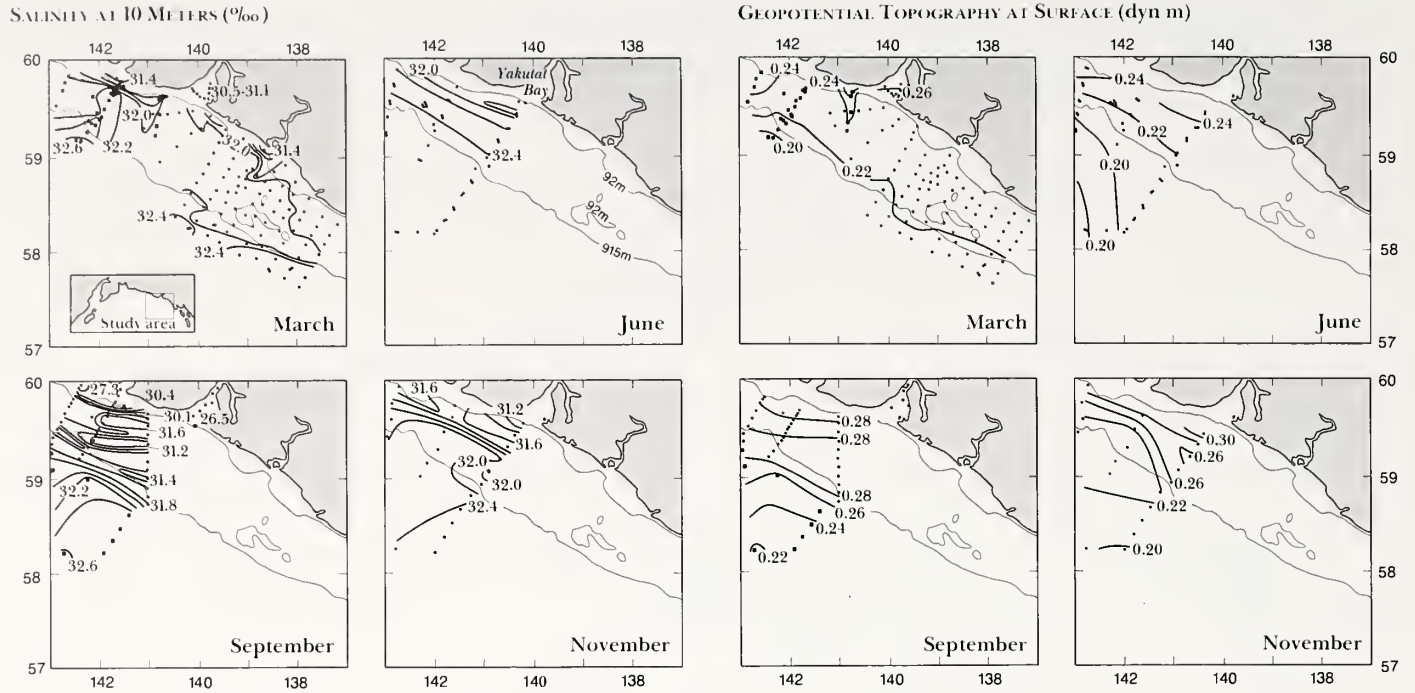


Figure 3-7. Salinity (‰) at 10 m and geopotential topography (ΔD , dyn m) of the sea surface (0/90 db) for the periods: 2 to 22 March 1977 (squares) and 23 to 31 March 1979 (circles); 5 to 12 June 1975; 9 to 11 September 1976 (squares) and 12 to 15 September 1977 (circles); and 1 to 2 November 1975.

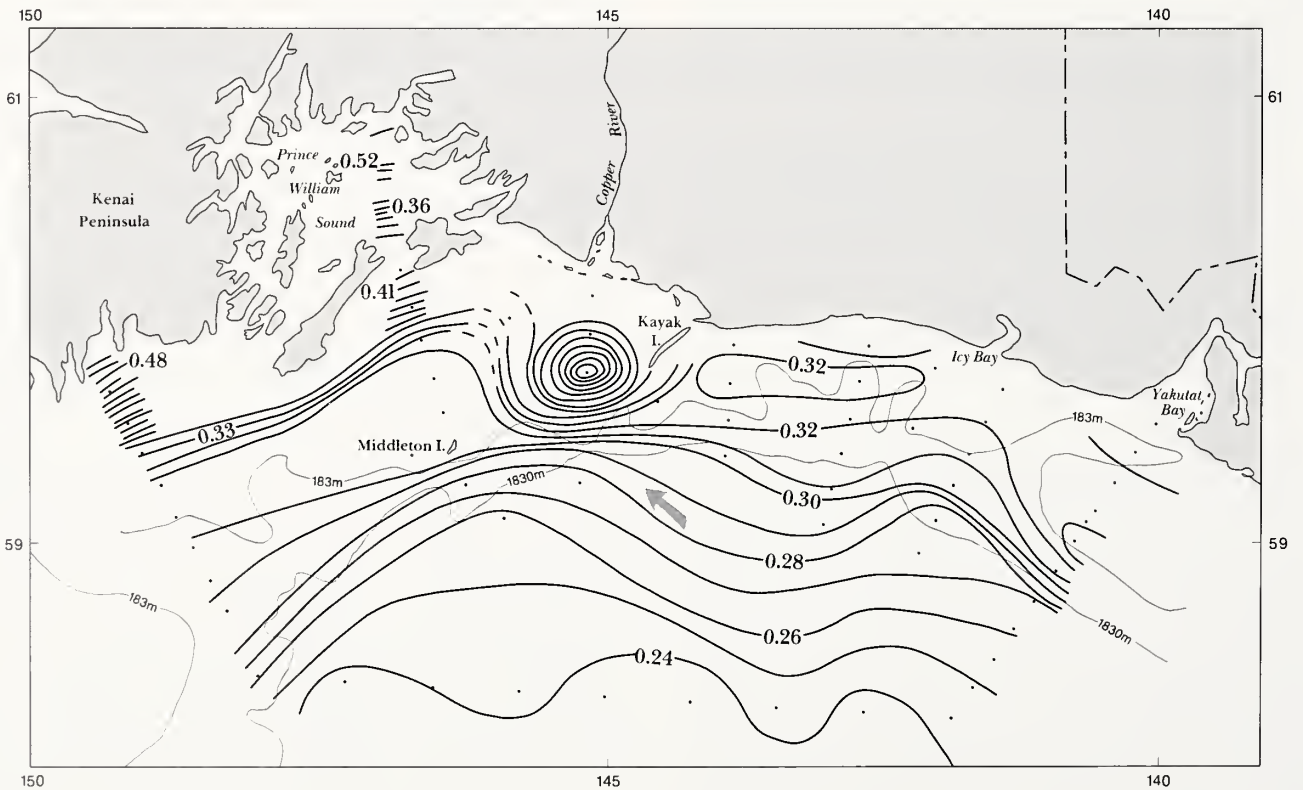


Figure 3-8. Geopotential topography (ΔD , dyn m) of the sea surface (0/100 db) during September 1976. (Modified from Royer *et al.* 1979.) Arrow denotes direction of current flow.

alongshore flow to the northwest with no apparent increase in flow in September. (Use of 50 db as the reference level allows one to extend the data about 20 km farther inshore, an area of low-salinity water during September. This only adds about 3 dyn cm to the range, however, which suggests there was no intense flow inshore.) Although more data would be useful for making these inferences, it seems unlikely that a major increase in speed and transport occurs during the fall, as is typical for the central and western Gulf.

Royer *et al.* (1979) compared maps of dynamic topography over the central Gulf using results from satellite-tracked drifting buoys. Figure 3-8 shows a map of geopotential topography at the surface (referred to 100 db). Those contours less than 0.30 dyn m represent the inshore part of the Alaskan Stream; east of Kayak Island (~144°W), there was little relief shoreward of the Stream. An intense (>50 cm/s) clockwise eddy was present in the lee of Kayak Island, and the coastal flow extended seaward to merge with the oceanic flow. To the west the flows were separate, but there was a large increase in relief across the coastal flow. Royer (1983a) noted that the Kayak eddy appears to be a permanent feature, and the waters in the eddy should have a relatively long residence time.

Surface salinity distributions are shown in Figure 3-9 along with the salinity at 50 m, and the sigma-t difference between the surface and 50 m for an area along the Kenai Peninsula and in lower Cook Inlet-upper Shelikof Strait during October 1978 (Schumacher and Reed 1980). Salinity was slightly less along the Kenai Peninsula than in lower Cook Inlet, as shown in Figure 3-4. However, salinities may be even lower at certain times. Horizontal salinity gradients were reduced at depth, and the sigma-t differences were greatest along the Kenai Peninsula where investigators found the lowest surface salinities.

The water had no measurable vertical density gradient over Portlock Bank, where tidal mixing is relatively efficient, and scattered zero-gradients existed elsewhere. Vertical sections of temperature, salinity, and sigma-t along the line of stations crossing Portlock Bank for March and October 1978 are shown in Figure 3-10. The typical seasonal range of surface temperature is apparent, but the most striking feature is the marked decrease in salinity nearshore during the fall. All properties were completely mixed vertically over Portlock Bank.

Another interesting feature is the increase in salinity that occurs in the fall at a level of about 100 m just offshore from the low-salinity water. This increase seems to be in response to the decrease in salinity and consequent increase in westward velocity that is needed to satisfy continuity of momentum and mass (Schumacher and Reed 1980; Pietrafesa and Janowitz 1979).

Geopotential topography (0/100 db) for this region during March 1978 and October 1978 is shown in Figure 3-11. In March, relief across the westward flow was only 5 dyn cm, but it increased to 20 dyn cm in October. In fall, the water moved through Kennedy Entrance (the northernmost channel to Cook Inlet-Shelikof Strait) and turned south near Cape Douglas. This later flow is in agreement with flows inferred by Muench, Mofjeld, and Charnell (1978). They con-

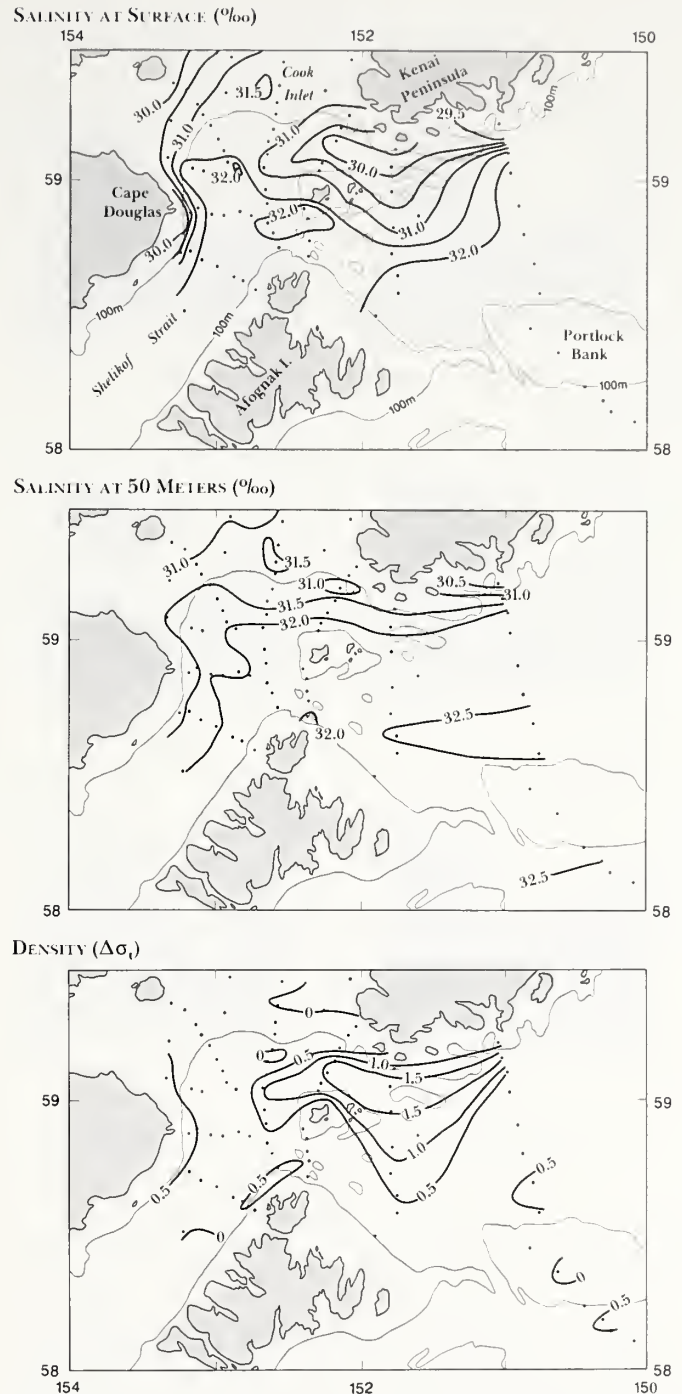


Figure 3-9. Distributions of surface salinity, salinity at 50 m, and density difference between 50 m and the surface during 9 to 22 October 1978. (Modified from Schumacher and Reed 1980.)

cluded that Cook Inlet has an estuarine circulation with the outflow concentrated on the western side.

Schumacher and Reed (1980) reported the results of data analyzed from six sections south of the Kenai Peninsula. They found that peak speeds varied from 13 to 30 cm/s during winter, spring, and summer, but during October of 1977 and 1978, they found maximum computed flows of 89 and

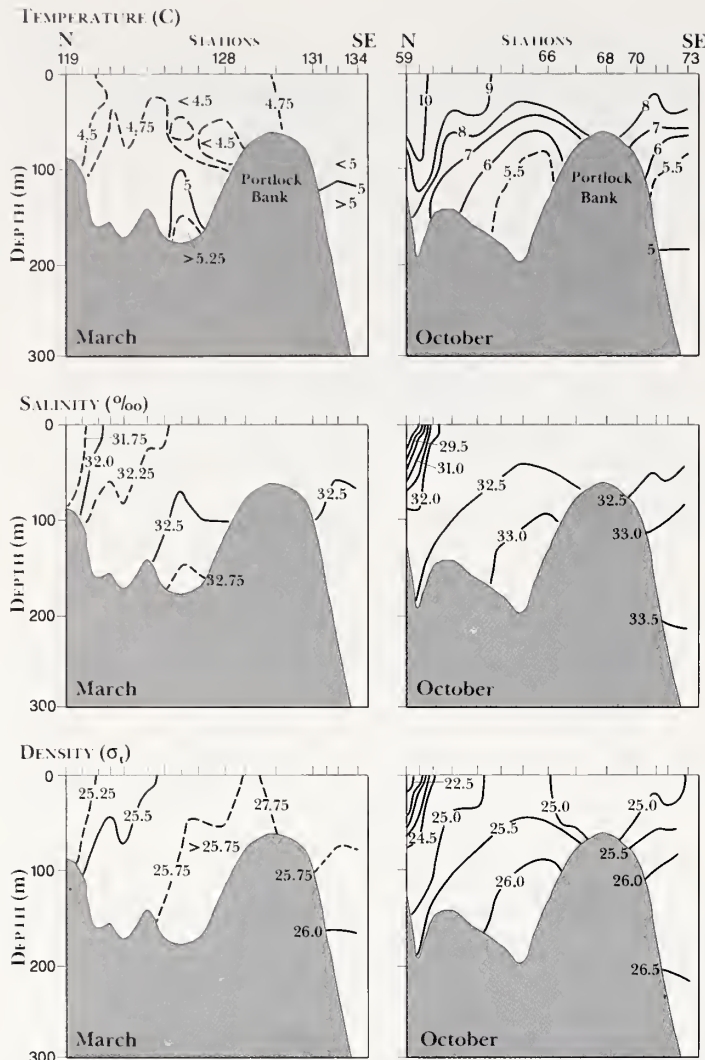


Figure 3-10. Vertical sections of temperature, salinity, and density off the Kenai Peninsula on 20 March 1978 and on 10 October 1978. (Modified from Schumacher and Reed 1980.)

133 cm/s, respectively. Volume transport varied in a similar manner from 0.1 to 1.2×10^6 m³/s. Royer (1981b) reported similar transports off Seward and a maximum computed geostrophic speed of 66 cm/s.

We (Schumacher and Reed 1980) earlier called this coastal geostrophic current the 'Kenai Current' because it is quite distinct from the Alaskan Stream. Royer (1981b), however, used the term 'Alaska Coastal Current,' and we now concur with this designation because of recent evidence for its considerable westward extent. The most intense part of the flow, with its dramatic increase in speed and transport in fall, seems to form near 145°W and is most readily apparent along the Kenai Peninsula. We do not imply that a westward coastal current does not exist east of 145°W, but the available data suggest that it is less developed and lacks the marked seasonal change found farther west.

Royer (1979) first provided evidence of the mechanism that produces the large seasonal change in the Alaska Coastal Current. He demonstrated that changes in flow

were highly correlated with freshwater discharge in the form of local precipitation and accumulated drainage from land. He also produced a hydrological model that showed maximum discharge in September or October (see also Royer 1981b and 1982). This discharge produces a marked lowering of surface salinity and a consequent increase in geopotential gradient across the flow.

Although winds were not as highly correlated with flow as freshwater discharge, it is our belief that winds are important to the coastal current. This conclusion was also drawn by Royer (1983a), who suggested that the action of winds is necessary to constrain the westward flow in a narrow coastal stream. Winds near the Kenai Peninsula are from the east, except during one or two months in summer, and they produce coastal convergence. On the other hand, they do not produce intense coastal convergence except in winter on the east side of the Gulf (Brower *et al.* 1977). This difference in winds may explain why the flow is weak and the low-salinity water is not concentrated along the coast (Ingraham 1979) on the east side of the Gulf.

How far westward does the Alaska Coastal current extend? The salinity distributions in Figure 3-4 show low-salinity water on the shelf all along the Alaska Penin-

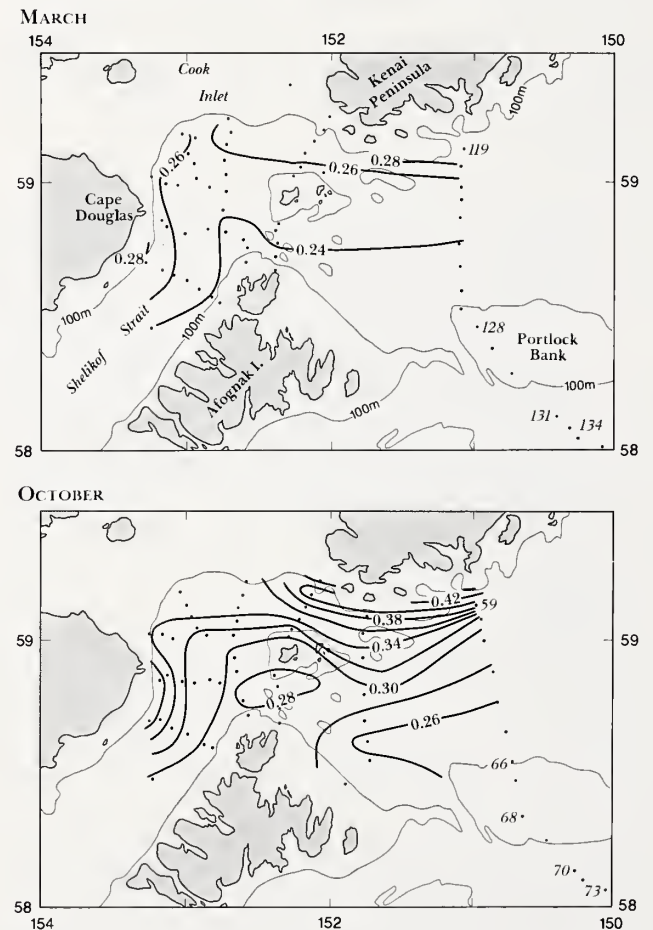


Figure 3-11. Geopotential topography (ΔD , dyn m; 0/100 db) during 13 to 21 March 1978 and 9 to 22 October 1978. Italicized numbers denote sampling stations. (Modified from Schumacher and Reed 1980.)

sula to Unimak Pass. Geostrophic flow data computed from the coastal stations on these cruises also show westward flow. Schumacher, Pearson, and Overland (1982) analyzed results from both current moorings (with bottom pressure measurements) and hydrographic data near Unimak Pass and concluded that fluctuations in flow through the pass were largely barotropic as a result of wind-induced sea level variations. They also concluded that there was a westward net flow as an extension of the Alaska Coastal Current.

Schumacher and Reed (in press) examined conditions along the Alaska Peninsula for evidence of continuity of this flow. Data from seven current moorings between 155 and 159°W provide evidence for westward flow. The seasonal signal of sea level at Sand Point (Shumagin Islands) is best explained by a fall increase that is highly correlated with upstream stations, and property distributions suggest westward baroclinic flow. A vertical section of sigma-t density normal to the Peninsula near 158°W, with profiles of the geopotential anomaly, is presented in Figure 3-12. We interpret the Alaska Coastal Current as being that water (with lowest density and greatest geopotential anomaly) inshore from Station 29. Westward flow continued offshore to Station 23, but there was an eastward flow of equal intensity immediately offshore. This latter feature seems likely to be a bathymetrically trapped, counter-clockwise gyre that results from vorticity constraints on motion in the trough. Lagerloef (1983) examined an apparently similar feature in a trough offshore from Kodiak Island.

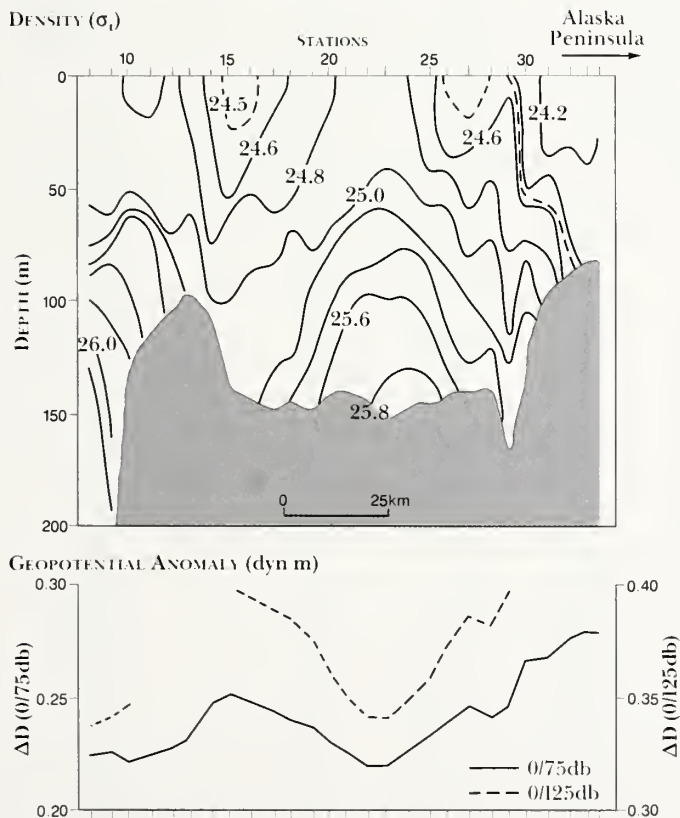


Figure 3-12. Vertical section of density and geopotential anomaly off the Alaska Peninsula near 158°W during 28 to 29 October 1977.

Direct Current Measurements

Investigators have used several satellite-tracked drifters in the shelf waters to provide current estimates of short duration. During September 1975 to September 1976, nine buoys were released near 140°W and drogued at an effective depth of about 35 meters. These buoys generally followed the coastal current westward (Royer *et al.* 1979). The drifters confirmed the general alongshore movement indicated by geostrophic flow, although drifter speeds were usually greater than those computed. This discrepancy is to be expected because of inadequate spacing of the CTD stations.

Most of the buoys moved shoreward into Prince William Sound. This movement was not indicated by geopotential topography and was attributed to an entrainment process resulting from an upper layer that moved offshore while a lower layer moved onshore (Royer *et al.* 1979). Muench and Schumacher (1980) reported the results from six other drifters: two of them moved along the Kenai Peninsula into Shelikof Strait; one had little movement; two moved along the shelf southeast of Kodiak Island; and one was in the Alaskan Stream.

During the period from 1974 to 1978, moored current-meter measurements were made at 27 sites on the shelf. Measurements were also made at 12 other sites in lower Cook Inlet. In 1980, a mooring was also deployed near Unimak Pass, and an additional site was occupied off southeast Alaska near Yakutat. The results from all of these measurements (with durations longer than approximately 2 mo) are presented in Table 3-2; the locations are shown in Figure 3-13. With one exception, the information in Table 3-2 is based on 35-h filtered data; hence the effects of tidal and inertial motion have been essentially removed. (The 2.9-h filtered variance includes the effects of tidal motion; it is apparent that it is often several times greater than the 35-h variance because of strong but variable tidal currents.)

As discussed above (Table 3-1 and Fig. 3-6), measurements were also made at two sites in the Alaskan Stream off Kodiak Island, and an additional mooring was occupied in the edge of the Alaskan Stream off Seward (Niebauer *et al.* 1981). Finally, a program of long-term measurements in the coastal flow off Seward has been completed (T. C. Royer, University of Alaska, pers. comm., 1984), but results are not yet available.

Our attempt to generalize the results of the current measurements in Table 3-2 is illustrated in Figure 3-14. This presentation gives approximate net flow vectors for each site. These vectors were formed by taking vector averages of flow from all of the meters at approximately the same levels at each site and then taking a final average of results from all of the levels. No attempt was made to weight or adjust the data for their duration.

Some of the data in the northeast Gulf were analyzed by Hayes (1979), Hayes and Schumacher (1976), and Lagerloef, Muench, and Schumacher (1981). Net flow (Table 3-2 and Figure 3-14) was generally alongshore with speeds typically between 5 and 20 cm/s. The eddy kinetic energy (one-half the 35-h filtered variance) was relatively large, especially in comparison with the mean kinetic energy (one-half the net

MOORING	LAT. (deg - min)	LONG.	METER DEPTH (m)	WATER DEPTH (m)	START	END	NET FLOW SPEED DIR. (cm/s) (deg)	VARIANCE (cm ² /s ²) (35-h filter)	VARIANCE (cm ² /s ²) (2.9-h filter)				
62K	59-38	142-06	20	188	17Mar77	8Jun77	15.4 307	305	412				
			50		17Mar77	8Jun77	13.2 308	266	352				
			100		17Mar77	22May77	10.4 320	126	189				
62L	59-38	142-07	178	194	17Mar77	8Jun77	4.9 315	58	110				
			61		9Jun77	12Sep77	10.7 296	127	221				
			61		9Jun77	12Sep77	7.0 293	107	183				
69	59-50	145-42	184	93	9Jun77	12Sep77	3.1 321	38	79				
			20		3Mar76	17May76	6.6 322	127	495				
			69B		59-50	145-43	20	97	18May76	19Aug76	4.8 328	66	516
SAI	58-32	138-22	50	118	18May76	19Aug76	3.2 301	18	210				
			87		18May76	19Aug76	1.8 271	11	126				
			2		25Oct80	1Apr81	8.7 66	274	391				
SLSA#19	59-46	141-34	10	51	25Oct80	1Apr81	5.9 78	154	238				
			20		23Oct76	17Mar77	29.7 289	405	906				
			40		23Oct76	17Mar77	18.6 288	217	426				
W1	59-47	141-37	45	55	18Mar77	8Jun77	8.1 293	158	269				
			53		18Mar77	15May77	8.1 282	114	180				
			SLSB#8		59-40	141-39	49	99	4Mar76	14May76	10.6 301	63	122
#14	59-40	141-40	74	100	8Mar76	13May76	9.8 299	51	107				
			50		15May76	22Sep76	5.8 299	71	175				
			77		15May76	24Sep76	5.4 300	50	171				
#20	59-40	141-42	50	102	22Oct76	17Mar77	23.5 300	174	310				
			W2		59-40	141-41	58	108	18Mar77	8Jun77	16.1 300	183	267
			83		18Mar77	8Jun77	12.9 297	125	208				
SLSC#9	59-19	142-02	98	251	18Mar77	8Jun77	10.2 291	92	171				
			105		18Mar77	8Jun77	7.9 283	62	120				
			51		7Mar76	12May76	5.6 333	446	526				
#21	59-20	142-07	100	251	7Mar76	12May76	5.6 328	325	396				
			200		7Mar76	12May76	7.2 317	136	256				
			SLSD#16		59-59	142-19	22	52	22Aug76	6Nov76	25.6 285	619	963
SLSE#17	59-50	142-31	42	99	22Aug76	15Mar77	11.5 281	150	229				
			45		22Jul76	25Jan77	26.9 296	210	321				
			70		22Jul76	12Feb77	25.4 290	168	265				
C1A	59-11	153-18	20	42	6Oct77	15Mar78	15.9 199	124	1459				
			34		6Oct77	15Mar78	9.0 198	86	678				
			C1B		59-11	153-19	18	40	28May78	23Aug78	9.2 202	48	1043
C2A	59-14	153-02	35	64	28May78	18Oct78	4.3 193	35	383				
			20		6Oct77	10Feb78	8.2 227	135	1048				
			C2B		59-14	153-08	18	62	28May78	18Oct78	14.6 218	176	1817
C3A	59-24	152-53	20	59	7Oct77	15Mar78	8.3 234	48	2392				
			50		7Oct77	15Mar78	1.7 230	26	990				
			C3B		59-25	152-53	25	64	28May78	18Oct78	17.2 232	111	2942
C4A	59-17	152-54	55	84	28May78	2Sep78	0.6 095	24	762				
			20		7Oct77	15Mar78	3.2 273	120	1865				
			65		7Oct77	15Mar78	1.6 239	80	886				
C4B	59-17	152-55	19	83	2Jun78	18Oct78	3.0 246	50	1205				
			64		30May78	18Oct78	1.3 158	71	898				
			C5A		59-10	152-56	20	128	7Oct77	15Mar78	21.0 250	296	1039
C5B	59-10	152-54	65	135	7Oct77	15Mar78	16.3 240	185	806				
			27		31May78	20Sep78	19.1 252	433	2388				
			127		31May78	28Sep78	2.5 200	55	299				
C6A	59-18	152-38	20	71	7Oct77	18Mar78	2.5 275	142	2516				
			C6B		59-19	152-38	26	77	31May78	17Oct78	0.6 256	95	2586
			71		31May78	17Oct78	3.2 119	31	804				
C7A	59-19	152-12	65	71	8Oct77	3Feb78	1.5 353	23	3650				
			C7B		59-19	152-11	17	68	31May78	16Oct78	4.2 310	81	6430
			62		31May78	16Oct78	1.8 237	14	2047				
C8B	59-02	152-04	63	190	29May78	14Oct78	22.1 287	419	4765				
			64		29May78	19Aug78	14.2 284	108	3360				
			179		29May78	14Oct78	7.8 259	33	1734				
C9B	58-47	152-16	66	124	29May78	14Oct78	10.6 300	164	3499				
			67		29May78	14Oct78	10.4 297	166	3473				
			114		29May78	14Oct78	11.4 300	91	1369				
C10A	58-30	153-11	20	170	5Oct77	13Mar78	27.8 230	573	799				
			65		5Oct77	13Mar78	23.4 229	368	490				
			C10B		58-30	153-12	25	175	28May78	9Oct78	14.4 222	222	366
C10B	58-30	153-12	70	175	28May78	9Oct78	12.0 221	185	255				
			165		28May78	9Oct78	4.3 200	117	166				

MOORING	LAT. (deg - min)	LONG.	METER	WATER	START	END	NET FLOW		VARIANCE	VARIANCE
			DEPTH (m)	DEPTH (m)			SPEED (cm/s)	DIR. (deg)	(cm ² /s ²) (35-h filter)	(cm ² /s ²) (2.9-h filter)
C12A	59-32	152-14	20	50	28May78	17Aug78	3.8	42	10	3865
			46		28May78	16Oct78	4.0	30	10	2393
C13A	59-28	152-41	26	68	28May78	16Oct78	5.2	189	75	4108
K1A	57-45	154-44	100	228	16Oct76	30Mar77	26.7	237	339	585
K2A	58-37	153-05	20	164	16Oct76	31Mar77	42.5	214	535	951
			100		16Oct76	31Mar77	26.7	228	281	470
K5A	56-33	152-40	20	95	18Oct76	25Mar77	15.0	192	175	789
			80		18Oct76	25Mar77	13.5	184	95	292
K6A	57-13	152-26	23	75	19Oct77	9Mar78	21.5	283	274	799
			65		19Oct77	9Mar78	14.5	272	112	324
K6B	57-14	152-23	32	82	21May78	5Oct78	15.6	278	60	399
			72		21May78	5Oct78	8.3	263	18	188
K7A	57-04	152-18	28	80	19Oct77	10Mar78	10.6	337	155	670
			70		19Oct77	10Mar78	7.7	326	54	259
K7B	57-05	152-13	29	84	21May78	3Oct78	9.0	319	48	380
K8A	57-07	152-45	25	150	19Oct77	9Mar78	25.1	202	228	422
K8B	57-05	152-43	30	155	21May78	3Oct78	17.9	216	60	156
			75		21May78	3Oct78	10.7	220	32	115
K9A	57-01	152-37	25	158	19Oct77	9Mar78	2.8	300	170	436
K9B	56-59	152-34	13	146	21May78	5Oct78	5.0	222	107	424
			58		21May78	5Oct78	4.4	260	94	356
K10A	56-51	152-26	142		21May78	5Oct78	3.8	293	15	77
			144	154	19Oct77	9Mar78	5.6	332	60	148
K10B	56-50	152-23	24	153	21May78	4Oct78	4.7	291	44	198
			69		21May78	4Oct78	5.8	307	48	207
K11B	56-02	155-06	149		21May78	4Oct78	6.3	339	18	85
			25	60	22May78	28Jul78	10.1	224	46	3179
K12A	55-59	156-18	18	213	24Oct77	8Mar78	24.6	203	797	1862
			205		24Oct77	8Mar78	6.9	182	233	563
K13B	56-24	156-49	28	115	22May78	7Oct78	13.9	220	152	666
			111		22May78	7Oct78	2.7	202	35	191
M1A	55-47	158-39	51	71	28Oct77	7Mar78	16.1	219	151	343
M1B	55-25	157-59	90	110	28Oct77	6Mar78	7.3	29	105	333
M1D	55-46	157-31	70	118	28Oct77	6Mar78	10.6	324	93	428
WGC-1A	54-02	163-00	20	188	5Sep75	1Nov75	27.2	264	320	732
			103		5Sep75	1Nov75	14.9	257	106	268
WGC-1B	54-01	163-00	20	194	2Nov75	12Mar76	12.2	243	236	340
			100		2Nov75	30Dec75	21.5	263	465	671
WGC-1C	54-01	163-00	20	186	13Mar76	11Jun76	25.1	254	206	564
			50		13Mar76	11Jun76	24.4	254	158	445
WGC-1D	54-01	163-06	100		13Mar76	11Jun76	19.1	243	113	278
			175		13Mar76	11Jun76	7.7	225	60	123
WGC-1E	54-01	163-06	20	89	12Jun76	9Oct76	11.2	253	103	446
			50		12Jun76	9Oct76	10.3	255	69	361
WGC-1F	54-03	163-06	18	88	1Oct76	29Apr77	23.6	258	431	1203
			78		1Oct76	18Dec76	12.2	250	98	290
WGC-2A	57-27	150-29	20	88	30Apr77	8Sep77	16.2	262	110	511
			76		29Apr77	7Sep77	7.1	249	35	143
WGC-2B	57-27	150-29	20	185	22Sep75	17Nov75	33.5	226	120	1027
			100		22Sep75	17Nov75	25.7	224	51	353
WGC-2C	57-27	150-29	24	185	10Mar76	8Jun76	21.8	227	194	586
			54		10Mar76	8Jun76	24.1	232	152	457
WGC-2D	57-34	150-49	104		10Mar76	10May76	24.8	235	77	390
			179		10Mar76	8Jun76	13.0	182	114	661
WGC-2E	57-34	150-49	20	92	8Jun76	18Oct76	3.2	245	32	1320
			50		8Jun76	18Oct76	3.7	235	18	1133
WGC-2F	57-34	150-50	20	90	19Oct76	24Mar77	2.3	241	138	1857
WGC-3B	55-11	156-58	20	111	25Mar77	8Sep77	4.7	221	45	1350
			80		25Mar77	8Sep77	2.8	179	12	510
WGC-3C	55-12	156-57	20	112	10Jun76	17Oct76	21.4	256	170	1816
			28		18Oct76	6Mar77	26.1	229	661	1289
WGC-3D	55-12	156-58	90		18Oct76	21Mar77	19.8	232	171	1052
			20	112	10Jul77	18Nov77	24.1	255	168	1664
UP3	54-10	164-00	47	67	22Mar80	15Aug80	2.0	229	78	262



Figure 3-14. Approximate net current speeds and directions derived from the current data in Table 3-2.

speed squared). There was a tendency for flow in the same direction throughout the water column; often the speeds did not decrease in the vertical until quite near the bottom. Net flow tends to be considerably greater in winter than summer as discussed by Lagerloef *et al.* (1981). These various characteristics suggest flow that is significantly affected by eddies (also noted by Royer 1983a) and has large effects from local wind forcing. There may be an appreciable component of barotropic flow, especially during the strong winter winds, as suggested by Lagerloef *et al.* (1981) and Reed and Schumacher (1981).

Results from moorings in the western Gulf (K1-K13, MI numbers, and WGC-1, 2, and 3 on Fig. 3-13) are somewhat unsatisfactory in that none of them sampled the nearshore Alaska Coastal Current before that flow moved into Kennedy Entrance and Shelikof Strait. The results are interesting, however, and reveal at least two subtle differences from results obtained in the northeast Gulf. First, the eddy-energy level seems to be generally lower than that to the east. Second, the open-shelf moorings appear to have net flows that, although also alongshore, decrease more rapidly in the vertical than those to the east. These features suggest rather stable flow that is not strongly affected by local winds. However, the possibility of remote wind forcing, which alters large-scale pressure gradients and flow (as discussed by Battisti and Hickey 1984), cannot be ruled out.

Moorings K5-10 were located in the vicinity of Kiliuda Trough off Kodiak Island; the results reveal a bathymetrically trapped eddy (Lagerloef 1983). Data from the MI moorings seem to reflect a similar feature. The existence of numerous deep troughs in the western Gulf may produce complexities in the flow field at several sites. We

have not attempted to analyze the results from the moorings in detail here, but the data are listed for possible use by others.

Sea Level

Adjusting sea level variations for the static effects of atmospheric pressure changes results in a variable that reflects the density of nearby waters. Favorite *et al.* (1976) and Ingraham *et al.* (1976) provided information on sea level in the Gulf of Alaska, and Reid and Mantyla (1976) used data at Yakutat to infer aspects of subarctic circulation. Reed and Schumacher (1981) examined spatial differences in the seasonal cycles of sea level around the Gulf and interpreted the features in terms of coastal currents. Enfield and Allen (1980) and Chelton and Davis (1982) analyzed interannual variations in the Pacific, including some stations in the Gulf of Alaska. They, along with Cannon, Reed, and Pullen (1985), detected changes in west coast and Alaskan sea level that appear to be linked to El Niño events.

Reed and Schumacher (1981) examined the seasonal cycles of adjusted sea level at Sitka, Yakutat, Seward, Seldovia, Kodiak, and Dutch Harbor (Table 3-3). Annual maximum sea levels at Seward and Seldovia approximately coincide with seasonal minimum salinities (densities) as well as maximum flows of the Alaska Coastal Current. Both stations are just inshore of this flow and should be affected by it. Sitka and Yakutat, however, have maxima later in the year, near the time when coastally convergent winds are at their maximum. Kodiak and Dutch Harbor are not located in the path of the Alaska Coastal Current, so neither their phase nor their small range reflects its effect. A correlation analy-

Table 3-3.
Summary of features in the adjusted mean monthly sea-level deviations from the annual means (from Reed and Schumacher 1981).

LOCATION	TIME OF MINIMUM	TIME OF MAXIMUM	ANNUAL RANGE OF DEVIATIONS (cm)
Sitka	June	December	14
Yakutat	April	November	14
Seward	April	October	14
Seldovia	April	September	13
Kodiak	March	December	9
Dutch Harbor	April	December	8

sis showed that the pairs Sitka–Yakutat, Seward–Seldovia, and Kodiak–Dutch Harbor were highly correlated with each other, but not with other stations.

A long series of monthly anomalies (from the long-term means) of adjusted sea level are shown in Figure 3-15 for stations off our west coast from southern California to the head of the Gulf of Alaska. This figure resulted from an examination of the effects of El Niño events at high latitudes. The large events of 1941, 1958, and 1982–83 are readily apparent in the spatially coherent, rapid rises of sea level. The last two events produced large changes in Alaskan waters. Royer and Xiong (1984) also reported positive temperature anomalies of approximately 2C off Seward in early 1983 and also in early 1977. Not all large changes in sea level are related to El Niño events, however. Numerous anomalies, often spatially incoherent, are also apparent in Figure 3-15. Regardless of their cause, large interannual, as well as seasonal, changes do occur in the Gulf of Alaska.

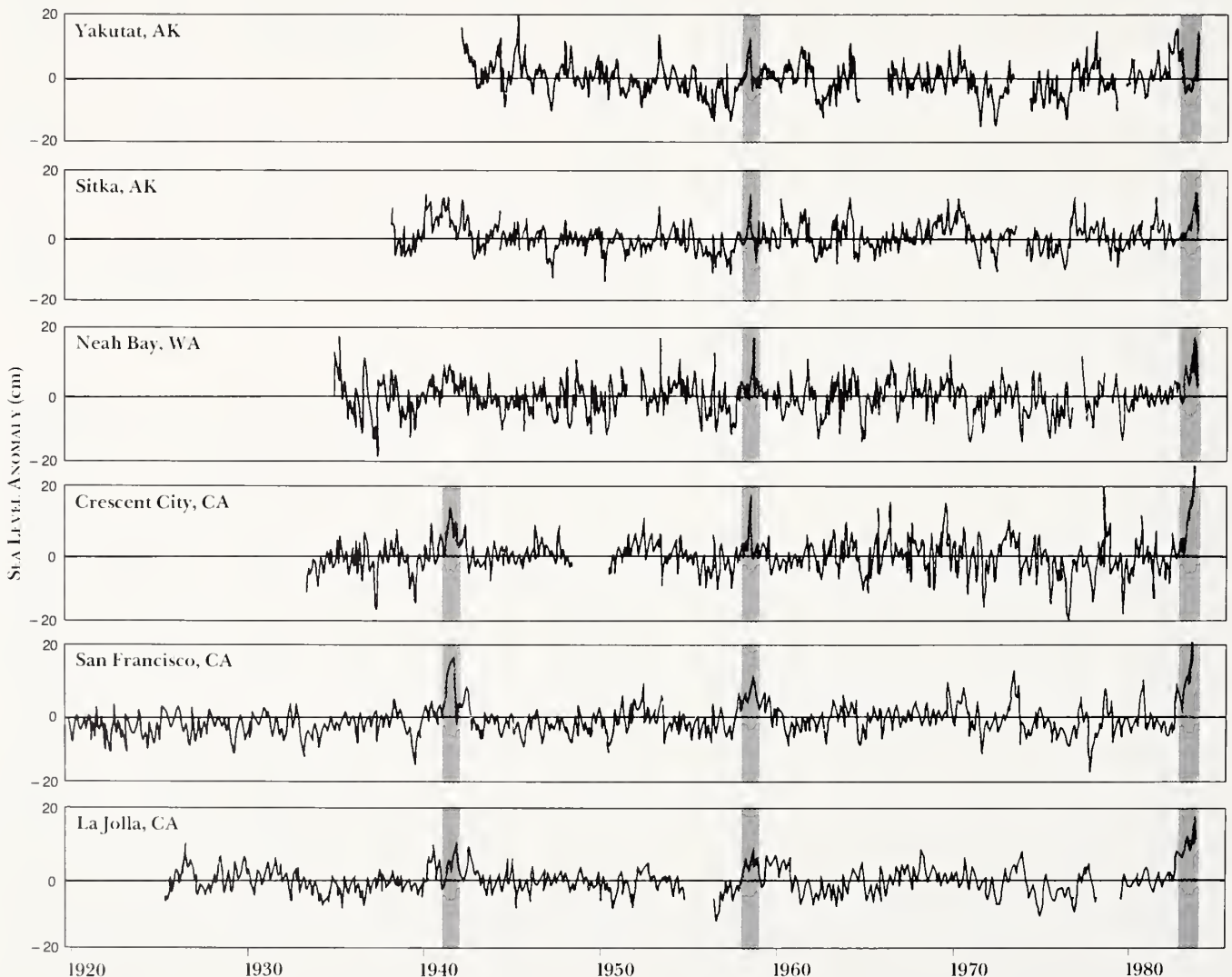


Figure 3-15. Monthly anomalies of sea level from California to the Gulf of Alaska. The data were adjusted for variations in atmospheric pressure, and the time series were detrended. Shading indicates sites having El Niño events in 1941, 1958, and 1982–83. (Modified from Cannon *et al.* 1985.)

Some Implications

The Alaska Coastal Current is a permanent system of coastal flow that exists from southeast Alaska around the Gulf to Unimak Pass. The largest seasonal changes and highest velocities, however, occur in the northern Gulf near the Kenai Peninsula. It would seem that such a feature would have an effect on water exchange in the inshore estuaries and fjords. Although this appears to be the case, the details have not been well documented. Royer (1983a) suggested that the absence of strong winds in summer in the northern Gulf eliminates downwelling of near-surface waters and permits the relatively warm and salty offshore waters to move inshore. Such movement into Prince William Sound was observed by drifters (Royer *et al.* 1979). Surface waters tend to move seaward, but are apparently constrained by winds, except in the Kayak eddy where they move well offshore.

Coastal winds around the Gulf of Alaska vary greatly with time, of course, but also have considerably different seasonal cycles in different regions. In the northern Gulf of Alaska, the winds produce near-shore downwelling. Upwelling occurs only for two to three months in summer when winds are very weak (Royer 1983b; Schumacher and Reed, in press). West of Kodiak Island, however, wind stress is generally in the proper direction to produce upwelling (Schumacher and Reed, in press). Monthly mean speeds (and stress) are small, however, which supports the lack of observational evidence for upwelling in the western Gulf.

The Alaska Coastal Current shows both very large seasonal changes in salinity and very high velocities at times. It is primarily these two features that make it an atypical continental shelf current. Does it have an analogue elsewhere? Royer (1983b) suggested that the Norwegian Coastal Current has strong similarities to the system in the Gulf of Alaska. Large amounts of freshwater discharge and high velocities occur off Norway, but the coastal current there has flow reversals and seems to be strongly affected by wavelike eddy motions (McClimans and Nilsen 1983). Further comparisons of these systems might provide additional insight into the dynamics of coastal flow in the Gulf of Alaska.

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Chemical Distributions and Signals in the Gulf of Alaska, its Coastal Margins and Estuaries

4

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ABSTRACT

This chapter combines the limited chemical data for the Gulf of Alaska, its coastal margins, and its estuaries with recent physical oceanographic studies to determine how these distinct domains interact. We suggest how the interactions may be detected and quantified chemically. A basic understanding exists for the circulation and interaction of all domains. An improved understanding of these interactions and their importance will result if future chemical studies are: 1) closely integrated with physical oceanographic measurements of transport and circulation, and 2) careful to involve measurements of radioactive and transient tracers.

Introduction

A surprisingly small amount of chemical work has been done on the deep Gulf of Alaska. The most extensive chemical data sets exist for coastal fjords and estuaries adjacent to the shelf, and the fewest chemical data are available for the continental shelf of the Gulf of Alaska. This chapter synthesizes chemical oceanographic studies in the Gulf of Alaska by treating the deep sea, the shelf, and the fjords and estuaries as distinct oceanographic domains. In the chapter, we consider circulation, chemical distributions, and variability in each domain. We also consider how each of these domains interacts physically with adjacent domains and how the interactions may be detected and quantified chemically. This approach summarizes what is known about chemical processes in the Gulf of Alaska and, at the same time, points the way to future work.

We will rely heavily on physical oceanographic studies that shed light on how these domains circulate and interact since there are few chemical data for the Gulf of Alaska, its continental shelf, and coastal inlets. This chapter contains little new data, and includes data from studies performed prior to the introduction of reliable analytical methods for nutrients, trace metals, dissolved gases and radioisotopes. Note that it is necessary to depart from the geographic constraints of this volume (*i.e.*, north of 52°N and east of Great Sitkin Island, 176°W) in order to make use of the valuable time-series data collected at Ocean Station 'P'.

Deep Waters

The locations of the chemical data used in this chapter are shown in Figure 4-1; the types of data are listed in Table 4-1. Some of the earliest chemical data for the Gulf of Alaska region were collected during 1933–1934 (Barnes and Thompson 1938). There have been two major field efforts in the Gulf of Alaska, separated by some 20 years, whose results can be used to produce sections of large-scale chemical distributions (NORPAC 1960, 1965; Reid 1973; and Cline, Feely, Kelly–Hansen, Gendron, Wisegarver, and Chen 1985). Many of the earlier data (collected before the development of continuous CTD profilers) were collected at 'standard' depths and did not sample either the oxygen minimum or the deeper waters with good resolution. Reid (1973), using principally the NORPAC data, presented chemical sections of the western Gulf of Alaska as part of a larger effort aimed at determining the source of Pacific Intermediate Water. The GEOSECS program performed comprehensive chemical measurements in the Atlantic and Pacific oceans; part of this data set (Broecker, Spencer, and Craig 1982; Craig, Broecker, and Spencer 1981) includes a 1973 section along the far-western edge of the Gulf of Alaska (176°W). This section contains the most comprehensive chemical data available for this area. The chemical and current measurements of Warren and Owens (1985), taken some 100 km east of the GEOSECS section, are an important complement to the GEOSECS data. Station P (50°00'N, 145°00'W) has been

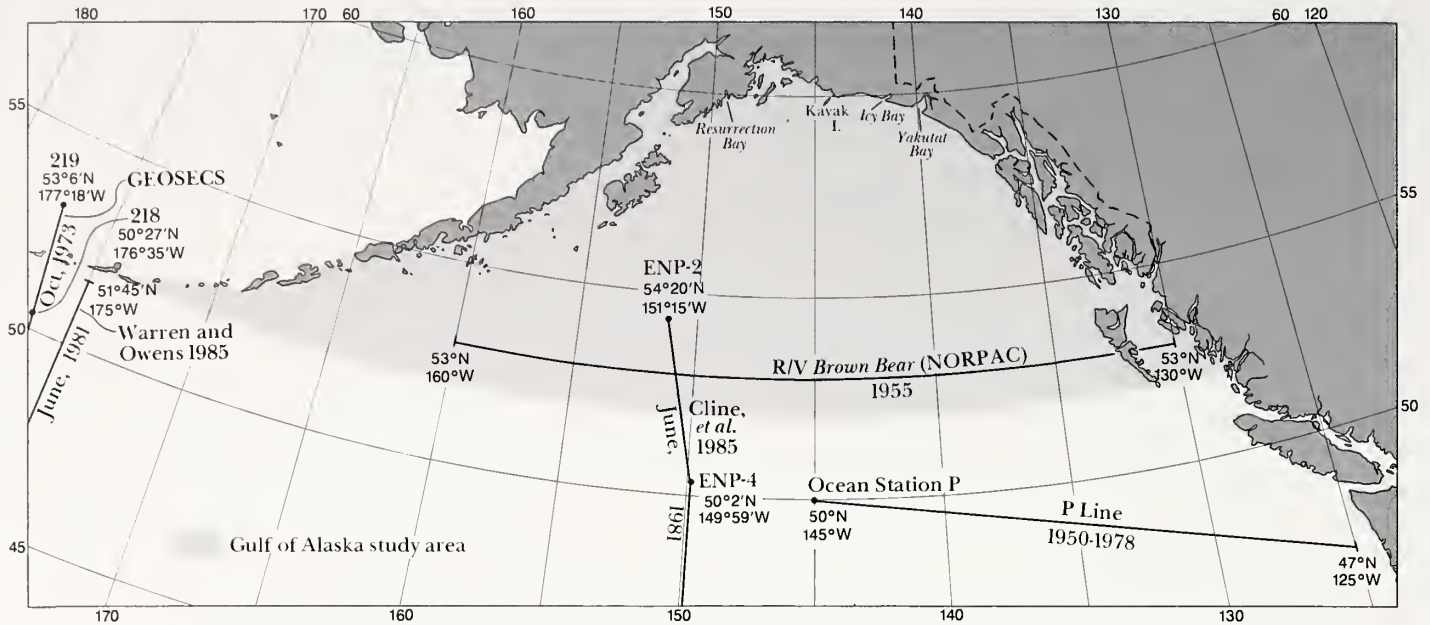


Figure 4-1. Location of oceanographic sampling stations and sections in the Gulf of Alaska.

occupied for more than 25 years, beginning in 1950, and provides the only data set that allows consideration of annual and longer-term variability in the deep Gulf of Alaska. Published data for Station P consists mainly of T, S, and oxygen depth distributions (Tabata 1981). Other chemical data have been collected, but are not yet available for distribution (C.S. Wong, Sidney, B.C., pers. comm., 1984).

Deep waters are not formed in the North Pacific (Reid 1965, 1973; Warren 1983) because low salinity in the near-surface water reduces its density and prevents it from sinking to great depth. However, Pacific Intermediate Water is formed during winter convection (Reid 1973). It occurs in N-S sections of the Pacific Ocean as a low-temperature, low-salinity tongue centered at depths of 300 to 600 m at middle and low latitudes. The processes governing the presence of this low-salinity surface water are not completely clear. For example, Warren (1983) emphasizes processes that result in a low regional evaporation rate, while Royer (1979, 1982) presents a case for high terrestrial runoff.

Depth distributions from a station located in the approximate center of the Gulf of Alaska (ENP-2, Cline *et al.* 1985) are presented in Figure 4-2. Distinctive chemical features of the deep Gulf of Alaska include some of the highest oceanic silicate, phosphate, and nitrate concentrations, as well as the best-developed oxygen minimum to be found in the world ocean. While the depth of the oxygen minimum varies somewhat with location (doming in the central Gulf), it occurs consistently at sigma-t values between 27.3 and 27.4. The oxygen and phosphate distributions result from the decomposition of particulate organic matter that sinks from surface ocean waters. While this is also the case elsewhere, concentrations of oxygen and phosphate in the Gulf of Alaska differ substantially from concentrations in other ocean waters at similar latitudes.

The oxygen minimum is well developed in the Gulf of Alaska—not because of higher surface water productivity

Table 4-1.
Gulf of Alaska Data Sources.

Reference	Notes
Barnes and Thompson (1938)	Some of the earliest data for the Gulf of Alaska. Mostly surface T, S, PO ₄ , and Si(OH) ₄ .
NORPAC (1960)	Compilation of data collected in the North Pacific prior to 1955, mostly T, S, and O ₂ .
NORPAC (1965)	Data collected in the North Pacific during 1959, mostly T, S, and O ₂ .
Reid (1965)	Synthesis of NORPAC (1960, 1965) data plus additional data. Contains chemical sections of Gulf of Alaska.
Dodimead <i>et al.</i> (1962)	Extensive T, S, and O ₂ data for the Gulf of Alaska collected during summer 1962.
Kort (1966)	Extensive T, S, O ₂ , nutrient, organic carbon, fallout isotope, and trace metal data for the entire Pacific Ocean. Few Gulf of Alaska data.
Hokkaido University (1957-1984)	T, S, O ₂ , NO ₃ , PO ₄ , and Si(OH) ₄ , at many locations in the Gulf of Alaska, usually to maximum of 1,500 meters.
Anderson <i>et al.</i> (1977)	Long-term averages of nutrients and chlorophyll for many locations in the Gulf of Alaska.
Broecker <i>et al.</i> (1982) Craig <i>et al.</i> (1981)	GEOSECS Hydrographic Report GEOSECS Atlas
Feely and Chen (1982) Chen (1982)	Total CO ₂ and alkalinity sections along 150° W longitude.
Warren and Owens (1985)	T, S, O ₂ , NO ₃ , PO ₄ , Si(OH) ₄ , and currents along 175° W longitude.
Cline <i>et al.</i> (1985)	T, S, O ₂ , NO ₃ , PO ₄ , Si(OH) ₄ , alkalinity, total CO ₂ , Freon-11, and Freon-12 in western (~170° E), central (170° W) and eastern (150° W) North Pacific sections.

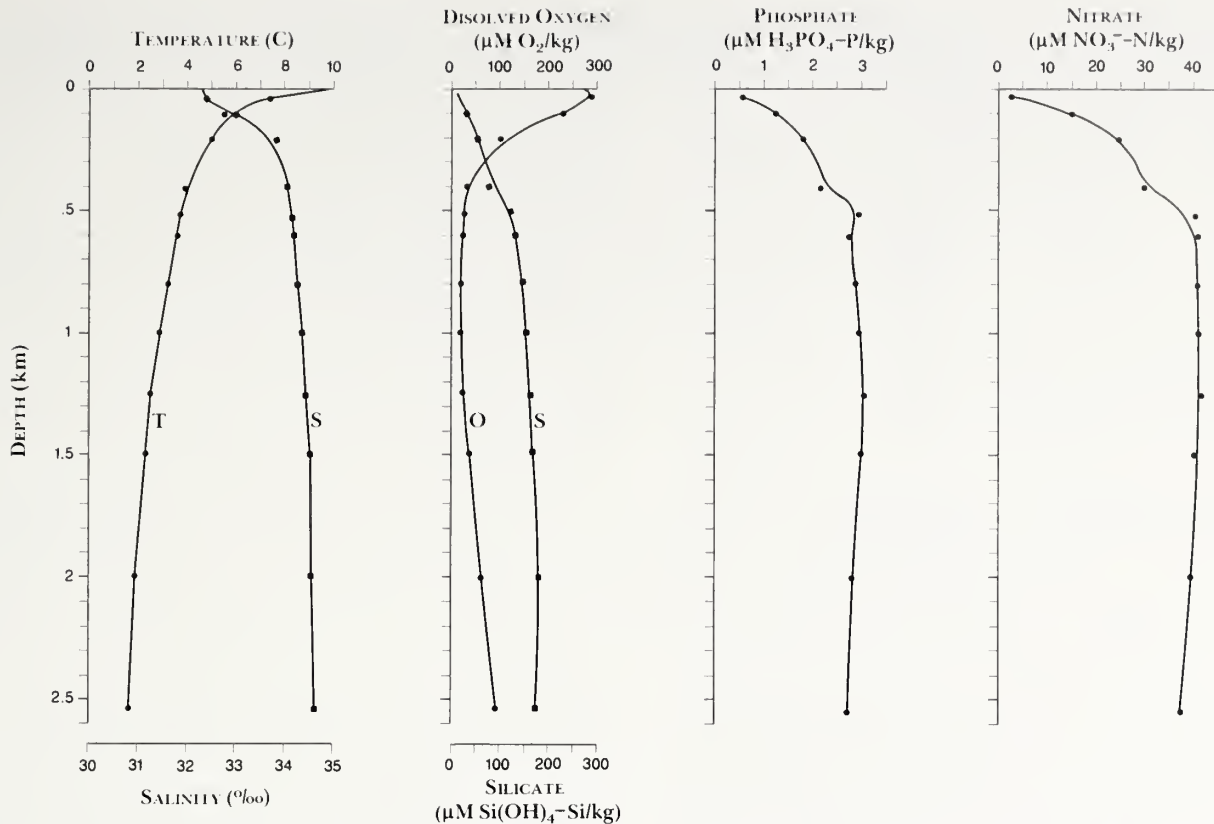


Figure 4-2. Chemical profiles for the central Gulf of Alaska, Station ENP-2 (15 June 1981; 54° 20'N, 151° 15'W). (Modified from Cline *et al.* 1985.)

(Sambrotto and Lorenzen, Ch. 9, this volume)—but because the deep waters circulate poorly, and because they carry the accumulated products of decomposed organic matter from the deep waters of other ocean areas (Broecker and Peng 1982).

The abyssal waters of the northeast Pacific share several characteristics:

- they are the farthest from areas of bottom water formation and ventilation
- they are very uniform in their major properties
- they are the oldest abyssal waters in the world ocean (Mantyla and Reid 1983)

Abyssal waters enter the Gulf of Alaska from three possible directions: 1) from the west along the Aleutian Trench (Warren and Owens 1985); 2) from the southwest through the Emperor Seamount Chain; and 3) from southeast of the Hawaiian Islands (Mantyla and Reid 1983).

Pytkowicz and Kester (1966) have analyzed the extensive NORPAC oxygen and phosphate data to determine both the sources and the flow direction for the intermediate and deep waters of the northeast Pacific, including the Gulf of Alaska. They calculated horizontal gradients of apparent oxygen utilization (AOU) (Redfield, Ketchum, and Richards 1963) in order to determine directions for intermediate water motion east of 150° W. They also used horizontal gradients of phosphate in a similar manner. Their results indicate that water moves into the Gulf from the south and southwest at a depth of 1,000 m, and moves out of the Gulf to

the south at depths of 1,500 and 2,000 meters. Reid and Mantyla (1978) considered the entire North Pacific and used maps of geopotential anomaly at 1,000 db to show anticyclonic circulation.

The recent direct current observations of Warren and Owens (1985) at 175° W show a zonal eastward flow into the Gulf with a westward flow adjacent to the Aleutian Islands. The Pytkowicz and Kester study and the Warren and Owens study cover widely separated parts of the Gulf of Alaska, and both appear to be in general agreement. However, they keynote the need for more direct current measurements in deep and intermediate waters.

The movement of abyssal water into the Northeast Pacific Ocean and the Gulf of Alaska requires both upwelling and a compensating surface flow of water in the reverse direction along the coastal margin. Evidence of upwelling is provided by the doming of the oxygen minimum (Reid 1965), whereas the compensating surface flow is represented by the Alaskan Stream.

Results of measurements at GEOSECS Station 218 (part of a section along the western edge of the Gulf of Alaska) are presented in Figure 4-3. This station includes many of the same parameters shown in Figure 4-2, but also includes carbon isotope data. This station shows a very intense oxygen minimum/nutrient maximum at about 1,000 m ($\sigma_t = 27.4$). Both the current meter measurements and the oxygen and silicate data from the Warren and Owens (1985) study indicate that water is moving into the Gulf of Alaska (50° N) at velocities between 1 and 3 cm/s at all depths. This means

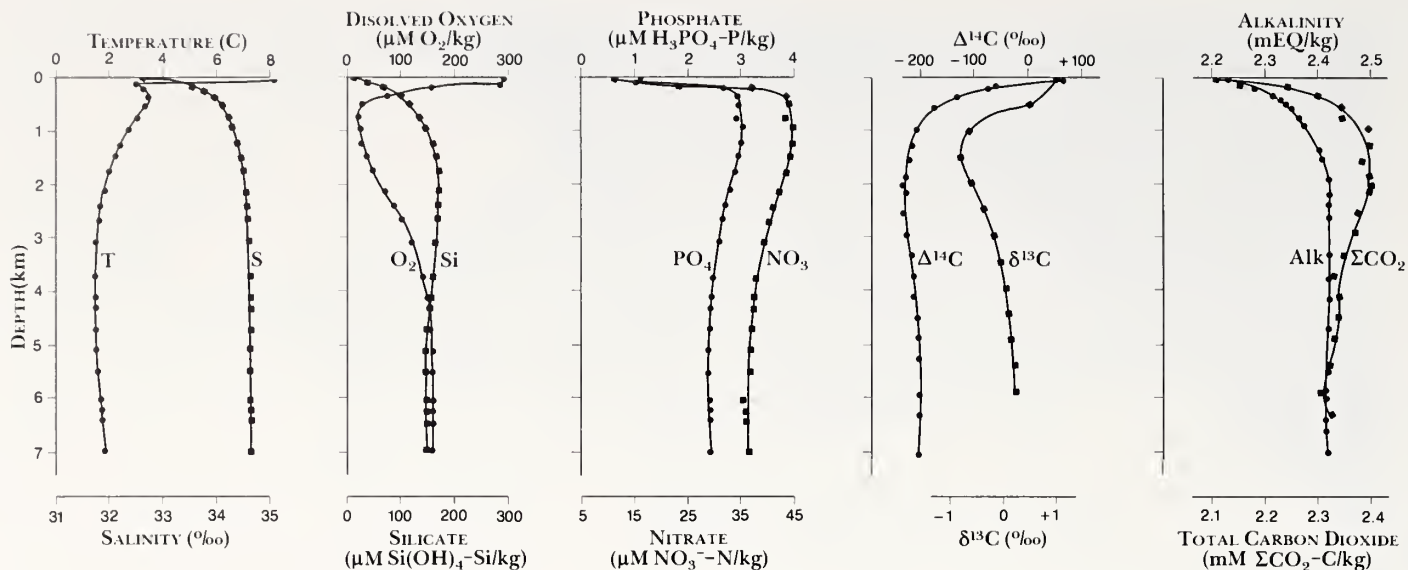


Figure 4-3. Chemical profiles at GEOSECS Station 218. Data are from Broecker, Spencer, and Craig (1981); Östlund and Stuiver (1980); and Kroopnick (1985).

that the western boundary must be a source of low-oxygen, high-nutrient waters that are characteristic of depths greater than 500 m in the Gulf of Alaska. The measurements of Warren and Owens (1985) also confirm the presence of a narrow, westward-flowing surface current along the south slope of the Aleutian Islands that carries high-oxygen, low-silica water out of the Gulf.

Fluxes across the southern boundary of the Gulf of Alaska cannot be constrained as well as those on the western boundary, but questions about long-term variability in the Gulf can be addressed using the Station P data. Studies of nutrients (Anderson, Lam, Booth, and Glass 1977), primary productivity (McAllister, Parsons, and Strickland 1960), and ²²²Rn (Peng, Takahashi, and Broecker 1974) have been performed at this station. Anderson *et al.* (1977) measured annual variations in nitrate and showed that surface nitrate was never less than 10 µM, even during peak uptake.

Other observations of surface waters (Hokkaido University 1981) confirm the fact that measurable nitrate is always present, and indicate that nitrate probably does not limit surface productivity. A well-established population of pelagic grazers appears to be responsible for the relatively high surface-nutrient concentrations (Miller, Frost, Batchelder, Clemons, and Conway 1984).

An analysis of nearly 25 years of T, S, and oxygen data from Station P (Tabata 1981) showed that surface temperatures varied annually from 5 to 12°C, and that salinity varied between 32.65 and 32.85‰, although there are instances of brief incursions of higher-salinity water. These analyses extend to approximately 1,000 m, and the sigma-t surface associated with the oxygen minimum frequently moves between depths of 900 and 1,000 m (Fig. 4-4).

As expected, variations in T, S, and oxygen are much smaller at depth than at the surface, but several long- and short-term trends are evident. Three trends in the oxygen data were identified by Tabata: 1) above average values during 1958 to 1964, 2) below average values during 1968 to 1970,

and 3) a subsequent return to normal values. The oxygen changes did not correlate well with temperature, and Tabata suggested that periods of below-average oxygen were related to the intrusion of oxygen-deficient water that formed along the Pacific coast of North America. If Tabata's assumption is confirmed, it could be evidence for a link between deep-water and coastal-water processes.

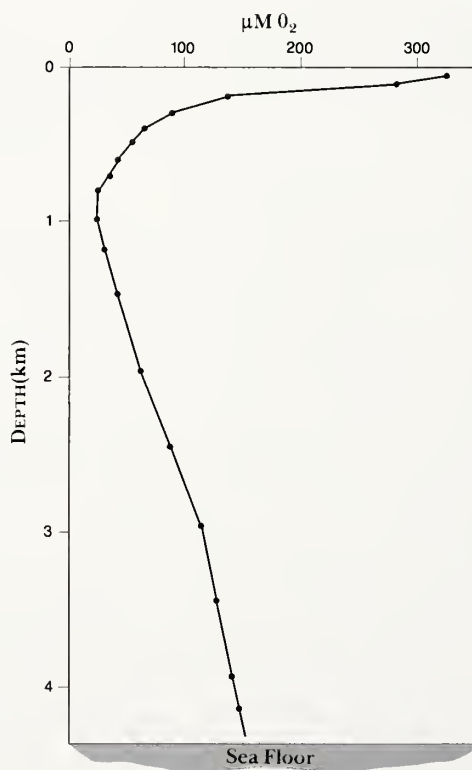


Figure 4-4. Dissolved oxygen profile at Station P (April 1978; 50° N, 145° W). Institute of Ocean Sciences (1978) data.

Distributions of natural and fallout radioisotopes can be used to estimate process rates, but there are only a few measurements of radioactive species in the Gulf of Alaska. Silker (1972) reported surface concentrations and a few vertical profiles of the fallout isotopes ^{90}Sr , ^{95}Zr , ^{95}Nb , ^{106}Ru , ^{144}Ce , and the natural cosmogenic isotope ^7Be for the North Pacific Ocean, but only a few of these measurements were made north of 50°N . Silker used ^7Be profiles to estimate vertical eddy diffusivities of 0.5 to 0.7 cm^2/s .

Michel and Suess (1975) determined tritium in surface water for a number of locations in the North Pacific during the 1970s, but none of their stations were located in the Gulf of Alaska. Fine and Ostlund (1977) and Fine, Reid, and Ostlund (1981) reported tritium data for approximately the same area. Both studies inferred that tritium concentrations in surface waters of the Gulf of Alaska should be among the highest in the world ocean.

Radiocarbon was measured (M. Stuiver and P. Quay, University of Washington, pers. comm., 1984) in surface samples collected during a transit between Dutch Harbor and Seattle in June 1982; the results are shown in Figure 4–5. In the absence of modern or fossil carbon inputs, $\Delta^{14}\text{C}$ values reflect radioactive decay and are useful in determining relative ages of water masses. The radiocarbon data of Stuiver and Quay clearly suggest the influence of older, deeper water on surface waters in the Gulf of Alaska central gyre. These data are in agreement with the chemical section data of Reid (1965). The negative $\Delta^{14}\text{C}$ in their easternmost sample could be the result of two processes: 1) Columbia River input, or 2) coastal upwelling. More depth-distribution data are necessary before the source of this older water can be determined. Similar $\Delta^{14}\text{C}$ values occur at depths of ~ 100 m in the GEOSECS data (Östlund and Stuiver 1980).

The upwelling rate (Craig 1969) and source–water depth for the upwelled water could be obtained in the central Gulf

if vertical profiles of $\Delta^{14}\text{C}$, nutrients, and total CO_2 were available. The GEOSECS Pacific radiocarbon section of Ostlund and Stuiver (1980) shows a distinct lens of very old ($\Delta^{14}\text{C} = -240\text{‰}$) water at depths of 2,000 to 3,000 m along the western boundary of the Gulf of Alaska. Kroopnick's (1985) analyses of stable carbon isotopes ($^{13}\text{C}/^{12}\text{C}$) of total CO_2 for the same GEOSECS samples show a lens of water with the lowest $\delta^{13}\text{C}$ values found in the world ocean. Organic matter undergoes isotopic fractionation during respiration in which the light isotope (^{12}C) is selectively added to the total CO_2 reservoir. These negative or light $\delta^{13}\text{C}$ values reflect the fact that this water is very old. The current measurements of Warren and Owens (1985) suggest that this water is carried into the Gulf, so radiocarbon and ^{13}C could be valuable tracers for physical processes in the Gulf of Alaska.

The carbon dioxide system in the Gulf of Alaska has been studied in some detail. The partial pressure of CO_2 in surface waters has been measured in underway transects across the Gulf of Alaska (Gordon, Park, Hager, and Parsons 1971; Gordon, Park, Kelley, and Hood 1973; and Kelley and Hood 1971). These studies showed elevated CO_2 partial pressures that are consistent with upwelling of deep water.

Recent carbonate system data (Feely and Chen 1982; Chen 1982; and Feely, Byrne, Betzer, Gendron, and Acker 1984) suggest that deep Gulf of Alaska waters are particularly susceptible to increases in atmospheric CO_2 . These authors calculated that the degree of aragonite and calcite supersaturation is lowest in the surface and intermediate waters north of 50°N in the Gulf of Alaska, as a result of the high total CO_2 -to-alkalinity ratio. Further, Feely *et al.* (1984) provide calculations that suggest that the surface waters could become aragonite-undersaturated during the next century as increases in atmospheric CO_2 cause further decreases in surface-water carbonate ion activity. Betzer,

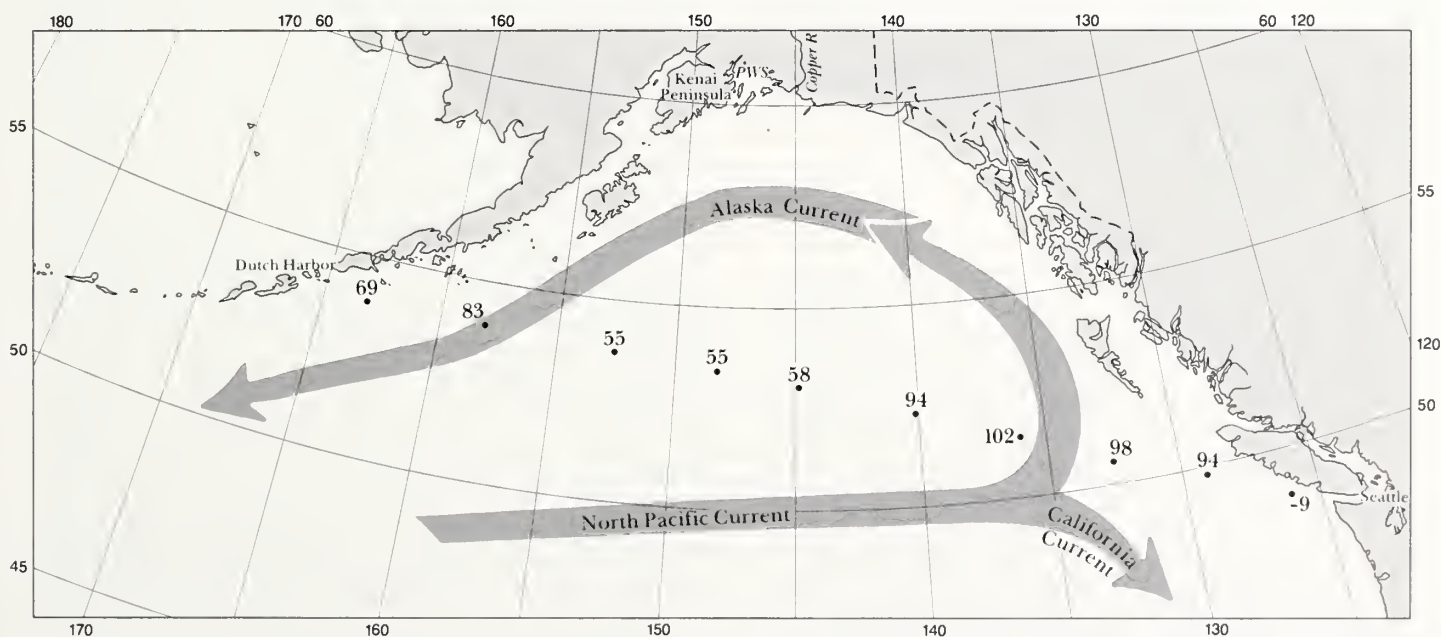


Figure 4–5. Surface ^{14}C data (collected June 1982) of Stuiver and Quay (unpubl. data). Data are reported as $\Delta^{14}\text{C}$ (‰) and are plotted on the surface circulation scheme of Dodimead, Favorite, and Hirano (1963).

Byrne, Acker, Lewis, Jolley, and Feely (1984) showed that aragonite pteropod tests are quite soluble at depth in the western Pacific and suggested that biogenic particle fluxes through the euphotic zone are almost large enough to balance the Pacific Ocean alkalinity budget.

Anthropogenic chlorofluoromethanes (Freon-11 (CCl_3F) and Freon-12 (CCl_2F_2)) have been measured in the Northeast Pacific (Gammon, Cline, and Wisegarver 1982). These compounds are biologically inert and are stable over time scales exceeding 1,000 years. Since their atmospheric input function is known, they can be used as transient tracers. Chlorofluoromethanes appear to be in saturation equilibrium with surface waters (Wisegarver and Cline 1985). The recent chlorofluoromethane solubility determinations of Warner and Weiss (1985) cover the temperature range of from 0 to 40C for both pure water and seawater. These values appear to supersede those of Wisegarver and Cline (1985).

Cline *et al.* (1985) used a one-dimensional model (which considered the vertical advection and diffusion of an exponentially driven conservative tracer) with these data in order to estimate both vertical diffusivities ($K_z \cong 0.3\text{--}0.7 \text{ cm}^2/\text{s}$) and upwelling velocities ($w \cong 9\text{--}10 \text{ m/y}$). These are the best estimates for these important parameters in the Gulf of Alaska at the present time and are in agreement with Silker's (1972) estimate for K_z .

Freons were used as surrogate tracers of CO_2 in conjunction with precise measurements of carbon dioxide system components (Cline *et al.* 1985) and were used to estimate the amount of excess CO_2 in North Pacific gyre waters. Unlike radiocarbon, ^{13}C , and tritium, chlorofluoromethanes can (and must) be analyzed at sea. Improvements in blank reduction should lower the detection limit to less than 10^{-8} micromoles. This improvement, coupled with the fact that the transient from bomb-introduced tritium is decaying, makes chlorofluoromethanes an important tracer for future work. Chlorofluoromethanes have been used successfully to trace bottom and intermediate water in the Atlantic (Bullister and Weiss 1983; Weiss, Bullister, Gammon, and Warner 1985), and could be a valuable tool in studies of the origin of Pacific Intermediate Water.

Continental Shelf Waters

Most chemical studies on the Gulf of Alaska shelf have been conducted in limited areas, such as the northeast Gulf shelf near Icy Bay, lower Cook Inlet, or Shelikof Strait (Larrance, Tennant, Chester, and Ruffio 1977; Atlas, Venkatesan, Kaplan, Feely, Griffiths, and Morita 1983), and address specific questions, making it difficult to generalize using these data. Much of our understanding of seasonal changes in Gulf of Alaska shelf waters is the result of: 1) the time-series occupation of a hydrographic section (the GAK line) across the shelf from Resurrection Bay (Royer 1975), and 2) measurements from a single station (GAK-1) located at the mouth of Resurrection Bay. While limited nutrient data are available for this region of the shelf, summer and winter profiles for a station near GAK-1 are shown in Figure 4-6. Although the station has been occupied irregularly

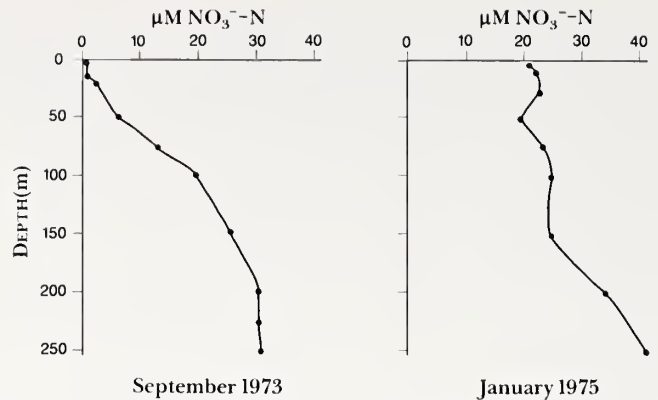


Figure 4-6. Summer and winter nutrient profiles from a station near the mouth of Resurrection Bay (RES-5; $59^{\circ} 50' \text{N}$, $149^{\circ} 28' \text{W}$).

since 1970 (Xiong and Royer 1984; Royer and Xiong, University of Alaska, unpubl. data), it still provides time-series data sufficient both to resolve seasonal changes in water types on the shelf and to detect several El Niño/Southern Oscillation events in the Gulf of Alaska. This data base was enlarged by OCSEAP-sponsored observations, which included extensive hydrographic measurements, satellite-tracked drifters (Royer, Hansen, and Pashinski 1979), and moored current meter observations (Reed and Schumacher, Ch. 3, this volume).

The large-scale seasonal changes in the bottom water of the coastal Gulf of Alaska depend on seasonal changes in the meteorological regime (Royer 1975) and are controlled by the relative positions of the Aleutian Low and the North Pacific High. The dominance of the Aleutian Low during winter causes a series of severe storms and strong easterly winds. As a result of the storms, Ekman transport leads to coastal convergence and downwelling (Royer 1981a). The convergence and downwelling then cause both the accumulation of low-density surface waters along the coast and the replacement of warm, high-salinity bottom waters on the shelf. The surface waters become densest during winter due to lack of coastal runoff and due to cooling.

The dominance of the Pacific High in summer brings fair weather and possibly a weak reversal of the wind field, permitting warm, relatively high-salinity waters from the central Gulf to move back over the shelf at depths of 100 to 200 meters. Thus, the relative positions of the Aleutian Low and the North Pacific High meteorological systems lead to seasonal changes in the temperature and salinity of Gulf shelf waters, as shown in Figure 4-7. Muench and Heggie (1978) have shown that a combination of tidal action and waters of varying density is important in the bottom water renewal of fjords adjacent to the Gulf of Alaska. These waters originate from no deeper than about 250 m in the central Gulf, and although they do have low-oxygen, high-nutrient signatures, the unique waters from the deep Gulf of Alaska are not transported across the shelf and into the coastal inlets.

The Alaska Current flows westward along the shelf break (Hayes and Schumacher 1976); and a portion of the coastal flow is diverted offshore by Kayak Island to join the Alaska Current. Two quasi-permanent gyres to the west of Kayak

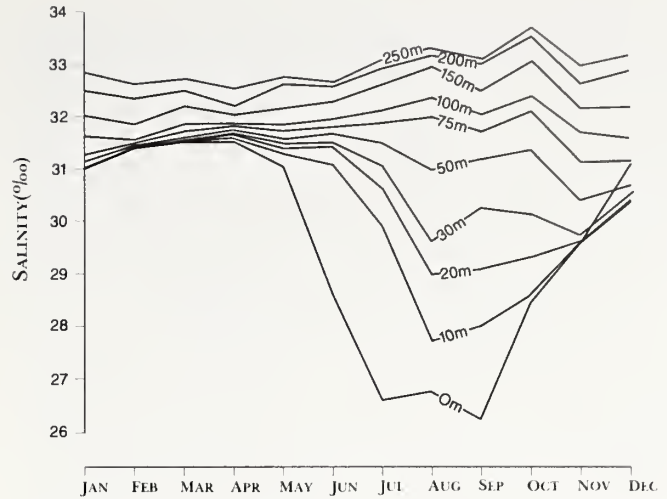
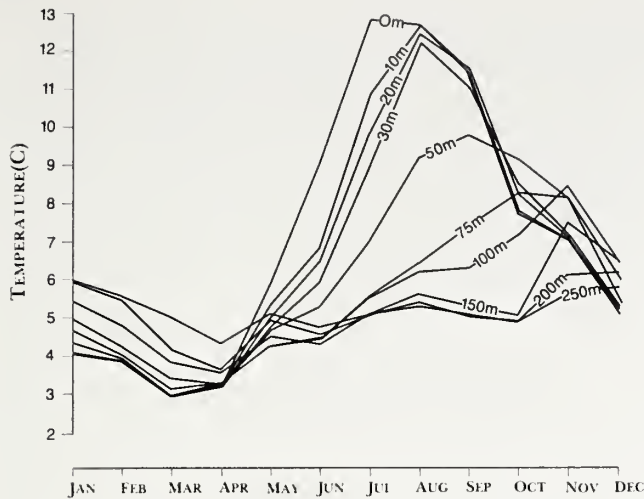


Figure 4-7. Monthly means (1970-1983) of temperature and salinity at selected depths from a station near the mouth of Resurrection Bay (GAK-1: 59° 50'N, 148° 50'W). (Modified from Xiong and Royer 1984.)

Island influence coastal circulation and the distribution of suspended particulate matter (Feely, Baker, Schumacher, Massoth, and Landing 1979). The nearshore cyclonic gyre transports suspended matter from the Copper River west along the coast and into Prince William Sound. The off-shore anticyclonic gyre combines with the coastal flow diverted by Kayak Island (which contains suspended matter from glaciers to the east), to transport suspended matter from both sides of Kayak Island off the shelf.

Downslope movements of near-bottom water during winter also transport suspended material offshore. Niebauer, Roberts, and Royer (1981) analyzed a current-meter record from the shelf break that showed both current veering and rotation occurring from July through September. They hypothesized that the fluctuations were eddies, which may also be an important shelf mixing and transport process.

Runoff from major rivers entering the Gulf of Alaska has been summarized by Roden (1967). Precipitation is high along the Gulf coast, averaging some 240 cm/y; some glacial fields receive over 800 cm/y (Royer 1982, 1983; Wilson and Overland, Ch. 2, this volume). Freshwater discharges estimated to average 23,000 m³/s enter the coastal Gulf of Alaska through numerous ungauged streams and rivers, reaching a maximum in October (Royer 1982) (Fig. 4-8). This freshwater runoff appears to be a driving mechanism for a coastal current, which has recently been identified (Royer 1979, 1981b; Schumacher and Reed 1980). The influence of the Aleutian Low tends to confine this current to the coast in the northern Gulf of Alaska. This feature has been termed the 'Kenai Current' (Schumacher and Reed 1980) because it reaches its maximum intensity adjacent to the Kenai Peninsula. However, additional work (Royer 1983) has shown that this feature extends from Southeast Alaska to the Bering Sea (Schumacher, Pearson, and Overland 1982) and is sufficiently large to make the term Alaska Coastal Current more appropriate.

The Alaska Coastal Current may have a volume transport in excess of 10⁶ m³/s at velocities in excess of 150 cm/s. It is one of the major avenues for influx of freshwater to the

North Pacific Ocean. The Alaska Coastal Current could also be important in the transport and dispersion of eggs, larval forms, and chemical species in coastal waters and fjords.

The OCSEAP program conducted during the 1970s on the Gulf of Alaska shelf focused on impacts related to petroleum exploration and production. As a result, a number of studies were directed toward determining accurate baseline concentrations of natural petroleum compounds in the water, the sediments, and the biota of the region. Petroleum transport mechanisms were also studied in the field and the laboratory. Most field studies were conducted in the nearshore and shelf waters that were expected to be heavily impacted by petroleum development. Cline (1977) measured C₁ to C₄ hydrocarbons both at the surface and at near-bottom for a number of nearshore transects from Yakutat to Resurrection Bay. These measurements were directed toward detection of petroleum seeps in areas of seismic activity. Concentrations were typically in the range of 0.001 to 0.010 micromolar.

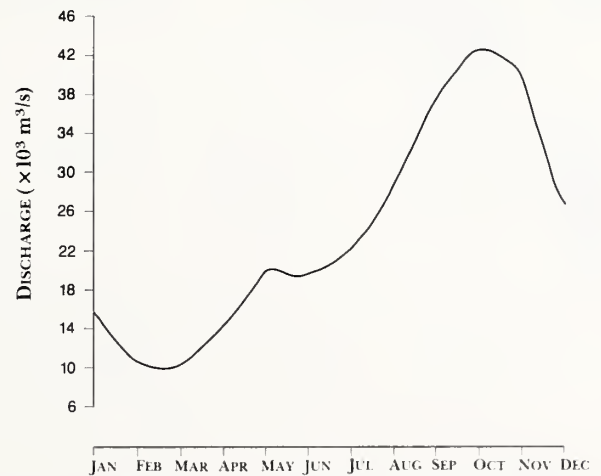


Figure 4-8. Mean monthly freshwater discharge for southeast and southcoast Alaska estimated from precipitation. (Modified from Royer 1982.)

Cline (1977) suggested that methane might hold promise as an indicator of natural seeps since its concentration was quite variable and methane-enriched plumes could be followed for considerable distances. Shaw (1977) measured hydrocarbon concentrations in water, sediments, biota, and seston at a number of locations in the Gulf of Alaska and Cook Inlet. These measurements emphasized the heavier, aromatic hydrocarbons and buoyant 'tar' particles. Typical concentrations in sediments were in the $\mu\text{g}/\text{kg}$ range; tissue concentrations were a few micrograms per gram.

The results of these and other studies indicate that hydrocarbon concentrations in the Gulf of Alaska are similar to those found in other marine environments (Shaw 1977), and that the Gulf of Alaska cannot be considered heavily impacted by petroleum-related hydrocarbons at this time. A large body of hydrocarbon data exists, and a baseline for comparing future hydrocarbon concentrations is established, but uncertainty concerning natural sources, sinks, and transport mechanisms appears to preclude the use of hydrocarbons as quantitative tracers.

Landing and Feely (1981) investigated the chemical composition of both trapped suspended particles and bottom sediments in the vicinity of Icy Bay and were able to quantify fluxes of trace metals, silica, carbon, and nitrogen. Their study showed that fluvial inputs of continental material dominated the inorganic fraction of the suspended particles. By comparing the trapped particulate material and the underlying sediments, Landing and Feely quantified several key factors, including elemental accumulation rates, the remineralization of particulate organic matter, and the remobilization of trace elements. They found that the majority of remineralization occurs within the sediments below the zone influenced by resuspension, and appears to be biologically mediated.

Fjords and Estuaries

Of all the areas in the Gulf of Alaska, the fjords have been studied most extensively. Pickard (1961) summarized oceanographic features of British Columbia inlets and some of the larger inlets of Southeast Alaska (1967), and Pickard and Stanton (1980) summarized Pacific fjords studied by the University of British Columbia. Study locations of Alaskan fjords and inlets adjoining the Gulf of Alaska are presented in Figure 4-9. Table 4-2 summarizes these studies and gives information on sill depths, locations, the types of data collected, indication of the frequency of sampling, and the duration of the studies. This table presents two noteworthy points about studies on Alaskan fjords in general. First, the observation time-scale is just sufficient to resolve seasonal changes, and second, the duration of the studies rarely exceeds two to three years, so no time-series data set that permits interannual comparisons has resulted. There are few observations of chemical species like nutrients, and only a few current measurements. Exceptions to the above points are Boca de Quadra, Port Valdez, and Resurrection Bay.

Port Valdez and Boca de Quadra have been the foci of comprehensive interdisciplinary studies due to actual or impending industrial development. Burrell (Ch. 7, this volume) considers seasonal cycles in Boca de Quadra. The Port Valdez studies have spanned almost a decade (Hood, Shiels, and Kelley 1973; Colonell 1982). Resurrection Bay has also been frequently sampled, largely because of its proximity to University of Alaska Institute of Marine Science facilities and also because of the effort put into maintaining the time series at Station GAK-1, near the mouth of Resurrection Bay. The emphasis of most studies on other fjords listed in Table 4-2 has been on explaining their circulation well enough to:

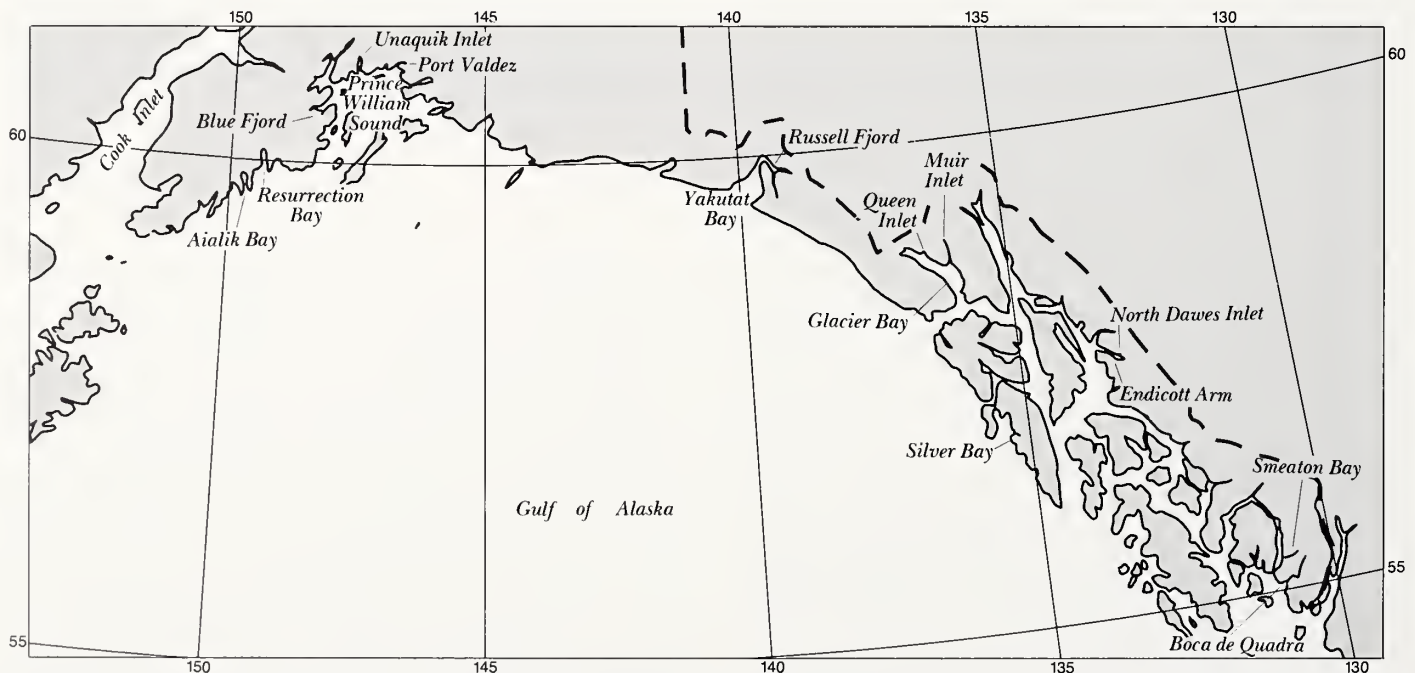


Figure 4-9. Study locations of fjords and inlets adjacent to the Gulf of Alaska (refer to Table 4-2 for study descriptions).

- employ them as locations for the study of high sedimentation rates associated with glaciers (Hoskin, Burrell, and Freitag 1976, 1978)
- use them as 'geochemical buckets' (Heggie 1977) where studies on trace element cycles may be undertaken under conditions of minimum advection
- use them for studies of unusual concentrations of marine mammals or crustaceans (Carpenter 1983).

Anoxic conditions have not been observed in Alaskan fjords, indicating that their bottom waters are renewed at least annually (Muench and Heggie 1978).

Muench and Heggie (1978) provided a basic explanation for both the time and the duration of circulation in fjords fronting on the Gulf of Alaska shelf. This explanation serves as a very good departure point for generalizing how the bottom waters of these fjords interact with Gulf of Alaska shelf waters. The Muench and Heggie study built upon results of a study of Russell Fjord (Reeburgh, Muench, and Cooney 1976) and then used an expanded data base to explain the circulation of virtually all fjords on the southcentral Alaskan coast. The Russell Fjord study showed that there was little or no slope in the isopleths along the Fjord's long axis, indicat-

ing a lack of entrainment. Each tide added boluses of water over the sill that could be identified using 'NO' (Broecker 1974). (This conservative parameter is produced by combining observations of dissolved oxygen and nitrate in the proper ratio.) The seasonal change in the density of shelf waters (Royer 1975) was also tracked by changes in the value of 'NO' (Reeburgh *et al.* 1976), providing a seasonal signature for the boluses. During April, these boluses were sufficiently dense to sink to the bottom of the fjord, but as source waters became less dense during summer, the boluses interleaved at both intermediate and near-surface depths.

Muench and Heggie (1978) considered fjords with 1) shallow sills, 2) intermediate-depth sills (about 150 m), and 3) deep or unrestricted sills. Bottom waters in shallow-silled fjords, such as Russell Fjord and Aialik Bay, are renewed between February and April when surface shelf-waters are most dense. Reduced freshwater input and winter cooling produce these dense waters. Deep and bottom waters in fjords with intermediate-sill depths (such as Port Valdez) closely follow shelf-water density changes and lead to fairly continuous flushing. Fjords with deep or unrestricted sills (such as Prince William Sound or Resurrection Bay) are flushed between July and October when warm, saline water

Table 4-2.

Studies of fjords and inlets adjacent to the Gulf of Alaska (refer to Fig. 4-9 for location map).

NAME	LOCATION		STUDY	CONTROLLING SILL DEPTH (m)	DATA TYPES ^a	SAMPLING DURATION/ FREQUENCY
	N LATITUDE	W LONGITUDE				
Boca de Quadra	55° 10'	130° 40'	Burrell (this volume)	85	Comprehensive, Cur	40 Cruises/4 Years
Smeaton Bay	55° 20'	130° 45'	Burrell (this volume)	140	Comprehensive, Cur	
Silver Bay	57° 15'	135° 12'	McAlister <i>et al.</i> (1959)	64	T, S, O ₂ , Nut, Alk, Cur	2 Cruises/1 Year
Endicott Arm	57° 40'	133° 20'	Nebert (1972)	33	T, S, O ₂ , Cur	5 Cruises/2 Years
N. Dawes Inlet	57° 31'	133° 01'	Loder and Hood (1972)		DOC, POC	
Glacier Bay Muir Inlet	59°	136° 10'	Quinlan (1970); Matthews and Quinlan (1975)	62	T, S, O ₂	11 Cruises/2 Years
Queen Inlet	59°	136° 40'	Hoskin <i>et al.</i> (1976)	115	T, S, SS	2 Cruises/1 Year
Yakutat Bay	59°	139°	Burrell, Unpubl. data	25	T, S	1 Cruise
Russell Fjord	59° 45'	139° 15'	Reeburgh <i>et al.</i> (1976)	30	T, S, O ₂ , Nut	4 Cruises/1 Year
Prince William Sound	60° 40'	147°	Schmidt (1977)	300 T, S, O ₂ ,	Nut	10 Cruises/3 Years
Port Valdez	61° 05'	146° 28'	Hood <i>et al.</i> (1973) Colonell (1982)	110-128	Comprehensive, Cur	6 Cruises/1 Year
Blue Fjord	60° 28'	148° 15'	Hoskin <i>et al.</i> (1978)	115	Comprehensive, Cur	12 Cruises/2.5 Years
Unaquik Inlet	61°	147° 30'	Muench and Heggie (1978)	4	T, S, SS	2 Cruises/1 Year
Resurrection Bay	60°	149° 25'	Heggie (1977); Heggie <i>et al.</i> (1977)	185	T, S, O ₂ , Nut, Cu, Mn, Cur	24 Cruises/2.5 Years
Aialik Bay	59° 50'	149° 40'	Carpenter (1983)	6-10	T, S, Biological	6 Cruises/2 Years
Cook Inlet	60°	153°	Rosenberg and Hood (1967)		T, S	2 Cruises
			Feely and Massoth (1982)		T, S, SS	4 Cruises

^a Symbols for parameters measured are: Cur (currents); T (temperature); S (salinity); O₂ (dissolved oxygen); Nut (nutrients); Alk (alkalinity); DOC (dissolved organic carbon); POC (particulate organic carbon); SS (suspended solids); Cu (copper); Mn (manganese).

from the central Gulf reoccupies the shelf under conditions of reduced convergence. This water from depths greater than 150 m is denser than winter surface water, but is unavailable to the shallow-silled fjords. This means that the bottom waters of both shallow and deep-silled fjords are renewed during high density 'windows' that occur in winter and summer, respectively. This flushing scheme is depicted schematically in Figure 4-10.

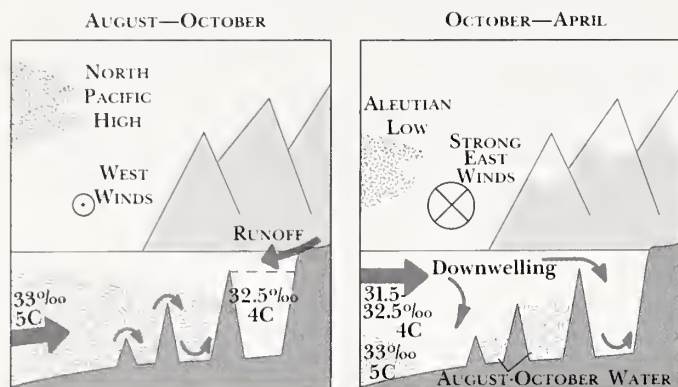


Figure 4-10. Schematic diagram showing response of bottom waters of deep, intermediate, and shallow-silled fjords to seasonal changes in shelf-water density. (Modified from Heggie 1977.)

Similar generalizations for Southeast Alaska fjords are hampered by the lack of a shelf- or source-water density time series, as well as by more complicated source-water hydrography and circulation. However, Nebert (1972) concluded that the flushing of Endicott Arm was driven by both density and the tides as in the examples above. It appears that the bottom waters of fjords with the shallowest sills and the most restricted circulation are replaced at rates of $\sim 1\%/d$ (Reeburgh *et al.* 1976). During summer, fjords are a large (but unquantified) source of freshwater to the coastal Gulf of Alaska.

Several recent studies have reported the processes controlling copper (Cu) and manganese (Mn) in distinctly different Alaskan coastal inlets. Feely, Chester, Paulson, and Larrance (1982) used collections from short-term sediment trap deployments in Kachemak Bay (Cook Inlet) to demonstrate a seasonal cycle in organically bound Cu and Mn. The organically bound metals were associated with fecal pellets, and showed strong enrichments late in the year. Feely *et al.* (1982) suggested that fecal pellets governed transport of Cu and Mn to the sediments and deeper waters. Copper (Heggie 1983) and manganese (Owens, Burrell, and Weiss 1980) were studied in Resurrection Bay, where bottom waters remain effectively isolated during part of the year. These studies emphasized removal and remobilization in surface sediments; both studies showed short residence times for both metals (Cu ~ 21 d; Mn ~ 10 d) in the deeper waters and indicated that input and removal processes rather than recycling controlled their geochemistry in this environment.

Interaction Between Domains

Although this chapter has emphasized the small chemical data base available for the Gulf of Alaska, it has also shown that we do have a first-order understanding of the major distributions and circulation patterns for the deep waters and the continental shelf, as well as for the coastal inlets and fjords. The physical oceanography of the Gulf of Alaska and its margins appears to be well-enough defined to permit the application of several isotopic tracers that, when combined with current and other water property measurements, could lead to a vast improvement in our state of knowledge. We submit that the system lends itself more to a careful application of selected tracers than to remedial chemical surveys. In this section, we address interactions between domains and suggest several chemical measurements that should be employed in future work to better understand mixing rates and interactions.

Gulf of Alaska/Pacific Ocean Interaction

Most of the information on interactions between the Gulf of Alaska and the Pacific Ocean has been obtained from deep sections (the GEOSECS and NORPAC data) and the recent work of Warren and Owens (1985). Good hypotheses for deep circulation have been advanced (Reid and Mantyla 1978), but none have been confirmed or quantified. Detailed observations of currents, nutrients, radiocarbon, and perhaps other parameters in specific, selected deep-water areas could lead to a quantum jump in understanding fluxes and mixing rates in the deep Gulf of Alaska. The Gulf of Alaska has been shown to be a major source—perhaps one of the most striking examples in the world ocean—of freshwater to the North Pacific, but estimates of the fluxes have been obtained indirectly.

This freshwater input is important in the formation of Pacific Intermediate Water (Reid 1973), and future work should include using conservative tracers such as tritium (Fine and Ostlund 1977) and $^{18}O/^{16}O$ ratios (Fairbanks 1982) to quantify the source function and fluxes of this freshwater. It is especially important to continue following the chlorofluoromethane transient with improved analytical techniques. Chlorofluoromethane measurements similar to those reported for the Atlantic (Bullister and Weiss 1983; Weiss *et al.* 1985) should be taken in the North Pacific coastal waters, as well as in the Pacific Intermediate Water.

Gulf of Alaska/Continental Shelf Interaction

The Alaska Current, eddies on the continental shelf, and the Alaska Coastal Current are all known to be important elements in mixing processes and in the transport of suspended sediments. However, there is no information on the scales of interaction between the shelf and the central Gulf. Radium-228 is a tracer whose introduction mechanism (dissolution from sediments) and decay rate (~ 7 -y half-life) make it a potential tracer for quantifying mixing between the continental shelf and Gulf of Alaska (Kaufman,

Trier, Broecker, and Feely 1973). Seasonal cross-shelf transects of ^{228}Ra could show the influence of coastal waters on the Gulf of Alaska. Chlorofluoromethanes should also be good tracers of shelf-water inputs to the subsurface central Gulf. As above, oxygen isotope ratios would be important in resolving shelf/Gulf interactions, as well as in determining how effectively the freshwater inputs are confined to the coast by both current and wind systems.

Continental Shelf/Fjord Interaction

The interactions between the continental shelf and the fjords are probably the best understood of the domains considered in this chapter. However, our information is still very descriptive. A good understanding of annual cycles is available, but for events occurring on time scales of days—or even weeks—there are few instances where any resolution has been reached. Time-series measurements should be attempted in the future using moored fluorometers and nephelometers, and chemical sensors currently under development. Fjords are large sources of freshwater to the Gulf of Alaska and are logical places to obtain seasonal source-function information on conservative water tracers like tritium and $^{18}\text{O}/^{16}\text{O}$ ratios. To date, the Alaska Coastal Current has only been traced using salinity. It may be possible to include compounds from terrestrial runoff, such as terpenes (Button 1984), as well as tritium and oxygen isotope ratios as tracers. Since all are runoff-related, they should have similar seasonal source functions and should become an independent, high-sensitivity means of tracing the Alaska Coastal Current.

Acknowledgments

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Geomorphology, Sediment, and Sedimentary Processes

5

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ABSTRACT

The Gulf of Alaska continental margin, from Cross Sound in the east to Chirikof Island in the west, has been shaped directly and indirectly by the forces of ice, plate tectonics, and ocean currents. Grounded ice extended to the shelf break at least once during the Pleistocene epoch, covering most or all of the shelf and sculpting broad flat banks and elongated troughs. Glacial, glacial-marine, and glacial-fluvial sediment was deposited in nearly all areas as the ice advanced. As the climate warmed and the ice retreated, the region was inundated by the sea, giving rise to the present geologic environments.

The high, youthful mountains to the north of the Gulf provide a plentiful source of sediment that is delivered to the coastline by a few large rivers and remnant glaciers. The major input of sediment occurs in the northeastern Gulf (Copper River, Alsek River, Bering Glacier, and Malaspina Glacier sources) and at the head of Cook Inlet (Knik, Matanuska, and Susitna River sources). Ocean currents in the northeastern Gulf carry the sediment predominantly to the west, depositing much of the load near the shore and in the troughs but delivering some sediment into Prince William Sound and Shelikof Strait. Large embayments in the eastern Gulf coastline accumulate thick, underconsolidated deposits of sediment delivered by local high-gradient streams and glaciers. The coarse sediment from the rivers at the head of Cook Inlet is deposited near the points of entry and, along with the relict glacial sediment in the remainder of the Inlet, is reworked by strong tidal currents. As a result, fields of large sand waves and other current-related bed forms have developed. The fine sediment from the rivers is transported south down the Inlet and is deposited as a progressively sorted sediment blanket throughout Shelikof Strait. The Kodiak Shelf receives little modern sediment, but ocean currents rework the relict glacial debris, leaving coarse-grained lag deposits on the shallow banks and winnowed, fine-grained sediment in the troughs.

Collision between the North American and Pacific lithospheric plates generates strong tectonic forces throughout the region. Over long durations of geologic time, these forces cause changes in seafloor elevation that create deep sedimentary basins and uplifted banks and islands. In the short term, strong and frequent earthquakes trigger submarine sediment slides in the deposits of soft sediment on the northeastern Gulf shelf and along the entire upper continental slope.

Introduction

The geomorphology, the sediment, and the sedimentary processes of the north central Gulf of Alaska continental margin have been studied by numerous investigators for a variety of purposes. The general nature of the geomorphology and surficial sediment throughout the entire Gulf of Alaska was first described by Gershanovich (1968) from data obtained on reconnaissance cruises by Russian vessels. A more recent compilation was presented by Sharma (1979). In addition, several area-specific geologic studies have been conducted: Cook Inlet (Sharma and Burrell 1970); Nuka Bay (von Huene 1966); Prince William Sound (von Huene, Shor, and Reimnitz 1967); Glacier Bay (Powell 1983); and elsewhere. Large, comprehensive data sets were collected in conjunction with studies preparatory for outer continental shelf (OCS) petroleum leasing in four major geographic areas: 1) the northeastern and north central Gulf of Alaska, from Cross Sound to Montague Island, 2) the Kodiak Shelf, from Amatuli Trough to Chirikof Island, 3) lower Cook Inlet, south of the Forelands, and 4) Shelikof Strait, between the Alaska Peninsula and the Kodiak island group (see summaries by Carlson and Schwab 1982; Hampton 1982a; Hampton 1982b; and Hampton, Johnson, Torresan, and Winters 1981). Figure 5-1 shows the area of study, including the four major geographic areas mentioned above.

This chapter summarizes the geologic studies of the north central Gulf of Alaska continental margin. In addition to a discussion of the entire region, each of the four major geographic areas is considered individually in separate sections. Within each section, the geomorphology of the sea floor, the nature and distribution of the sedimentary deposits, and the processes by which sediment is transported and deposited are also discussed. Most of the information in this chapter applies to the continental shelf, but data for both the continental slope and the outlying geographic areas are also included. Finally, an overview of the entire region is presented, pointing out the pervasive geologic factors while emphasizing those that make each area unique.

While present-day geologic features and processes are the primary focus of this discussion, a certain amount of historical perspective is necessary to clearly understand the present geology. An erosional unconformity that most likely occurred during the late Pleistocene age separates structurally deformed bedrock from overlying, relatively undeformed and presumably unconsolidated sediment throughout the region. This unconformity and the overlying sedimentary deposits are considered herein.

Methods

Seismic-reflection profiles and sediment samples are the primary data sources for geologic studies of the Gulf of Alaska. The large-scale aspects of geologic framework are deciphered mostly from deep-penetration, low-resolution records from 12- and 24-channel seismic-reflection systems, whereas the details of near-surface stratigraphy and geomorphology are studied with profiles from shal-

low-penetration, high-resolution systems such as sparkers, air guns, boomers, and tuned transducers. The thickness and spatial distribution of sedimentary units are determined using these seismic profiles, and the sediment transport and deposition processes are inferred from both the geometry and the amplitude of the seismic reflections.

Sediment samples from both on and beneath the seabed (collected with vibratory and gravity corers as well as grab samplers) are analyzed to determine the sediment's physical and chemical properties. Most samples are collected from large ships that cannot work safely in the shallow and rough waters near shore; therefore, there are few samples from this zone. Chemical and physical analyses are performed on samples of suspended sediment from the water column. These samples are collected using 0.4-mm pore-size membrane filters. Although sedimentary processes and sedimentary history are the two main items deduced from the analyses of sediment samples, geotechnical, hydrocarbon, and pollutant studies are also conducted.

Specialized instrumentation is used for certain purposes. For example, side-scanning sonar provides a plan view of the sea floor from which geomorphic features and sediment type can be discerned. Television and still photography can give similar information for small areas. Oceanographic instruments such as current meters, pressure transducers, and transmissometers yield data for quantification of sedimentary dynamics. Sediment strength properties can be measured with *in situ* probes, but strength and consolidation properties are measured in the laboratory using soil-mechanics testing equipment.

Regional Aspects

The north central Gulf of Alaska continental margin is a complex and dynamic subpolar geologic environment. Tectonic forces, climate, and oceanographic circulation are the major controls on geomorphology and sedimentation. Tectonic forces associated with the convergent-to-transform plate-margin setting of the Gulf of Alaska have produced rugged mountains along the entire coastline, as well as large sedimentary basins offshore. Continuing deformation generates large earthquakes and causes changes in sea-floor elevation, both of which modify the geomorphology and sedimentary environments. Active volcanoes, born from melted subducted lithosphere, line the Alaska Peninsula and northwest coast of Cook Inlet, and also exist farther east in the Wrangell Mountains (Arctic Environmental Information and Data Center 1974).

The subpolar climate maintains alpine glaciers near the shoreline in the vicinity of Cape Douglas on the Alaska Peninsula, along the south coast of the Kenai Peninsula, and in the Chugach and St. Elias Ranges east of the Copper River. Elsewhere, glaciers occur farther inland. Regional glaciation began in Miocene time, proceeding through several stages of advance and retreat. Grounded ice has extended out to the seaward edge of the continental shelf at least once (Karlstrom 1964; Péwé 1975; Plafker and Addicott 1976; von Huene, Crouch, and Larson 1976; Molnia and Sangrey 1979; Thrasher 1979; and Armentrout 1983). Within historic time,

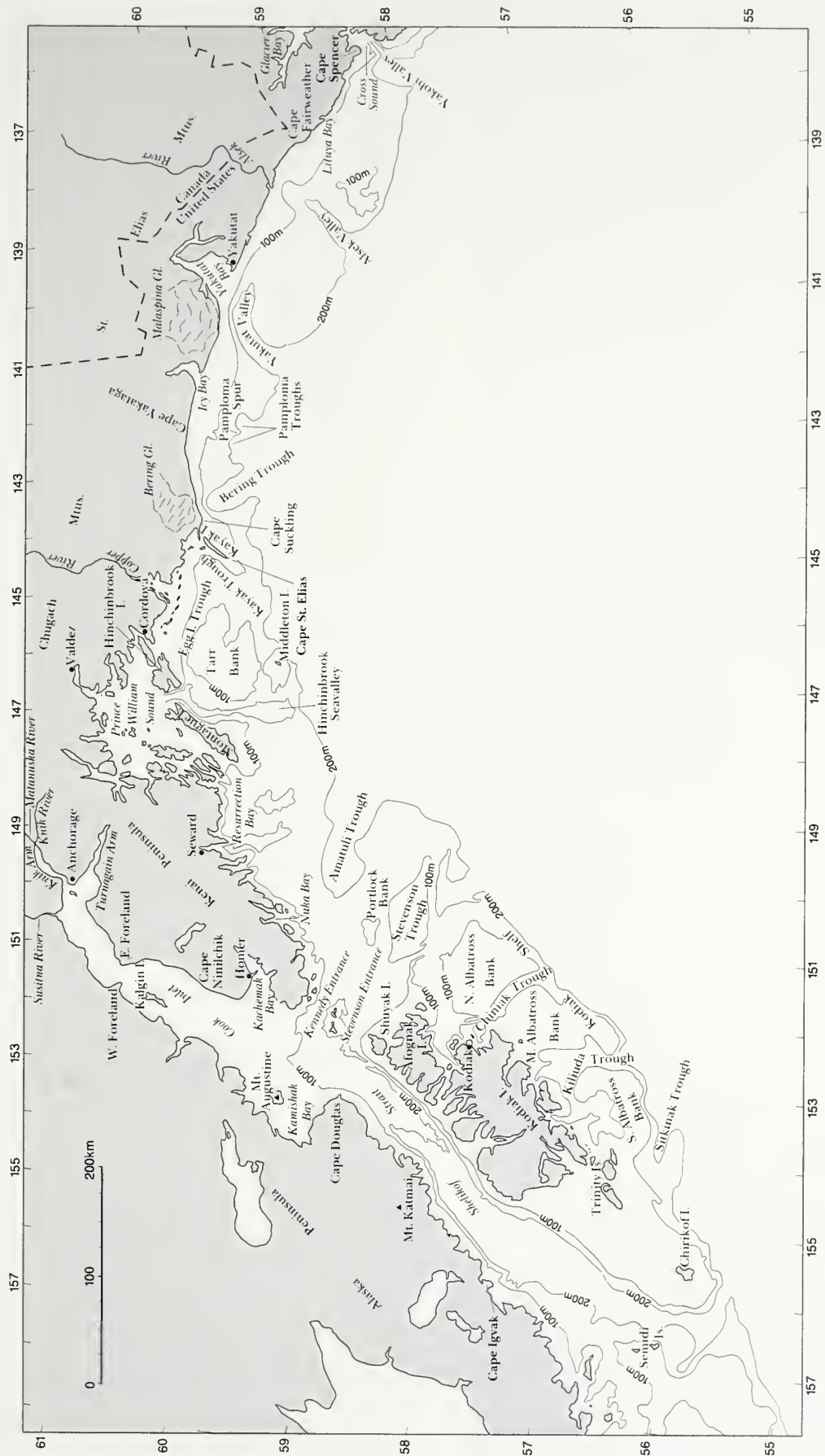


Figure 5-1. Location map of the Gulf of Alaska.

local advances across the present shoreline have occurred in the northeast Gulf of Alaska (Molnia 1977).

The maritime climate in the Gulf of Alaska is typified by heavy precipitation, strong winds, and relatively mild temperatures (see Wilson and Overland, Ch. 2, this volume). The Gulf lies along a major winter storm track. Heavy fall rainstorms and spring snowmelt produce peaks in the seasonally variable freshwater runoff, which generally increases to the east (Kramer, Clark, and Canelos 1978).

Regional oceanic circulation is controlled by the westward-flowing Alaskan Stream, which has a mean speed of 50 to 100 cm/s and is swiftest near the shelf break (Favorite 1967; Thomson 1972; Reed and Schumacher, Ch. 3, this volume). Circulation across the open shelf is relatively sluggish, with typical current speeds of less than 10 cm/s. The baroclinic Kenai Current flows close to the coast along the Kenai Peninsula westward into lower Cook Inlet (Schumacher and Reed 1980). Strong tidal currents are present in Cook Inlet, and estuarine conditions are created by fresh water entering the head of the inlet (Rosenburg, Burrell, Natarajan, and Hood 1967; Muench, Schumacher, and Pearson 1981). Flow from Cook Inlet (along with the regional pressure gradient set up by the Alaskan Stream) drives the circulation in Shelikof Strait where the mean current speed is 10 to 20 cm/s (Muench and Schumacher 1980). Large storm waves periodically traverse the Gulf of Alaska shelf. Maximum significant wave height for a 5-year recurrence interval is 13 m and for a 100-year interval, 22 m; extreme wave heights for 5- and 20-year recurrence intervals are 22 and 40 m, respectively (Brower, Searby, and Wise, Diaz, and Prechtel 1977). Waves of this magnitude exert significant force on the sea floor in shallow water and can cause sediment erosion and mass failure (Rappeport 1981; Schwab and Lee 1983).

The Gulf of Alaska continental margin has a mountainous, glaciated coast with major embayments such as Prince William Sound and Cook Inlet that are structurally controlled and erosionally modified. The arcuate continental shelf from Cross Sound to Chirikof Island generally widens from east to west, from 30 km near Cross Sound to 220 km west of Kodiak Island (Fig. 5-2).

The shallow regional unconformity on the Gulf of Alaska continental shelf appears clearly in seismic-reflection profiles as a discordant juncture between stratified and folded beds below and the stratified, horizontal or folded units above. The youngest known age for either the sedimentary deposits below the unconformity or for the ice-carved morphology of the surface itself has been used to deduce that this hiatus feature is of the late Pleistocene age and of glacial origin (McClellan, Arnal, Barron, von Huene, Fisher, and Moore 1980; Molnia and Carlson 1980; Quinterno, Carlson, and Molnia 1980; Carlson *et al.* 1982; and Hampton 1985). The depth of the unconformity below present sea level in the northeastern Gulf of Alaska, the Kodiak Shelf, lower Cook Inlet, and Shelikof Strait is depicted in Figure 5-3. Although the relief is subdued over broad areas, several basins and U-shaped channels exist. The maximum depth is over 1,100 m in Shelikof Strait.

Although the sedimentary sequence over the unconformity can be up to 800 m thick, a typical sedimentary deposit

is less than 100 m thick (Fig. 5-4). Many areas lack a sedimentary cover, and the bedrock surface is exposed at the sea floor. Samples of the underlying semi-lithified to lithified bedrock are composed of diamicton, sandstone, and mudstone (McClellan *et al.* 1980; Molnia and Carlson 1978, 1980). Sediment cores from the sequence above the unconformity are highly varied, both within and between geographic areas. Gravel- to clay-sized terrigenous material is the most abundant component, but volcanic ash and micro- and megafaunal shells are widespread. In places, volcanic or biogenic material is concentrated in distinct layers. The distribution of textural sediment types is shown in Figure 5-5.

Certain sedimentary and erosional events are inferred to have occurred in common over the entire Gulf of Alaska region. Pleistocene glaciers extended out to the shelf break, and platforms, troughs, and basins were eroded into the underlying bedrock. The initial retreat of the grounded ice from the shelf has been documented at about 12,000 years ago in the northeast Gulf of Alaska (Molnia, Levy, and Carlson 1980), and it probably occurred at nearly the same time on the Kodiak Shelf. When the Holocene sea-level rise began, the ice retreated rapidly across the open shelf because a grounded marine ice sheet is inherently unstable under these conditions (Thomas and Bentley 1978; Thomas 1979). However, due to the pinning effect of landmasses (Thomas 1979), ice may have remained for an extended time around the islands and in land-bounded areas such as Shelikof Strait and Cook Inlet. In any case, each area collected glacial and glacial-marine sediment before and during ice retreat. As the marine transgression swept through the region, the sediment accumulations were reworked and redistributed.

Despite these common aspects, each of the four areas under discussion is a unique sedimentary system. This was especially true during Holocene time. The main differences between each of the areas lie in the oceanographic conditions and the sediment supply rate.

Northeastern Gulf of Alaska

Geomorphology

General. The northeastern and part of the central Gulf of Alaska continental shelf between Cross Sound and Montague Island has an average gradient of about $0^{\circ} 15'$ from shore to shelf break (Atwood *et al.* 1981). The shelf is cut by eight prominent valleys; from east to west they are Yakobi Valley, Alsek Valley, Yakutat Valley, the two Pamplona Troughs, Bering Trough, Egg Island Trough, and Hinchinbrook Seavalley (Fig. 5-1). The valleys are separated by islands, banks, and ridges that are underlain by folded and faulted late Cretaceous and Cenozoic rocks.

The valleys have a U-shaped cross section and each is underlain by an ancestral valley. All but four (Alsek Valley, the Pamplona Troughs, and Egg Island Trough) have a concave-upward longitudinal profile with shoaling at the seaward end and closed depressions on the valley floor. Egg Island Trough has a convex-upward longitudinal profile, and Alsek Valley and the Pamplona Troughs have a uniform gentle longitudinal profile. The troughs are sediment sinks

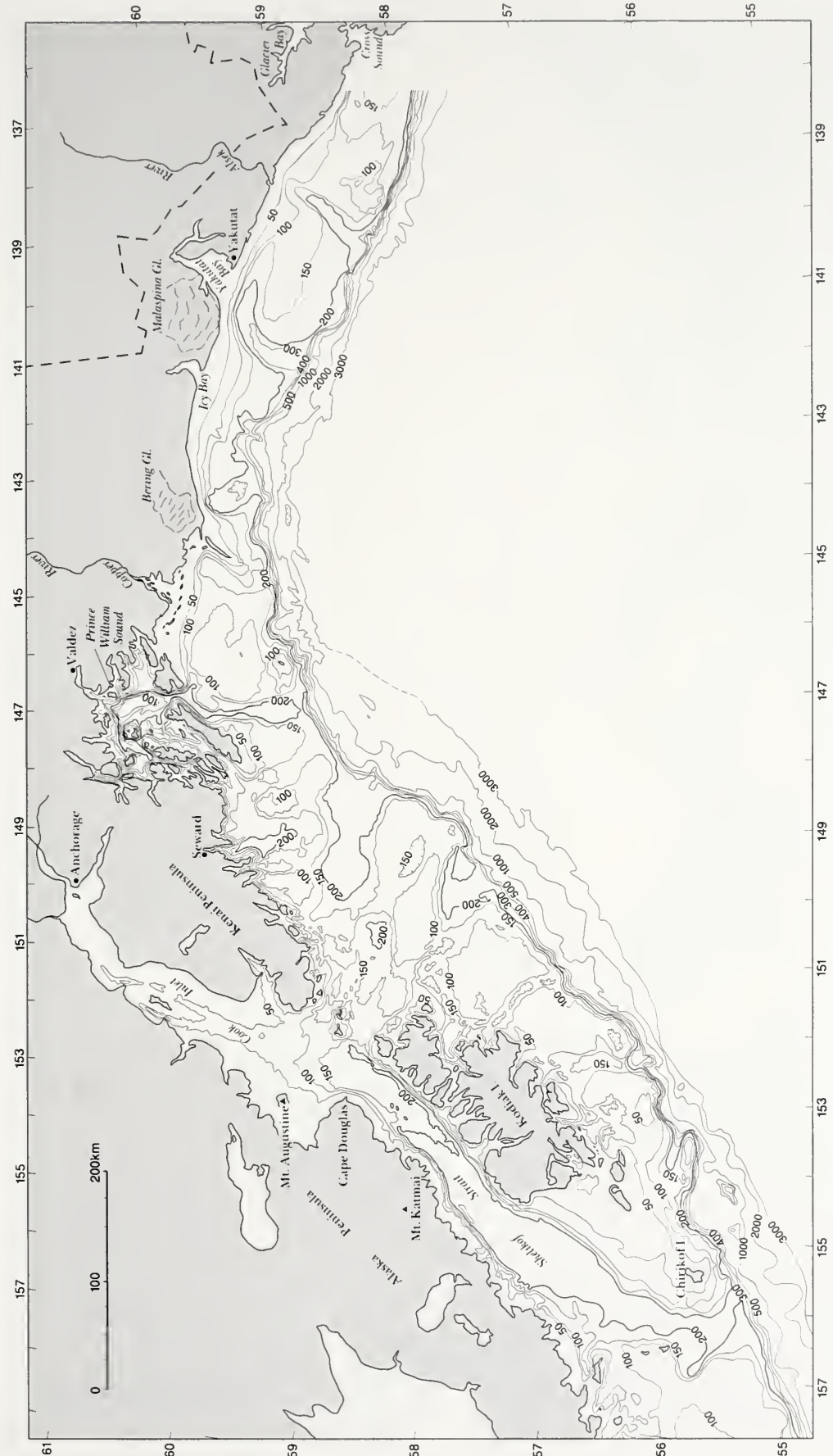


Figure 5-2. Generalized bathymetric map of the continental shelf and part of the continental slope. Isobaths in meters (data from Atwood *et al.* 1980; Bouma 1981; and Hampton 1985).



Figure 5-3. Depth beneath sea level to bedrock unconformity. Note that in the northeastern Gulf of Alaska a thin Pleistocene deposit was neglected in the measurements, but the general form of the unconformity is unaffected. Isopleths in meters (data, in part, from Carlson *et al.* 1982; Hampton 1985).

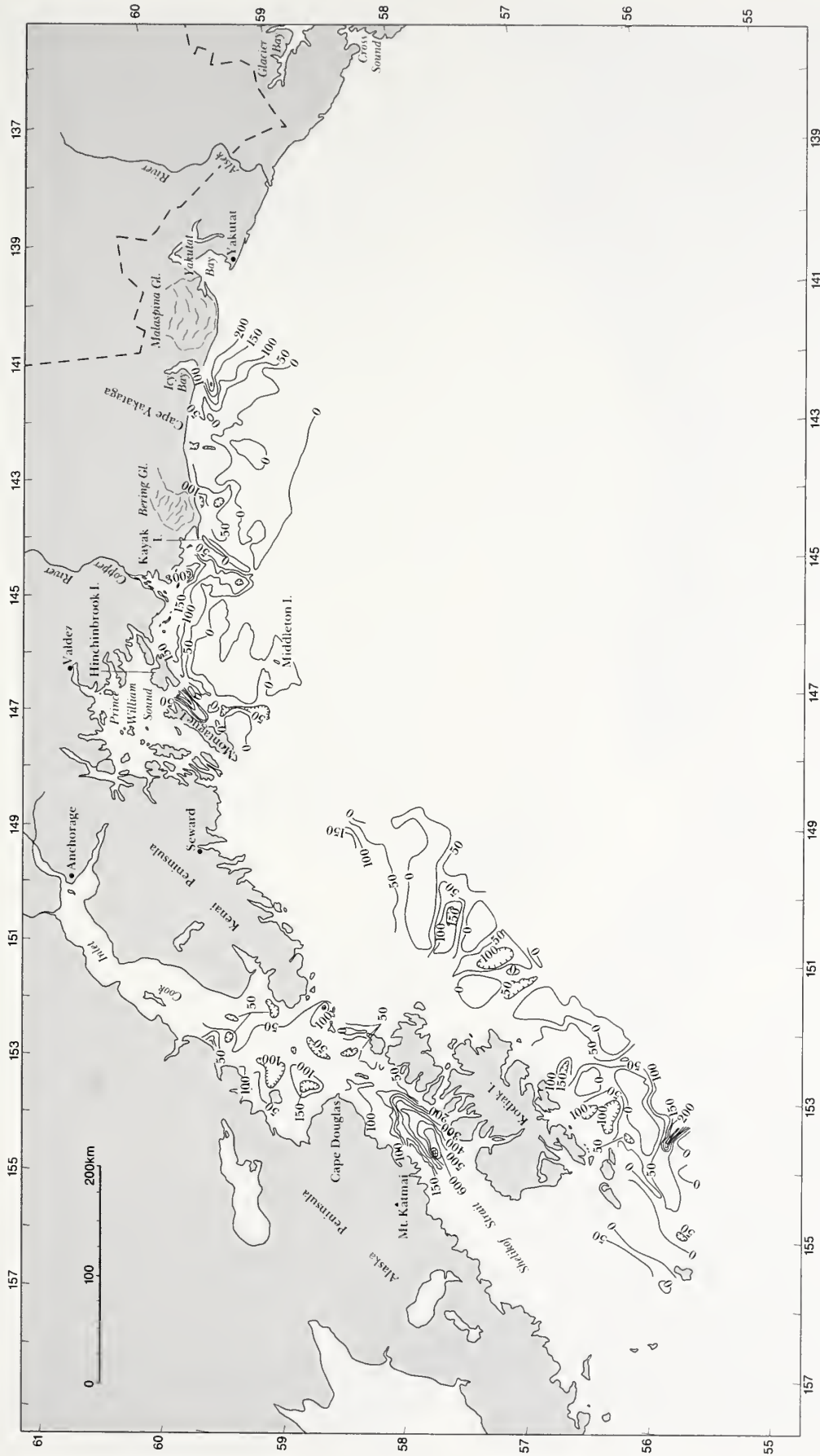


Figure 5-4. Thickness of sediment above the regional unconformity. Note that in the northeastern Gulf of Alaska, a thin Pleistocene unit above the unconformity was neglected in making the measurements, whereas all deposits above the unconformity were included in the other areas. Isopleths in meters of sediment (data from Carlson and Molnia 1975; Bouma, Hampton, Frost, Torresan, Orlando, and Whitney 1978; and Hampton 1983a, 1985).

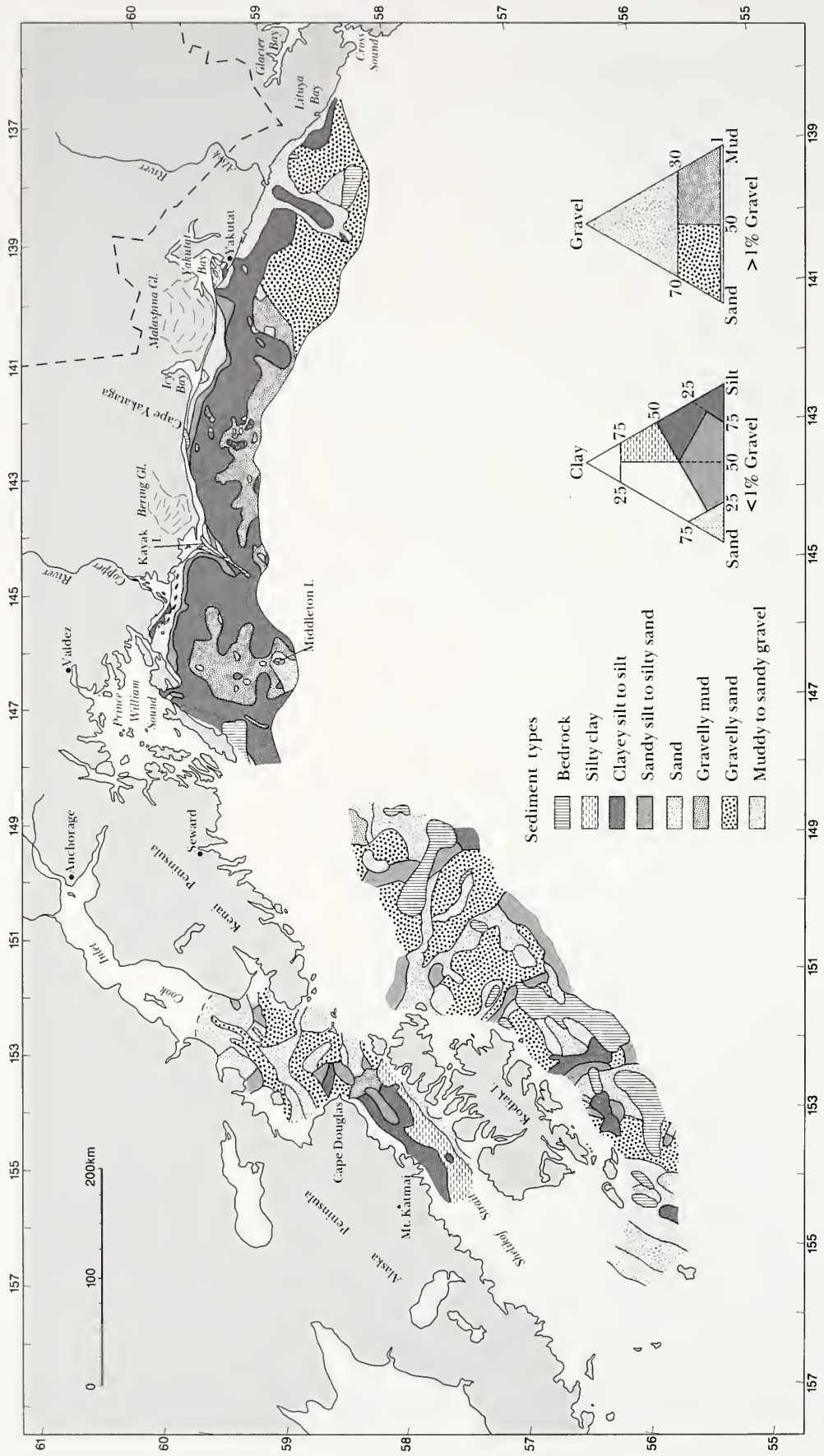


Figure 5-5. Distribution of sediment types. Classification triangle on left shows sediment-class boundaries for samples with less than 1% gravel; triangle on right shows sediment-class boundaries for samples with greater than 1% gravel (data, in part, from Carlson *et al.* 1977; Hampton 1982a).

that contain as much as 200 m of Quaternary sediment (Carlson *et al.* 1982).

Egg Island Trough is seaward of the Copper River prodelta and is oriented roughly parallel to the shoreline. Pamplona Troughs are incised into the outer shelf and upper slope on both sides of the high Pamplona Spur. Yakutat Valley cuts a broad arc across the shelf running parallel to the shoreline at its inshore end and perpendicular to the shoreline on the mid- and outer shelf. For a more extensive discussion of the shelf valleys, see Carlson *et al.* (1982).

Sizable morainal deposits have been surveyed on the shelf between Yakutat and Lituya Bays (Molnia 1981). The moraines have been detected over an area exceeding 2,500 m² in water depths ranging from 120 to 180 meters. Moraine heights in this area reach 12 meters. The moraines have been modified by erosion and sedimentation so that individual lobes cannot be correlated between survey lines.

Some geologic structures have sea-floor expression and affect the geomorphology. For example, many faults offset the sea floor, producing scarps up to 50 m high, particularly in the mid-shelf area between Pamplona Spur and Icy Bay. The shallow faults are related to development of the deeper structures on the continental margin (Bruns 1983, 1985; Bruns and Schwab 1983), and the general trend of the shallow faults is subparallel to major onshore structures, as shown in Figure 5-6. (Plafker 1967; Carlson and Molnia 1977; Carlson, Molnia, and Wheeler 1980; and Carlson, Plafker, and Bruns 1985). The seaward extension of the Fairweather Fault disrupts the sea floor in the area of Cross Sound and forms a major strike-slip contact between the North American and Pacific lithospheric plates (Carlson, Plafker, Bruns, and Levy 1979; von Huene, Shor, and Wageman 1979). This transform fault has been mapped for a distance of 320 km southeast across the continental margin and appears to provide the link between the major Fairweather and Queen Charlotte fault systems (Carlson *et al.* 1985).

The continental slope between Yakobi Valley and Hinchinbrook Seavally has been divided into three geomorphic segments (Atwood *et al.* 1981). Between Yakobi and Yakutat Valleys, the slope is steep (11°) and is crossed obliquely by several large ridges. The segment between Yakutat Valley and Bering Trough has a more gentle gradient (4°) and is smoother than the slope segments on either side. Numerous ridges and valleys dominate the slope morphology between Bering Trough and Hinchinbrook Seavally.

Sediment Slide. Many seismic-reflection profiles show the irregular sea-floor morphology and disrupted bedding commonly associated with submarine sediment slides (Carlson and Molnia 1977; Carlson, Molnia, and Wheeler 1980) (see Fig. 5-7). In fact, the northeastern Gulf of Alaska continental shelf has an unusual number of sediment slides compared with other shelf areas.

Seismic-reflection profiles along the Copper River prodelta, which has a gradual slope of less than 0.5°, show zones of disrupted or discontinuous reflectors in the Holocene sediment. The prodelta was investigated by Reimnitz (1972) shortly after the Great Alaskan Earthquake of 1964. He

attributed slump structures seen on high-resolution, seismic-reflection profiles to this earthquake. The slumps are present over an area of about 1,730 km that extends nearly 20 km offshore between Hinchinbrook Island and Kayak Island (Fig. 5-7) (Carlson and Molnia 1977).

A spectacular example of mass movement is located at the eastern edge of the Copper River prodelta (Fig. 5-8A) (Carlson and Molnia 1977; Molnia, Carlson, and Bruns 1977). This slide has a length of 17 km, a maximum width of 12 km, and a maximum thickness of about 115 meters. The estimated volume of material affected by this slide is $\sim 5.0 \times 10^9$ cubic meters. In addition to irregular sea-floor morphology and disrupted internal reflectors, some profiles show a well-preserved pull-apart scarp with an approximate 10-m relief and a well-developed toe. The toe is 20 m thick and is located 2 km upslope from the distal end of the slide mass. The toe of the slide is partly buried, suggesting erosion of the underlying sediment as the slide moved down the 1° slope into Kayak Trough. Post-slide deposition also accounts for some of the sediment cover. Apparently, the slide had enough momentum to push the toe past the thalweg of the trough, imparting a slight upward concavity to the top surface of the slide.

Another series of large slides occurs seaward of Icy Bay (Fig. 5-7). The Icy Bay-Malaspina slide area is about 90 km long by 10 to 20 km wide, in water depths from 48 to 220 meters (Carlson 1978). All of the inferred slide area shows undulatory surface morphology on high-resolution, seismic-reflection profiles. This region of mass movement shows decidedly different characteristics in different parts of the slide mass. At the extreme eastern quarter, reflectors in the seismic profiles have wave-like characteristics, both at the surface and in the subsurface. This area has a somewhat steeper slope than the western three-quarters of the slump area, owing to its location on the north side of Yakutat Valley. The wave forms are 0.5 km long from crest to crest and have 2- to 5-m relief. However, the profiles from the western three-quarters of the area show broken reflectors and more scarp-like surficial forms, suggesting discrete slump blocks (Fig. 5-8B). Some of the blocks appear to have undergone a slight amount of backward tilting. The blocks' average size is about 0.5 km wide (front to back) and they have a 2- to 5-m relief. This mass movement phenomenon seems to have characteristics classified by Varnes (1978) as both a rotational slump and failure by lateral spreading. The deeper underlying reflectors have a normal, parallel, flat-lying appearance characteristic of undisturbed sediment (Fig. 5-8B). The sediment adjacent to the slide area also shows normal well-bedded and parallel reflectors.

Side-scan sonographs were collected over a 160-km² area at the north edge of the slide area (Carlson 1978). Two north-south and two east-west side-scan lines crossed a series of irregularly shaped ridge- or scarp-like features. The north-south lines show that the linear scarps run nearly parallel to the sea-floor contours. Some of the scarps extend across the entire record and thus have a length of more than 200 meters. The east-west lines in the same area show these features as more curvilinear and arc- to U-shaped (Fig. 5-8C). Well-defined shadows, which run on several of the east-west lines, permit calculation of the scarp height from

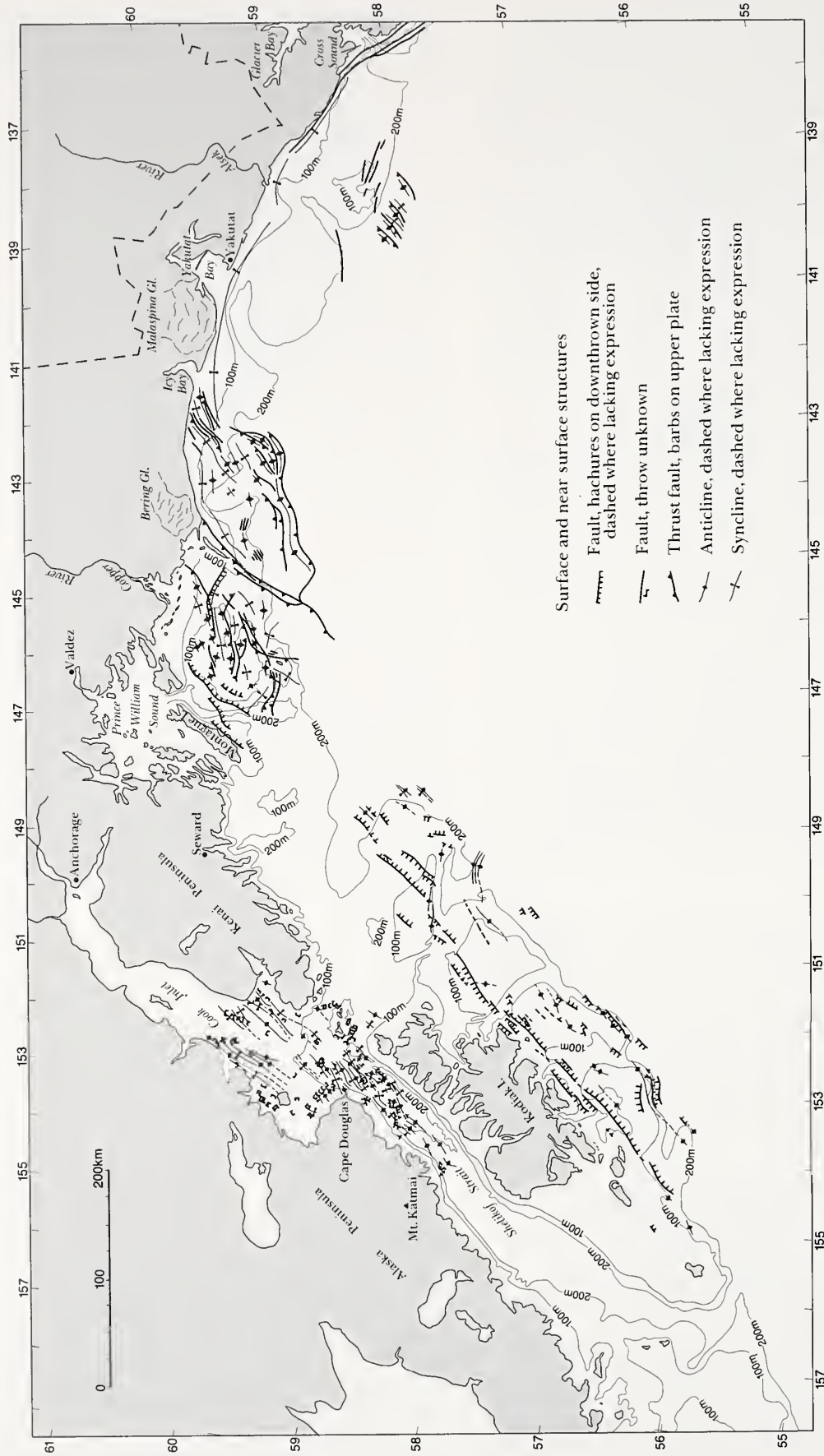


Figure 5-6. Mapped faults and folds at or within a small distance beneath the sea floor (data from Bouma and Hampton 1976; Carlson and Molnia 1977; von Huene *et al.* 1980; and Hampton 1985).

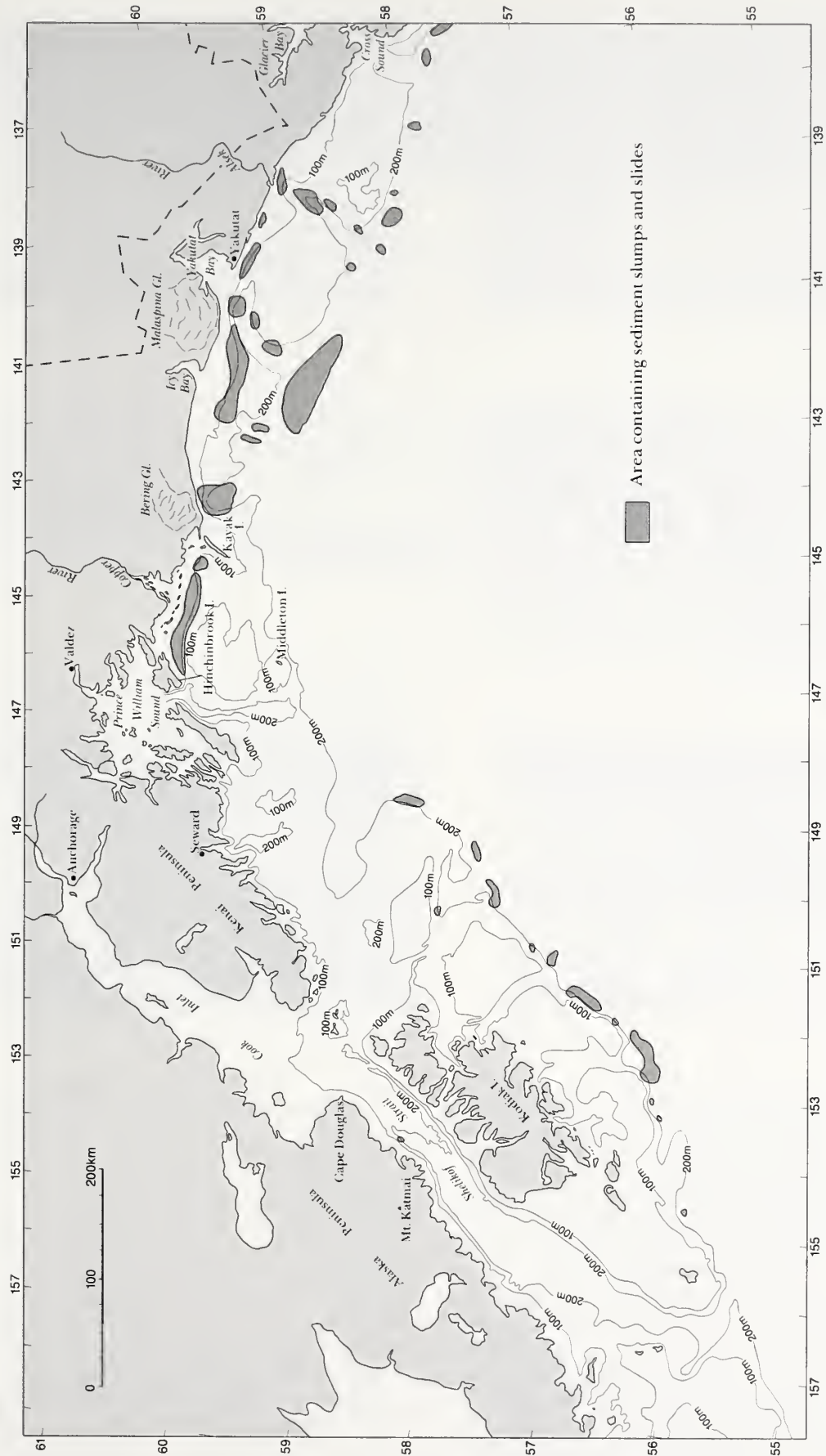


Figure 5-7. Mapped sediment slides. (Modified from Hampton, Bouma, Carlson, Molnia, Clukey, and Sangrey 1978.)

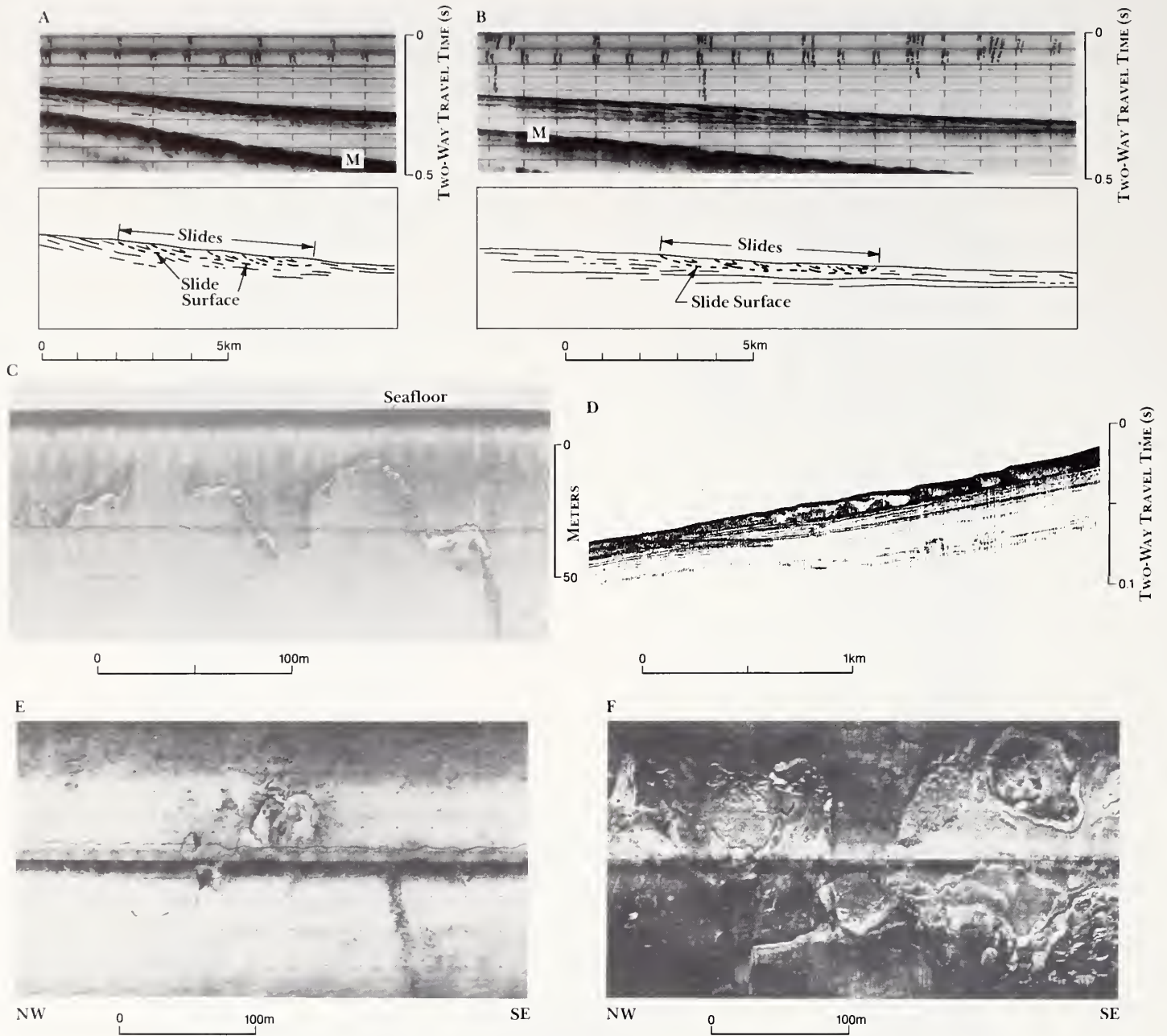
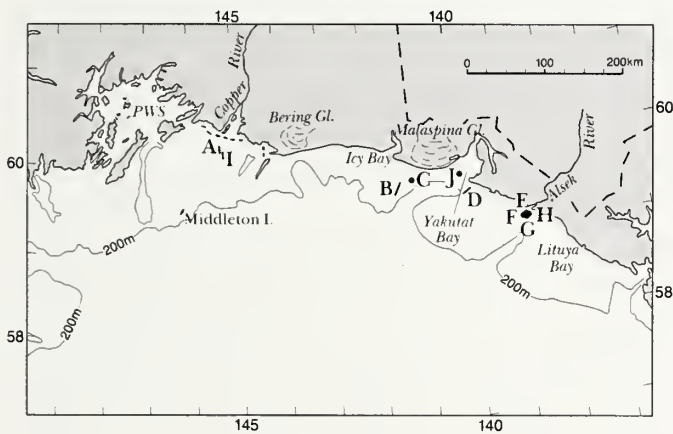
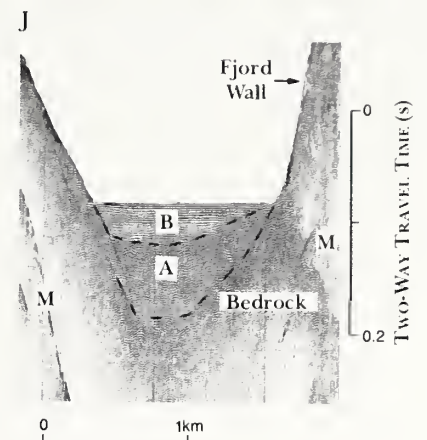
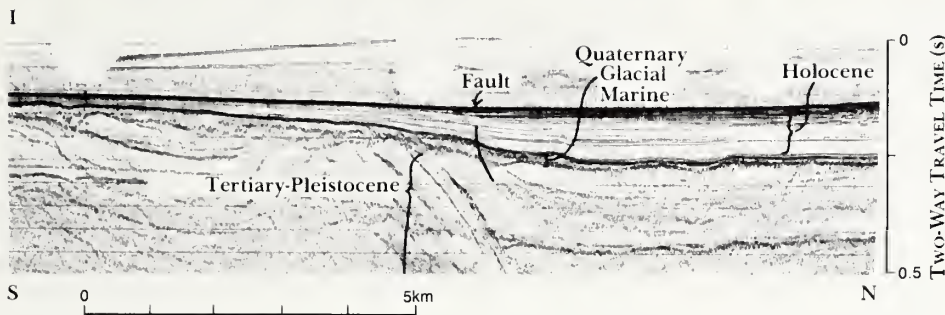
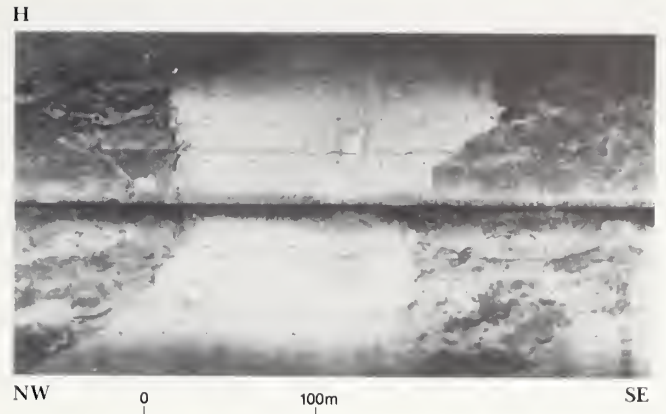
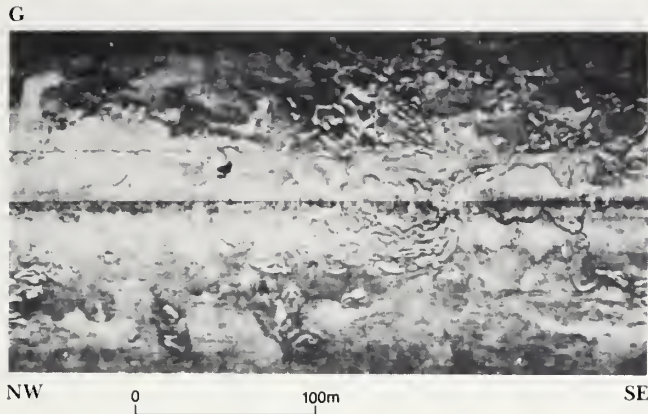


Figure 5-8. Seismic-reflection profiles and side-scan sonographs displaying geologic features of the northeastern Gulf of Alaska. M denotes sea-floor multiple reflection.

- A. Seismic-reflection profile of a sediment slide on the Copper River prodelta.
- B. Seismic-reflection profile of a sediment slide in the area of Icy Bay-Malaspina Glacier.
- C. Side-scan sonograph of a sediment slide in the area of Icy Bay-Malaspina Glacier.
- D. Seismic-reflection profile of a sediment slide near Yakutat.
- E. Side-scan sonograph in Zone 1 of the Alsek River sediment slide area.
- F. Side-scan sonograph in Zone 2 of the Alsek River sediment slide area.
- G. Side-scan sonograph in Zone 3 of the Alsek River sediment slide area.
- H. Side-scan sonograph in Zone 4 of the Alsek River sediment slide area.
- I. Seismic-reflection profile showing stratigraphic relation of acoustic units off the Copper River, which is typical for the northeastern Gulf of Alaska.
- J. Seismic-reflection profile showing stratigraphic relation of acoustic units in Glacier Bay, which is typical for the embayments of the northeastern Gulf of Alaska.



0.4 to 0.8 m (almost an order of magnitude less than the relief of the slump blocks on the high-resolution, seismic-reflection profiles).

The Yakutat slump is south of Yakutat Bay (Fig. 5-7). The slump begins 4 km offshore, is about 260 km² in area, and lies in 65 to 90 m of water (Carlson, Molnia, and Wheeler 1980). The slope of the sea floor is about 1° in the upper part of the slump and decreases to about 0.5° at the seaward edge. The slump is characterized by a series of blocks of clayey silt that have undergone rotational movement (Fig. 5-8D). The slump structures here are not as well developed as they are in the Icy Bay-Malaspina slide area. The step-like surfaces of the blocks have a tread length of about 100 m and a riser height of 3 to 4 meters. The slip surfaces extend 10 m below the sea floor, and the volume of slumped material is nearly 3 cubic kilometers.

Deposits of sediment slides and flows cover an area of at least 150 km² just seaward of the Alsek River (Fig. 5-7) (Molnia and Rappaport 1980, 1984). These sediment failures begin less than 2 km offshore in about 35 m of water and on a 0.5° slope. Carlson, Molnia, and Wheeler (1980) speculated that this failure zone possibly extends as far offshore as the floor of the Alsek Valley, where slides and flows disrupt sediment to a subbottom depth of 10 to 20 meters.

A detailed sonograph mosaic of the sea floor over a 20 km² area within the Alsek River prodelta failure shows four distinct zones (Schwab and Lee 1983; Molnia and Rappaport 1980, 1984):

Zone 1 (Fig. 5-8E) shows minimal disturbance and is characterized by broad expanses of nearshore sand that contain megaripples with their crests aligned parallel to the shoreline and with wave lengths of 1 to 5 meters. The average

sea-floor slope is 0.5° . Isolated sediment failures and depressions are present but cover only 10% of the zone.

Zone 2 (Fig. 5-8F) covers the west central part of the area and is characterized by many small slumps, slides, and a variety of flow types. The average sea-floor slope is 0.5° . Most individual failures have a well-defined boundary and are not superimposed. Many failures have an irregular blocky surface. The largest failures in the nearshore part of Zone 2 are circular slumps up to 300 m in diameter and elongated (bottleneck) flows up to 300 m long. Most failures, however, have a maximum dimension less than 50 meters. Because of the overlapping of failure features, the features in Zone 2 become larger and more complex as the distance from shore increases.

Zone 3 (Fig. 5-8G) is in the east central part of the area and contains broad expanses of massive sediment failures with displacement toward the head of Alsek Valley. The sea floor is relatively steep (1.3°). Individual failures have poorly defined boundaries and show evidence of layering and superposition.

Zone 4 (Fig. 5-8H) covers the eastern part of the area and is characterized by channels and chutes on a sea-floor slope of about 1.3 degrees. Linear troughs that run generally north and south occupy more than one half of this zone. These troughs are well defined, are typically 3 to 6 m deep, up to 400 m wide, and can be up to 1.8 km in length.

Embayments. The major embayments that indent the coastline of the northeastern and part of the north central Gulf of Alaska include, from southeast to northwest, Glacier Bay, Cross Sound, Lituya Bay, Yakutat Bay, Icy Bay, and Prince William Sound (Fig. 5-1). The sea floor within the embayments is generally smooth in areas of Holocene sediment accumulation, except for local mass-movement features. The sea floor tends to be rough in areas of bedrock outcrop and exposed glacial deposits. Typically, the smooth sea floor is nearly horizontal except near the points where sediment enters the embayment. Here, the sea floor may be gently inclined, as on a delta front, for example. The upper surface of bedrock commonly exhibits evidence of ice-induced erosion and the embayments are fringed by magnificent fjord systems.

Icy Bay is an embayment whose sea floor is smooth because of profuse modern sedimentation (Molnia 1979b), whereas the sea floor of Cross Sound is rough due to the presence of bedrock and glacial moraines (Carlson, Molnia, and Levy 1980). Linear and mounded moraine deposits occur across the mouth of Yakutat Bay and also have been described elsewhere in the Bay (Carlson, Molnia, Hampson, Post and Atwood 1978). These deposits also occur in Icy Bay (Tarr and Martin 1914; Molnia 1977; Carlson, Molnia, and Levy 1980; and Molnia and Carlson 1980).

Sediment

Stratigraphy and General Distribution. The sedimentary deposits above bedrock on the northeastern Gulf of Alaska shelf consist of three distinctive seismic-stratigraphic units (Molnia and Carlson 1980; Molnia 1981) (Fig. 5-8I). The two youngest units are of Holocene age

and mantle much of the shelf. The uppermost unit is composed largely of silty clay and is characterized on seismic-reflection profiles by relatively horizontal and parallel reflectors. Exceptions occur both in areas where sediment slides and gas accumulations have disrupted the subsurface reflectors (Carlson and Molnia 1977) and seaward of the barrier islands of the Copper River where the principal sediment is fine sand and the reflectors are highly irregular. The underlying Holocene unit is present off the Bering and Malaspina Glaciers and at the mouth of Yakutat and Lituya Bays where the most recent end moraines show a jumbled mass of irregular reflectors (not shown in Fig. 5-8I).

The Holocene units are underlain on some parts of the shelf by a glacial-marine unit of pebbly mud that is characterized on seismic-reflection profiles by irregular and distorted reflectors (Fig. 5-8I). Because of its stratigraphic position between Holocene and older rocks of Tertiary to Pleistocene age, a late Pleistocene age is assigned to this unit. Its unique seismic signature separates this unit from the overlying Holocene units. (Note that the late Pleistocene unit is not included on the isopach map, Fig. 5-4). In other areas of the shelf, the late Pleistocene unit is absent, and the Holocene unit is underlain directly by folded, faulted (and in many places truncated), stratified bedrock.

The thickness of Holocene sediment in the northeastern Gulf of Alaska ranges from 0 to more than 300 m (Fig. 5-4) (Carlson and Molnia 1975). The wedge of Holocene fine sand to silty clay that makes up the Copper River prodelta reaches about 325 m thick just southeast of the main channel of the Copper River.

Several areas of bedrock outcrop can be discerned on continental shelf seismic-reflection profiles. Rock exposures on islands and reefs suggest that bedrock includes the Orca, Katalla, and other formations of Tertiary age (Winkler 1973; Plafker 1974). The largest areas of submarine outcrop are on Tarr Bank and the Middleton Island platform (Fig. 5-4), although sediment sampling suggests that much of the bedrock on Tarr Bank might be covered by a thin veneer (<2 m) of Holocene mud that either is too thin or too acoustically transparent to be detected on the profiles. The outcrops are flanked by a thin band of Quaternary glacial-marine pebbly mud along the north and west sides (Carlson and Molnia 1977; Molnia and Carlson 1980). Smaller areas of Tertiary bedrock outcrop in the western half of the region include areas east of Montague Island, southwest of Hinchinbrook Island, along the outer shelf and upper slope, Kayak Island platform, and two unnamed structural highs near Cape Yakataga (Molnia and Carlson 1975, 1978) (Fig. 5-4).

Texture and Composition. Size analysis of several hundred sea-floor sediment samples collected on the continental shelf west of Yakutat Bay led Carlson, Molnia, Kittleson, and Hampson (1977) to conclude that the dominant sediment is clayey silt. It is especially prevalent between Kayak Island and Yakutat Valley, mantling much of the shelf except for the nearshore area between Yakataga and Yakutat, the Kayak Island platform, the crest and flanks of Pamplona Spur, and the outermost shelf (Fig. 5-5). Between Yakutat Valley and Yakobi Valley, clayey silt is most com-

mon in the shelf valleys and on the inner part of the shelf (Molnia 1981). West of Kayak Island, clayey silt is predominant in Kayak and Egg Island Troughs, in Hinchinbrook Seavalley, and on the outer shelf (except on the Middleton Island platform and Tarr Bank).

The second most common sediment is the gravelly mud that covers much of Pamplona Spur, the shelf edge east of Kayak Island, and Tarr Bank. East of Yakutat Valley, the gravelly mud covers the outer two-thirds of the shelf except in Alsek and Yakobi Valleys.

The amount of gravel (defined here as >2 mm in diameter) ranges from almost 75% in some samples to nil in others. The principal areas of gravel accumulation are on the moraines at the mouth of Lituya, Icy, and Yakutat bays, the top and flanks of Pamplona Ridge, and the Tarr Bank–Middleton Island platform.

The highest concentration of sand (0.0625–2 mm in size) occurs along the continually changing barrier islands that are prograding westward at the mouth of the Copper River (Reimnitz 1966), where many samples consist of more than 90% sand. Most of the sand is moderately well-sorted and medium- to fine-grained. Hayes (1976) classified the mineralogically immature sand of the barrier islands as litharenite, containing about equal parts of quartz and metamorphic rock fragments. Tarr Bank samples also have a relatively high sand content that ranges from 10 to 50%, with most of the samples in the 25 to 35% range. The Kayak Island platform is covered by sediment consisting of as much as 88% sand. Other areas of sand dominance are the nearshore zone off the Malaspina Glacier, a patch on the floor of Yakutat Valley, and the nearshore zone across the mouth of the Alsek River.

Concentrations of up to 80% silt (0.004–0.0625 mm in size) occur east of Kayak Island, especially seaward of the Malaspina and Bering Glaciers. Much of the shelf in this area is blanketed by clayey silt, a condition that can be attributed largely to the vast quantity of rock flour supplied by glacial meltwater. West of Kayak Island, the highest concentration of silt (60–72%) is in Kayak and Egg Island Troughs and in Hinchinbrook Seavalley. The highest concentration of clay (<0.004 mm in size), 30 to 50%, occurs in Egg Island Trough, Kayak Trough, Hinchinbrook Seavalley, and on much of the shelf between Kayak Island and Pamplona Spur, a distribution similar to that of silt.

The coastal areas have a variety of sediment types. As mentioned above, the barrier islands at the mouth of the Copper River are covered with fine- to medium-grained sand. The beaches that front morainial cliffs are composed of coarse sand to gravel, and some areas southeast of Lituya Bay have bedrock outcrops at the beach surface (Boothroyd and Ashley 1975; Hayes 1976; Reimnitz and Plafker 1976; and Molnia and Wheeler 1978). Further classification of northeast Gulf of Alaska beaches, on the basis of composition, beach slope, and biological cover, is given in an atlas by Sears and Zimmerman (1977).

The average clay-mineral assemblage in the sea-floor sediment on the shelf includes 61% kaolinite + chlorite, 37% illite, and 2% smectite (Molnia and Hein 1982). An exception is off the Copper River, where illite content of 65% and kaolinite + chlorite values of 35 to 48% have been

measured. Similar high illite (58%) and kaolinite + chlorite (36%) contents have been reported from the suspended load of the Copper River (Griffin, Windom, and Goldberg 1968). Molnia and Hein (1982) suggested that this Copper River anomaly is due to a recent flood event, perhaps as a result of the emptying of a glacial lake. Both groups of authors attribute the high kaolinite + chlorite concentrations at high latitudes to the effects of low-intensity chemical weathering processes and to glacial transport.

Forty sediment samples were analyzed for carbon content by Carlson *et al.* (1977). The highest concentration of carbonate carbon they found was 2.1% from a gravelly mud collected on Tarr Bank. The highest organic carbon content was 0.8% from a clayey silt sampled near the south end of Kayak Island. In general, sandy sediment contained the least carbonate and organic carbon, with values for each ranging from 0.1 to 0.5 percent.

The presence of bubble-phase gas (gas charging) has been inferred by analyzing the acoustic anomalies on high-resolution seismic-reflection records. Many of these projected gas occurrences are in areas of sediment slides (Carlson and Molnia 1977; Hampton, Bouma, Carlson, Molnia, Clukey, and Sangrey 1978; Molnia, Carlson, and Kvenvolden 1978; Molnia 1979a; and Carlson, Molnia, and Wheeler 1980). However, only 2 of 31 core samples analyzed for biogenic methane by Golan-Bac and Kvenvolden (1983) had the unusually high concentrations that indicate the presence of bubble-phase gas. One of the cores was from a fault zone southeast of Kayak Island and the other core came from an area west of the Alsek River prodelta failure area.

Physical Properties. The physical properties of about 150 gravity and vibratory core samples were determined from the northeastern Gulf of Alaska shelf by Lee and Schwab (1983). Also, they conducted nine in-place static cone penetration tests and five in-place vane shear tests. The geotechnical coring and testing stations are grouped into eight study areas (Fig. 5–9), which cover much of the continental shelf and most of the large submarine slides and slumps. The study areas are almost entirely within the Holocene silt and sand because most of the sediment failures occur there.

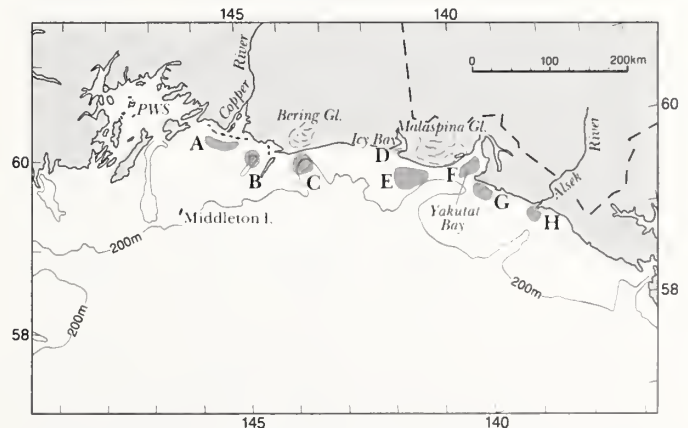


Figure 5–9. Geotechnical test areas in the northeastern Gulf of Alaska. A: Copper River prodelta, B: Kayak Trough, C: Bering Trough, D: Icy Bay, E: Icy Bay–Malaspina Glacier, F: Yakutat Bay, G: Yakutat, and H: Alsek River.

In the northeastern Gulf, the natural water content is by far the most commonly measured physical property of sediment samples. The saturated sediment of the shelf has a uniform grain density of about 2.8 g/cm³, and therefore, the water content uniquely determines its bulk density, porosity, and void ratio. The water content of near-surface (<6 m sub-bottom) sediment in the northeastern Gulf can be used as an index physical property for classifying sediment types. The more sophisticated strength and compression parameters, as well as other index properties, vary systematically with water content. For example, Figure 5-10 shows the average plasticity index for a core compared with the average water content for the same core. The water content serves as a good classification parameter because the Holocene sediment has low compressibility and is normally consolidated or only slightly underconsolidated throughout the region.

The physical properties of the Holocene sediment vary with water depth, distance offshore, sub-bottom depth, and location along shore. Of these four factors, water depth produces the widest variations in the sediment's properties. For each area in which there are enough data to define a trend, average water content increases with water depth (Fig. 5-11A). This fact reflects a transition from nearshore sand (water content less than about 32%) to increasingly finer-grained silt.

The Yakutat, Kayak Trough, and Copper River study areas share a common variation in water content, which increases from about 30% at a depth of 50 m to around 50% at 200 meters. Such a consistent variation probably represents a common equilibrium between the supply of sediment and the intensity of bottom currents that resuspend and redistribute the sediment. The Icy Bay-Malaspina study area shows lower water content (less plastic or coarser sediment) than the Yakutat, Kayak Trough, and Copper River areas at the same water depths. Such a shift perhaps indicates a slower supply of sediment or more intense bottom currents. The Alesek study area shows much higher water content (more plastic or fine grained sediment) for the same water depths, possibly because of the large quantities of glacial rock flour introduced by the Alesek River.

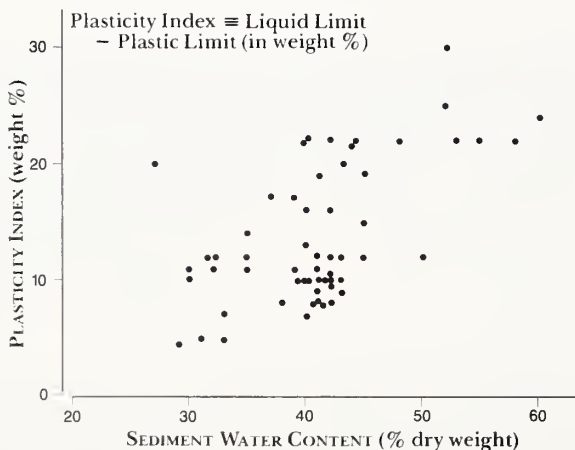
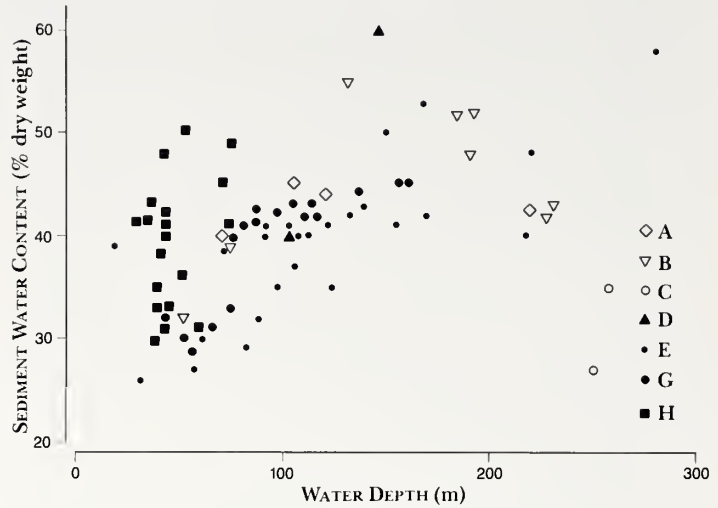
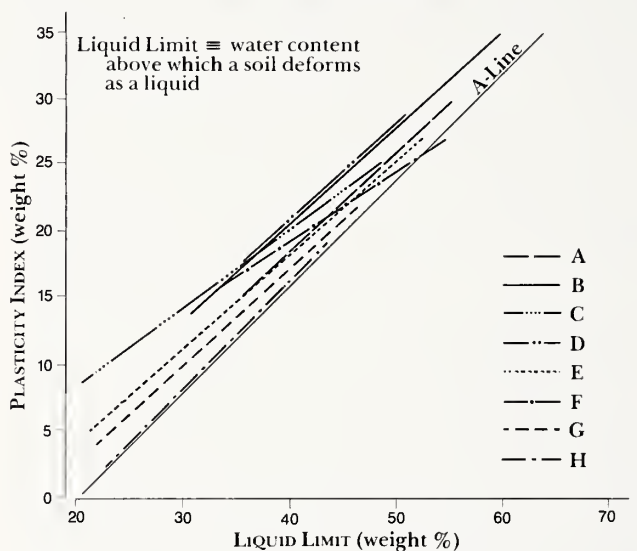


Figure 5-10. Relation of average plasticity index to average sediment water content. Each point represents a separate gravity core in the northeastern Gulf of Alaska.

A. SEDIMENT WATER CONTENT VERSUS WATER DEPTH



B. PLASTICITY INDEX VERSUS LIQUID LIMIT (PLASTICITY CHART)



C. SEDIMENT CLAY CONTENT VERSUS SEDIMENT WATER CONTENT

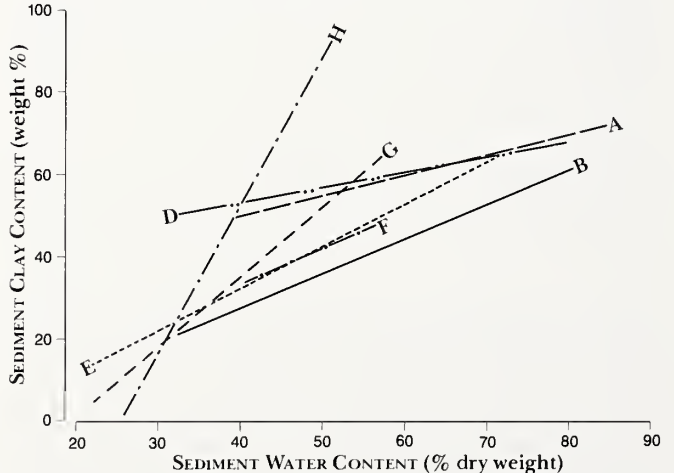


Figure 5-11. Relations between various index properties among the geotechnical test areas in the northeastern Gulf of Alaska (see Figure 5-9 for definition of letters designating test areas) (data, in part, from Lee and Schwab 1983).

The Bering Trough area has only two water content/water depth data points, but these are anomalous. Low water contents (25–35%, indicative of coarser-grained sediment) occur in deep water (250 m), probably because deep water exists close to shore (10 km). One Icy Bay data point (60% water content at 150 m water depth) is anomalously high and likely represents underconsolidation.

A series of linear-regression analyses (separated according to study area) were performed on plasticity-index/liquid-limit data that are used in the Unified Soil Classification System (Lambe and Whitman 1969: p. 35). Figure 5-11B shows this series, which was used to classify fine-grained sediment. Almost all of the northeastern Gulf of Alaska data, and all of the regression lines, fall above the A-line, which in this engineering classification designates low-to-high plasticity clay to silty or sandy clay. Note that the 'clay' designation here refers to plasticity behavior and not grain size. Among the regression plots (excluding the embayments and the anomalous Bering Trough), there is a consistent trend toward greater distance above the A-line as the Kayak Trough study area is approached from either side. Such a trend probably results from fundamental mineralogical changes, with more active clay minerals corresponding to greater distances above the A-line (Holtz and Kovacs 1981). Figure 5-11C shows a similar trend in the variation of the abundance of clay-sized particles with water content. Linear regression plots for each study area show less clay-sized sediment at the same water content when approaching Kayak Trough from either side. This trend may be a result of increased smectite content in Kayak Trough (Molnia and Hein 1982). Although the smectite content is low throughout the Gulf of Alaska shelf, the up-to-5% smectite content of the Kayak Trough clay fraction is sufficient to influence index properties (Seed, Woodward, and Lundgren 1964).

There are also significant subbottom depth fluctuations of geotechnical properties. Figure 5-12 shows typical water content profiles for water depths from 23 to 221 meters. Downcore fluctuations are large, ranging from 15% to over 40%, and indicating alternating layers of relatively plastic and less plastic sediment. In shallow-water cores, bedding is graded (2- to 2.5-m-thick beds are present in core 615A1). Such deposits may result from resuspension and redeposition of a part of the sediment column during major storms.

The relationships of consolidation and strength properties to water content are shown in Figure 5-13. The compression index, C_c , determines the settlement potential for structures set on the glacial-marine sediment. Figure 5-13A shows how the compression index varies consistently with natural water content. A similar previous correlation, shown by the plotted curve in Figure 5-13A (Lambe and Whitman 1969, p. 321), would have predicted slightly greater compressibilities. The coefficient of consolidation, c_v , determines the rate at which settlement will occur and is useful in predicting underconsolidation from sedimentation rates (Gibson 1958). The coefficient has a great deal of scatter but generally decreases with water content (Fig. 5-13B). The correlation roughly matches typical values presented previously, as shown by the diagonal line in Figure 5-13B (Lambe and Whitman 1969, p. 412; Lee and Schwab 1983).

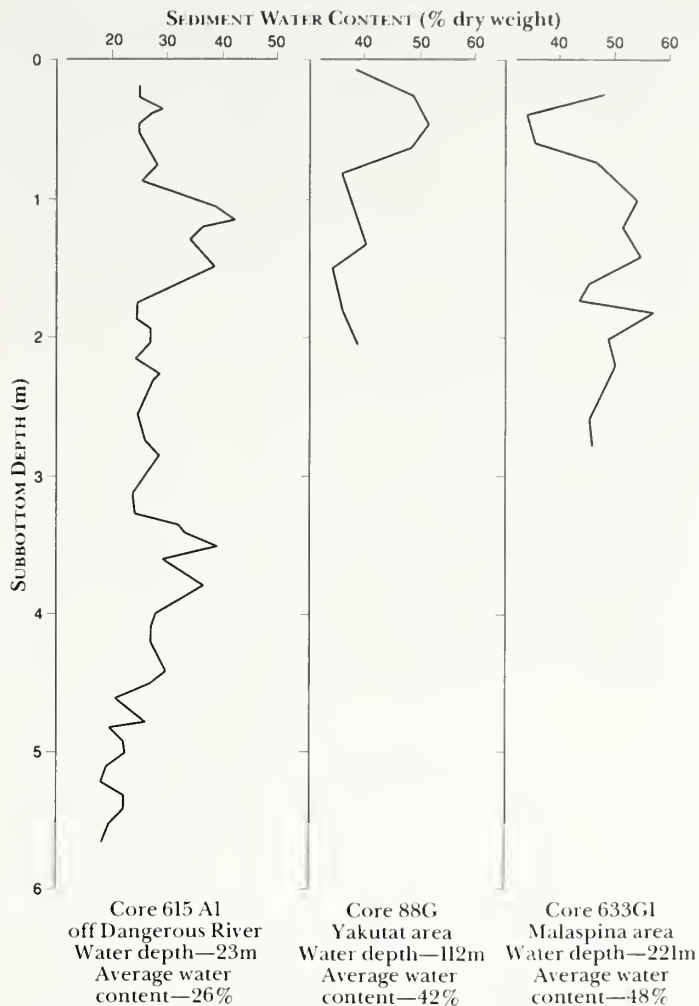
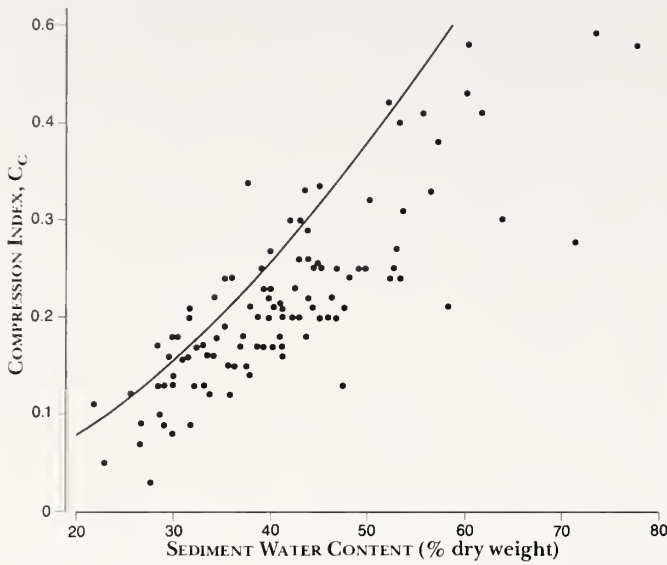


Figure 5-12. Downcore variation in water content in three environments (data, in part, from Lee and Schwab 1983).

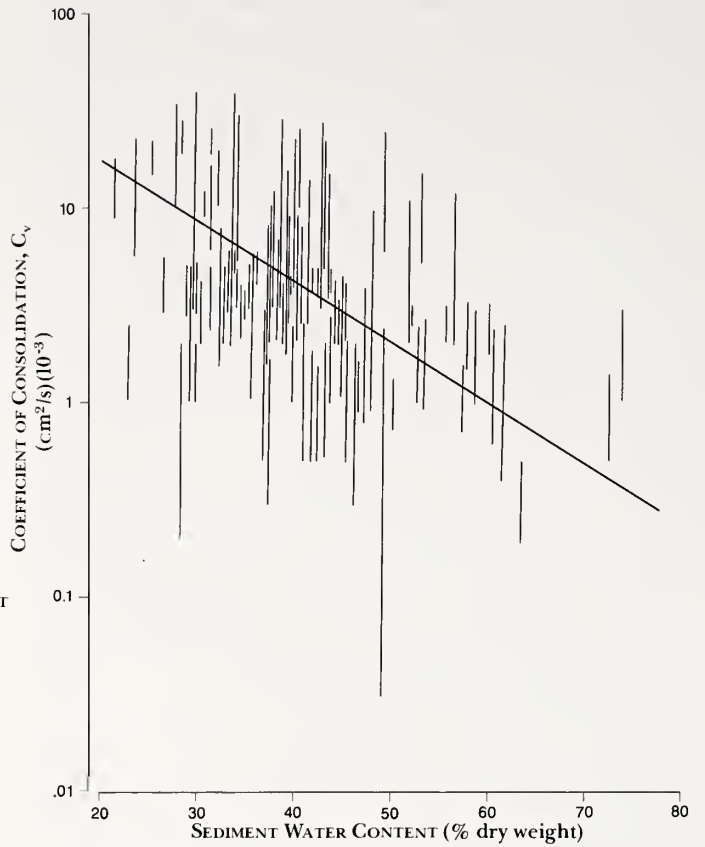
Maximum past consolidation stress was obtained from over 100 consolidation tests using the Casagrande (1936) procedure. In only 10% of the tests did the maximum past stress significantly exceed the in-place overburden stress, indicating a state of overconsolidation. Of these tests, several are suspect due to high sand content. About 25% of the tests indicate that in-place overburden stress was slightly greater than the calculated maximum past stress, which implies that the consolidation of the sediment had not yet reached an equilibrium state with the overburden stress (underconsolidation).

Lee and Schwab (1983) estimated areal variations in the degree of consolidation by using the sedimentation rate information of Molnia and Carlson (1980), the coefficient of consolidation data of Figure 5-13B, and the methods of Gibson (1958). The Kayak Trough, eastern Alek, and eastern Icy Bay-Malaspina areas were predicted to have a degree of consolidation ranging from 80 to 90%, and approaching 100% for the remaining shelf areas. The two embayment study areas (Yakutat Bay and Icy Bay) have highly underconsolidated sediment, with an estimated degree of consolidation of 20 and 30%, respectively. Earlier calculations by Sangrey, Clukey, and Molnia (1979) indicate higher levels of

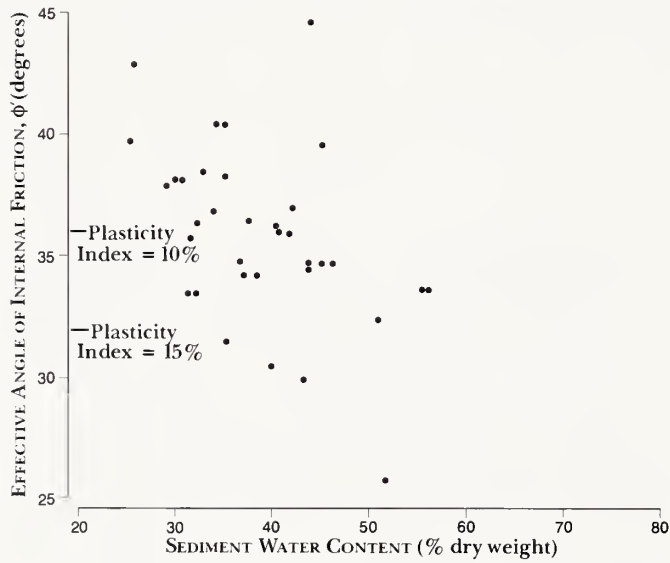
A. COMPRESSION INDEX VERSUS SEDIMENT WATER CONTENT



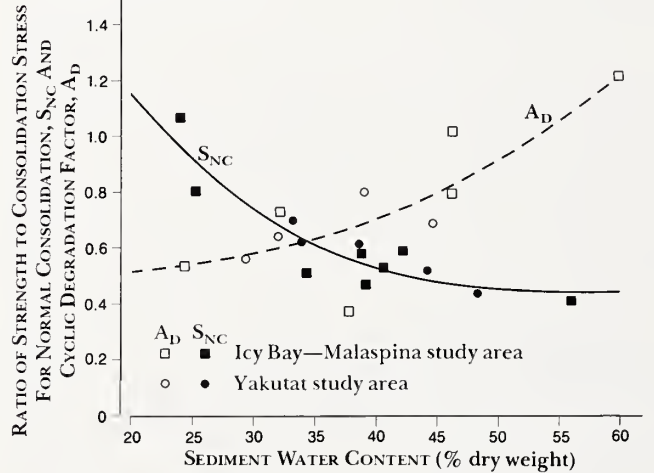
B. COEFFICIENT OF CONSOLIDATION VERSUS SEDIMENT WATER CONTENT



C. EFFECTIVE ANGLE OF INTERNAL FRICTION VERSUS SEDIMENT WATER CONTENT



D. RATIO OF STRENGTH TO CONSOLIDATION STRESS FOR NORMAL CONSOLIDATION, AND CYCLIC DEGRADATION FACTOR VERSUS SEDIMENT WATER CONTENT



E. CRITICAL EARTHQUAKE ACCELERATION VERSUS SEDIMENT WATER CONTENT

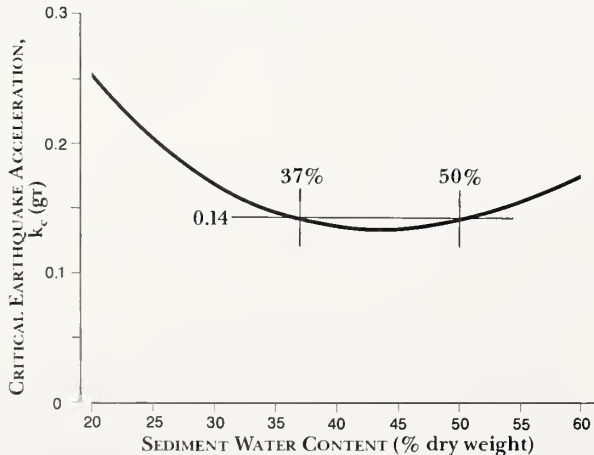


Figure 5-13. Correlation of various engineering properties with sample water content in the northeastern Gulf of Alaska (data, in part, from Schwab and Lee 1983).

underconsolidation for most areas, but their values of c_v appear anomalously low and were not included in the analysis (Fig. 5-13B).

The fully drained shearing strength corresponding to long-term loading conditions is expressed by the effective stress friction angle, ϕ' . A slight correlation with water content is evident (Fig. 5-13C). The measured values of 30 to 40° are representative of or slightly higher than those commonly reported for low plasticity soils, indicated in the figure by two horizontal lines for plasticity index of 10 and 15% (Lambe and Whitman 1969: p. 307). The effective stress friction angles would represent the long-term (drained) angle of repose of these sedimentary deposits. Because failure is occurring on slopes of less than 1° (Carlson and Molnia 1977; Schwab and Lee 1983), long-term drained loading clearly is not a factor. Rather, more rapid and transient earthquake and storm wave loads, coupled with cyclic strength degradation resulting from excess pore-water pressure generation, must be causing failure on such gentle slopes.

Lee and Schwab (1983) evaluated the undrained static shearing strength of several hundred core samples on shipboard, using a miniature laboratory vane shear apparatus. They found that in 10% of the samples, the static shearing strength exceeded 15 kiloPascals (kPa). By this measure, almost all of the Holocene clayey silt would be considered very soft (Terzaghi and Peck 1967: p. 30). These measurements are of limited value in dealing with silty sediment because of coring disturbance (Lee 1979). Indeed, four in-place vane shear tests in the northeastern Gulf of Alaska clayey silt yielded strength values about twice those of the core samples measured by Lee and Schwab (1983).

A preferable way of assessing undrained shearing strength is the normalized soil parameter (NSP) approach (Ladd and Foott 1974; Lee, Edwards, and Field 1981). Such an approach not only uses triaxial test results, but partially compensates for coring disturbance and may allow extrapolation below the level of sampling. For the generally normally consolidated Holocene clayey silt, the critical normalized soil parameter is the ratio of undrained strength to consolidation stress for normal consolidation, S_{NC} . The parameter S_{NC} varies directly with water content (Fig. 5-13D). Because cyclic loading from earthquakes and waves probably generates most slope failures, a cyclic strength degradation factor, A_D , is needed to estimate the appropriate reduced strength (Lee *et al.* 1981). This degradation factor varies inversely with water content (Fig. 5-13D). The product of A_D , S_{NC} , and a density term determines the level of seismic acceleration, k_c , needed to cause failure during an earthquake (Lee *et al.* 1981; Schwab and Lee 1983). A somewhat more complex function determines the storm-wave height needed for failure (Schwab and Lee 1983). The critical earthquake acceleration, k_c , varies with water content (Fig. 5-13E) (Lee and Schwab 1983). The factor k_c has a minimum of about 0.14g, corresponding to a critical water content range of 37 to 50 percent. Lee and Schwab (1983) found that core samples from several of the major slumps have water contents predominantly in this critical range. Sediment outside the slumps tends to have water content above or below the critical range.

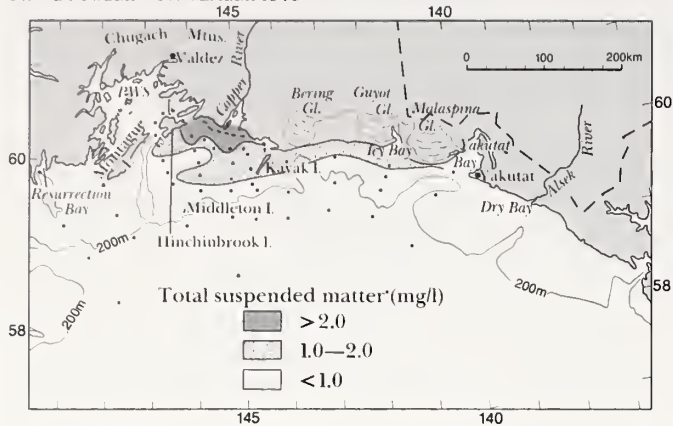
The shoreward edge of the Holocene sediment is predominantly sand. Several static cone-penetration tests in the sand disclose a very dense sediment (Lee and Schwab 1983), close to the maximum value (Schmertmann 1978).

Suspended Sediment. The suspended sediment in the northern and part of the north central Gulf of Alaska has been studied extensively using both satellite imagery (Reimnitz and Carlson 1975; Sharma, Wright, Burns, and Burbank 1974) and discrete water-column measurements (Feely, Baker, Schumacher, Massoth, and Landing 1979; Feely, Massoth, and Landing 1981; and Landing and Feely 1981). East of Kayak Island, surface suspended-matter distribution is dominated by the discharge of sediment from the coastal streams that drain the Bering, Guyot, and Malaspina Glaciers (Fig. 5-14). Near the Copper River, plumes of highly turbid water (>2.0 mg/l suspended sediments) extend as far as 40 km offshore. The highest concentration of suspended sediment occurs in July and August when maximum discharge occurs. The plume can be traced west along the coast, where a portion diverges into Prince William Sound through channels on either side of Hinchinbrook Island as well as to the southwest along the southern coast of Montague Island.

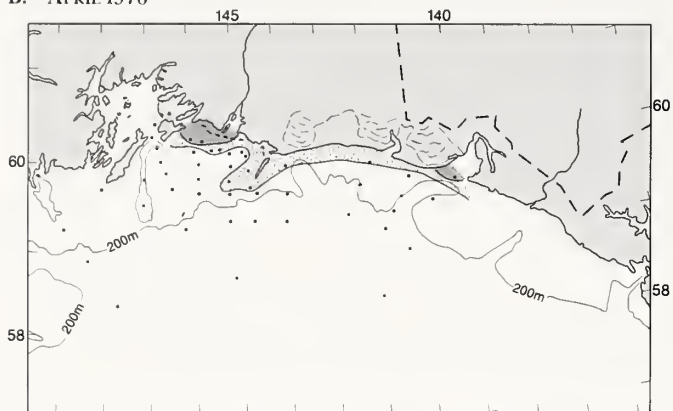
A strong vertical gradient of suspended sediment exists over most of the shelf. A pronounced suspended-matter minimum at about 50 m separates the surface plumes from the near-bottom nepheloid layer, which spans the bottom 50 to 80 m of the water column. In the near-bottom water, the suspended-matter distribution shows evidence for a decreasing concentration away from the coast (Fig. 5-15). Near-bottom concentration is highest south of the Copper River Delta and on either side of Kayak Island, varying between 1 and 10 mg/l. In the vicinity of the shelf break, near-bottom concentrations are generally below 0.5 mg/l. The near-bottom turbid plumes in the area east of Kayak Island are situated primarily over modern accumulations of silty clay and bear little resemblance to the surface plumes. For example, a comparison of the elemental composition of sediment trap and bottom sediment samples collected 30 km south of Icy Bay suggests that the near-bottom suspended matter more closely resembles the sediment than the surface plumes, although the number of measurements is limited (Table 5-1).

Embayments. Sedimentary deposits within the embayments in the northern Gulf of Alaska are as diverse as those on the open shelf. Seismic-reflection profiles show two distinct stratigraphic units above bedrock (Fig. 5-8J). The lower unit has hummocky and discontinuous reflectors, with some parallel-bedded sequences, and the deposits have irregular morphology. The overlying unit is typified by continuous and parallel reflectors, and the deposits fill depressions in the underlying sedimentary deposits or bedrock. The combined thickness of the two sedimentary units is commonly several tens of meters; the maximum observed thickness is greater than 200 m in Glacier Bay, 120 m in Lituya Bay, 350 m in Yakutat Bay, and 400 m in Prince William Sound (von Huene *et al.* 1967; Carlson, Molnia, Hampson, Post, and Atwood 1978; Carlson, Wheeler,

A. OCTOBER—NOVEMBER 1975



B. APRIL 1976



C. JULY 1976

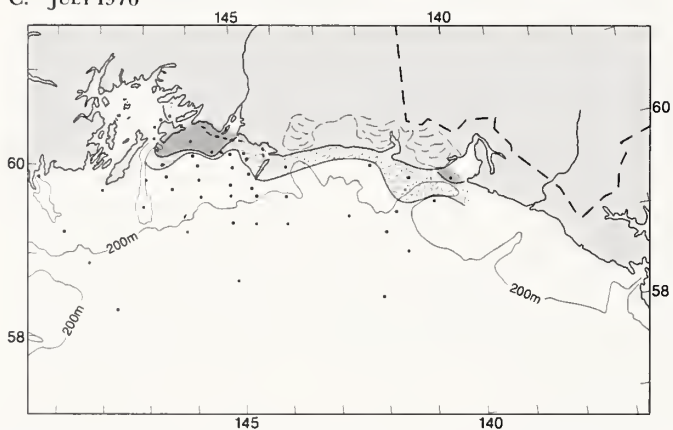
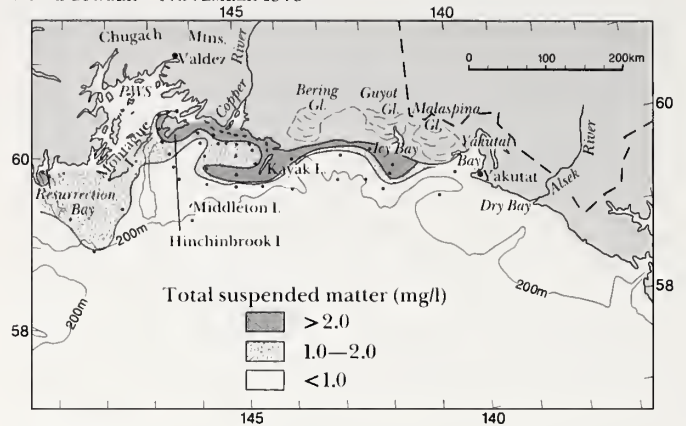


Figure 5–14. Distribution of total suspended matter at the sea surface in the northeastern and part of the northcentral Gulf of Alaska. (Modified from Feely *et al.* 1979.)

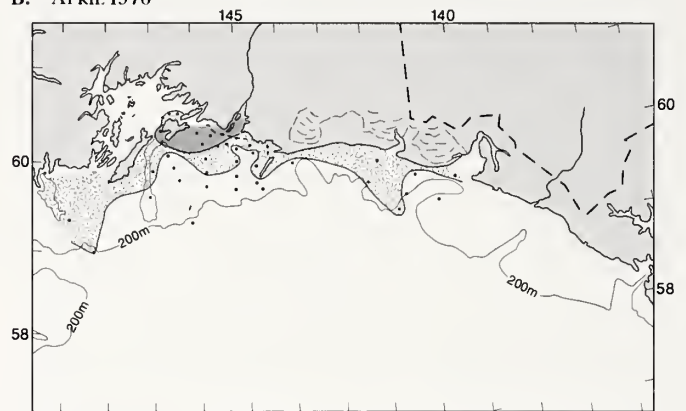
Molnia, and Atwood 1979; Mackiewicz, Powell, Carlson, and Molnia 1984; and Molnia 1979b).

Sediment in the embayments ranges widely in grain size. In Glacier Bay, for example, coarse diamict sediment has been sampled in front of glaciers, gravel and coarse sand have been sampled near the mouth of meltwater streams, and mud with sand interbeds was found on the flat floor of the central Bay (Carlson, Wheeler, Molnia, Post, and Powell 1983; Molnia 1983; and Powell 1983). Wright (1972) collected 74 samples in Yakutat Bay. They ranged from 100% gravel on moraines to 99% mud in the central basin.

A. OCTOBER—NOVEMBER 1975



B. APRIL 1976



C. JULY 1976

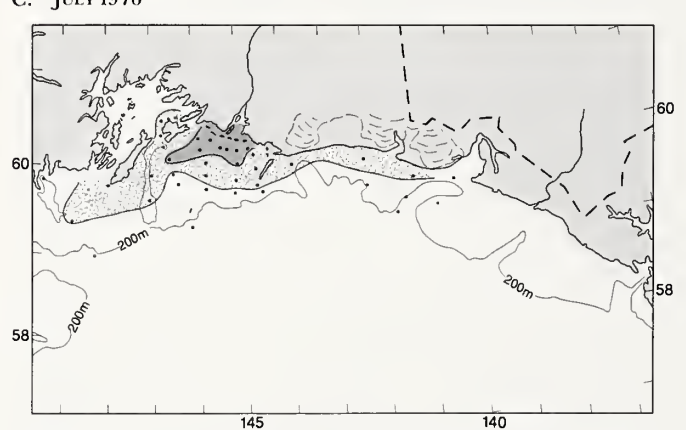


Figure 5–15. Distribution of total suspended matter at 5 m above the bottom in the northeastern and part of the northcentral Gulf of Alaska. (Modified from Feely *et al.* 1979.)

Sedimentary Processes

Sediment has been transported on the northeastern Gulf of Alaska shelf by a variety of forces, including:

- ice (both glaciers and icebergs)
- ocean currents (alongshore, surface, and bottom)
- waves (storm, seismic, and internal)
- mass movements (slumps, slides, and flows)
- rivers
- wind.

Table 5-1.

Summary of the elemental composition of suspended matter, sediment trap material, and sediments from the northeast Gulf of Alaska and suspended matter from the Copper River. Precision is given at the 1 σ level. (From Feely and Massoth 1982.)

SAMPLE DESCRIPTION	COPPER RIVER		NORTHEAST GULF OF ALASKA				
	SUSPENDED MATTER	NEAR-SHORE SUSPENDED MATTER	OFFSHORE SUSPENDED MATTER	NEAR-BOTTOM SUSPENDED MATTER	SEDIMENTS	SEDIMENT TRAP SAMPLE (96m) ^a	SEDIMENT SAMPLE ^a
Number of Samples	1	25	18	38	15	1	1
C (wt%)	1.0 ± 0.5	8.7 ± 3.8	29.1 ± 5.9	6.8 ± 3.7	–	1.3 ± 0.1	0.9 ± 0.1
Al (wt%)	9.3 ± 0.2	10.2 ± 1.3	0.9 ± 0.8	10.2 ± 1.0	7.2 ± 0.8	7.7 ± 0.9	8.1 ± 0.4
Si (wt%)	27.9 ± 0.5	30.4 ± 2.0	8.8 ± 8.5	30.9 ± 2.2	–	30.0 ± 2.2	28.2 ± 1.0
K (wt%)	1.8 ± 0.1	1.5 ± 0.2	0.3 ± 0.3	1.4 ± 0.2	–	–	–
Ca (wt%)	4.4 ± 0.1	2.9 ± 1.0	0.6 ± 0.3	2.7 ± 0.6	4.1 ± 2.2	–	–
Ti (wt%)	0.64 ± 0.01	0.56 ± 0.07	0.10 ± 0.05	0.55 ± 0.06	–	–	–
Fe (wt%)	6.7 ± 0.2	6.4 ± 0.9	1.4 ± 0.7	6.5 ± 0.7	4.6 ± 0.9	5.2 ± 0.3	5.2 ± 0.3
Cr (ppm)	126 ± 13	114 ± 19	54 ± 3	113 ± 13	126 ± 22	95 ± 3	100 ± 4
Mn (ppm)	1210 ± 50	1198 ± 97	321 ± 193	1230 ± 158	813 ± 111	970 ± 13	990 ± 16
Ni (ppm)	61 ± 5	78 ± 16	51 ± 15	74 ± 17	–	52 ± 4	51 ± 1
Cu (ppm)	63 ± 2	85 ± 14	79 ± 22	84 ± 16	–	43 ± 3	40 ± 2
Zn (ppm)	133 ± 5	251 ± 99	227 ± 95	199 ± 32	–	123 ± 12	16 ± 7
Pb (ppm)	–	–	–	–	–	12 ± 1	10 ± 1
Reference	b	b	b	b	c	d	d

^a The single sediment trap and sediment sample were from a station located approximately 30 km south of Icy Bay.

^b Feely, Massoth, and Landing (1981)

^c Burrell (1977)

^d Landing and Feely (1981)

Glacial deposits include the muddy gravel exposed at the sea floor on the bathymetric highs and at the edge of the shelf. These deposits are relict (Quinterno *et al.* 1980) and till-like, similar to those mapped by Miller (1953) on Middleton Island. Similar muddy conglomerate occurs onshore in the Yakataga Formation (Plafker and Addicott 1976). This coarse debris offshore probably was deposited during the Pleistocene when lobes of the massive piedmont glaciers extended seaward. The resulting pebbly or gravelly mud (diamicton) makes up a significant part of the sea-floor sediment on Tarr Bank, Middleton Island platform, and Pamplona Spur. The uplifting of these positive relief features and the winnowing action of waves and currents have kept the diamicton from being covered by the fine sediment being deposited elsewhere on the shelf.

The modern sediment on the shelf is principally clayey silt, derived from glaciers and transported by meltwater streams (Molnia and Carlson 1980). The four main sources of Holocene sediment are the Copper River, which annually supplies 97×10^6 mt of detritus (Reimnitz 1966), the Alsek River, which cuts through the St. Elias Mountains to drain part of Yukon Territory, and the two large piedmont glaciers, Bering and Malaspina. Sediment from the two glaciers is at present primarily transported as suspended matter, the plumes of which easily can be detected more than 30 km from shore using satellite imagery (Reimnitz and Carlson 1975). The similarity between the elemental composition of the one sample of Copper River suspended matter and the samples of nearshore suspended matter (Table 5-1) supports the notion that this river is a major source of sediment.

A secondary but significant source of fine sediment is wind. For example, in the fall of the year it often blows down the Copper River gorge with sufficient force to pick up sedi-

ment from the flood plain and carry dark clouds of silt as much as 40 to 50 km offshore (Carlson, Molnia, and Reimnitz 1976; Post 1976; and Swift, Molnia, and Jackson 1978).

The sediment, whether transported by rivers, glaciers, or wind, is subject to the rigors of the nearshore currents (Alaska Coastal Current System) that primarily move in a westward direction, similar to the offshore Alaska Stream (Reimnitz and Carlson 1975). Much of the Copper River sediment is being carried into Prince William Sound through channels to the north and south of Hinchinbrook Island (Burbank 1974; Carlson and Molnia 1978). Sediment contained in the Bering, Guyot, and Malaspina Glacier runoff plumes is carried along the coast until it reaches Kayak Island, where it is deflected offshore. Complex gyres of turbid water have been seen on both sides of Kayak Island on satellite imagery (Burbank 1974; Reimnitz and Carlson 1975). Occasionally, counterclockwise eddies form in the nearshore region between Yakutat Bay and Kayak Island. These eddies transport terrigenous material as much as 50 km offshore. Similarly, a clockwise gyre due west of Kayak Island transports a significant amount of suspended sediment to the southwest, past the outer edge of the shelf. Conservative estimates suggest that 3,000 to 24,000 mt of terrigenous sediment are transported offshore daily when the gyre is positioned near Kayak Island (Feely *et al.* 1979).

The near-bottom turbid plumes of sediment on the shelf might be derived partly by resuspension of the underlying fine sediment, as has been documented on the United States east coast shelf (Meade, Sachs, Manheim, Hathaway, and Spencer 1975; Biscaye and Olsen 1976). This is supported by the resemblance of the elemental composition of sediment trap samples to the sea-floor sediment (Table 5-1) and the existence of near-bottom plumes over modern accumulations of silty clay.

High-resolution seismic profiles, sea-floor television images, and bottom samples indicate that little of the suspended matter from either the Copper River or from sources east of Kayak Island accumulates on Tarr Bank or on the Middleton Island platform (Carlson, Molnia, and Levy 1980). The lack of sediment on these topographic highs probably is due to the scouring action of the large and forceful storm waves that are particularly frequent during the winter season of intense low pressure activity in the Gulf of Alaska (Wilson and Overland, Ch. 2, this volume).

The high sand content in the entrance between Hinchinbrook and Montague Islands (10–15%), and between Hinchinbrook Island and the mainland to the east (>50%), is related to the transport of sand from the Copper River along shore and into Prince William Sound (Carlson *et al.* 1977). Tidal action in the entrance probably winnows the fines from this sandy sediment. Further evidence of sediment transport into Prince William Sound is provided by a wedge of Holocene sediment building into the Sound (Carlson and Molnia 1978) and plumes of suspended matter that extend into the Sound (Reimnitz and Carlson 1975; Sharma *et al.* 1974).

Clay-sized sediment is not so prevalent on the northeastern Gulf of Alaska shelf as it is on shelves in many other parts of the world. The primary reason for this deficiency is that the source sediment is largely glacial flour, which is dominated by the silt fraction. In addition, the high wave energy in this dynamic environment may keep the clay in suspension and aid its transport off the shelf into abyssal depths. However, in some bays the energy is low enough to allow the clay-sized fraction to settle out of suspension. For example, Wright (1972) reported that sediment from parts of Yakutat Bay contains up to 85% clay-sized particles.

The rate of modern sediment accumulation, based on ^{210}Pb analyses of samples from two box cores, ranges from 17 mm/y for mud on the inner shelf near the Copper River pro-delta to 2 mm/y for sediment on the outer shelf near Middleton Island (Charles Holmes, U.S. Geological Survey, pers. comm., 1977). The Holocene sediment east of the Copper River is 150 to 200 m thick on the inner shelf and has been accumulating for about 10,000 years. The calculated rate of accumulation is 15 to 20 mm/y, equivalent to that obtained with the ^{210}Pb technique (Carlson *et al.* 1977; Molnia *et al.* 1980). Sedimentation rates at the mouth of Prince William Sound exceed 18 mm/y. Other areas of high sedimentation are south of Icy Bay (>20 mm/y) and south of Bering Glacier (>14 mm/y), areas that receive large quantities of locally produced glacial sediment. The sediment accumulation rates for the shelf sediment range from 0 to more than 28 mm/y, and the average rate is 4.5 mm/y (Molnia *et al.* 1980).

The sediment failures on the open shelf occur on slopes that are too gentle to have been caused solely by static gravitational force, according to a geotechnical analysis by Lee and Schwab (1983). Instead, a repeated-loading mechanism, such as earthquakes or water waves, is more probable. Values of the critical acceleration factor, k_c , indicate that sediment characterized by water content in the range of 37 to 50% is most susceptible to failure, and indeed, samples from some of the known failure areas contain more sedi-

ment with water content in this range than do samples from adjacent areas.

Further analysis by Schwab and Lee (1983) differentiated locations that would be subject to earthquake-induced failure from those that would tend toward storm-wave-induced failure. Shallower areas that are more likely to experience failure due to storm waves were separated by 35 to 75 m of water depth from the deeper areas where earthquakes are more likely to initiate failures. Only the Alsek study area contains significant clayey silt (water content greater than ~32% and therefore relatively susceptible to failure) in water depth less than 75 m (Fig. 5–12). Likewise, only the Alsek study area contains intricate mudflows and channels (Molnia and Rapoport 1980, 1984). Failures in the other study areas are more typically rotational slumps. The unique morphology of these Alsek failures is likely related to storm-wave initiation. The longer duration of major storms allows pore water movement, partial fluidization of the silty sediment, and flow over a considerable distance.

The high relative density indicated by the static cone-penetration tests in the sandy sediment at the shoreward edge of the Holocene sediment implies little likelihood of failure under either earthquake or wave loading. In fact, the scarps at the head of the Icy Bay–Malaspina slump (Carlson 1978) probably correspond to the boundary between stable sand and less stable clayey silt.

There appears to be no correlation between the occurrence of acoustic anomalies and the locations of sampled gas-charged sediment, except for the sediment off Kayak Island. Whether gas accumulation, the development of high pore pressure, and the subsequent degradation of sediment shearing strength is a significant factor in causing sediment failure on the northeastern Gulf of Alaska shelf is unknown. However, the extent of observed gas charging certainly is much less than the extent of mass instability. Repeated loading-strength degradation in the glacial silt deposits (Fig. 5–13D) is a more likely explanation for the widespread occurrence of sediment failures.

The coastal and nearshore zones comprise a variety of sedimentary environments. Hayes and Ruby (1977) divided the coastline between the Alsek River and Prince William Sound into three major classes: depositional (19%), erosional (23%), and neutral (58%). Examples of depositional shorelines are the barrier islands of the Copper River Delta and smaller deltas and spits within Yakutat and Icy Bays. The most dramatic erosion of shoreline has occurred both northwest and southeast of Icy Bay (Boothroyd, Cable, and Levy 1976; Molnia 1977). The shoreline northwest of Icy Bay has retreated 4.8 km since 1922, and the southeast shoreline along the Malaspina foreland has receded about 1.3 km since 1941 (Molnia 1977). The moderately well-sorted sand deposits of the nearshore zone reflect a dynamic environment. Storm waves and alongshore currents resuspend or keep the fine particles in suspension, and offshore currents transport them westward.

The embayments in the northeastern Gulf of Alaska have similar sedimentation histories, although the timing and rates differ (Molnia 1979b). Glacial scour produced a rough and channeled bedrock surface, and moraines and other

irregular to chaotic deposits of glacial sediment have accumulated (*i.e.*, the lower stratigraphic unit observed in seismic-reflection profiles; see Fig. 5–8J). After ice retreat, the modern regime includes copious input of glacial rock flour transported by meltwater streams (*i.e.*, the upper stratigraphic unit in Fig. 5–8J) and some direct ice deposition at the terminus of tidewater glaciers (von Huene *et al.* 1976; Molnia 1983). Minor ice rafting continues.

Ice retreat from Icy Bay occurred as recently as 80 years ago (Tarr and Martin 1914; Molnia 1977). In Glacier Bay, ice retreat from the open bay began 200 years ago, but glaciers still remain in marginal fjords where the retreat history has been well documented (American Geographical Society 1966; Carlson, Wheeler, Molnia, and Atwood 1979). Moraines left by the retreating ice serve as barriers to the dispersal of bed-load outwash material, and thick sedimentary deposits have been observed behind them (Carlson *et al.* 1983; Molnia, Atwood, Carlson, Post, and Vath 1984).

The meltwater streams are laden with rock flour; Powell (1983) measured a suspended-sediment concentration greater than 23 g/l in streams that flow into Glacier Bay, and a suspended load concentration of greater than 1 g/l has been measured in the Bay itself (Hoskin and Burrell 1972). Consequently, the sediment accumulation rate is high. Maximum measured values are 4 cm/y in Taylor Bay (Cross Sound) to more than 400 cm/y in Muir Inlet (Glacier Bay) (Molnia 1979b; Carlson, Wheeler, Molnia, and Atwood 1979; and Molnia *et al.* 1984). Sangrey *et al.* (1979) and Molnia (1979b) measured an accumulation rate of 140 cm/y in Icy Bay, indicating a highly underconsolidated sediment.

Turbidity currents and other sediment-gravity-flow processes occur frequently in the bays and inlets. Diamicton deposits near the terminus of glaciers have been interpreted as debris-flow (Powell 1980, 1983), whereas the coarse sand layers cored farther from land have been interpreted as turbidity-current deposits (Mackiewicz *et al.* 1984). Von Huene *et al.* (1976) detected many buried slump deposits in Nuka Bay, a fjord in the northern Gulf of Alaska, and attributed their presence to a mass sediment failure from material that was originally deposited on the steep fjord walls.

Enormous earthquake-generated rockslides following a magnitude 7.9 event in 1958 deposited a significant amount of sediment in Lituya Bay. One rockslide involved 31×10^6 m³, and a survey in the Bay showed that some channels received up to 79 m of fill (Miller 1960; Jordan 1962).

Sediment slides were also triggered by the Great Alaskan Earthquake of 1964, in particular on the outwash fan and delta at Port Valdez in Prince William Sound (Coulter and Migliaccio 1966) and in Resurrection Bay (Lemke 1967). The slide at Port Valdez involved about 7.5×10^7 m³ of unconsolidated gravel, plus disseminated silt and sand beds that compose the delta. A seismic-reflection profile shows that the toe of the slide now rests in 230 m of water, and the deposit is 40 m thick at its up-slope end and about 5 m thick at the toe (Carlson and Molnia 1978). The south side of the Port Valdez area was investigated geotechnically by Singh and Quigley (1983). Cyclic triaxial tests of a rock-flour deposit, the 'Valdez silt', disclosed a cyclic loading response nearly identical to that of the most vulnerable sediment on

the continental shelf. However, the slopes in Port Valdez are much greater than those on the shelf, ranging up to 26° (Palmer 1981). In a stability analysis, Singh and Quigley (1983) found that even the mild wave environment (maximum wave height of 3 m) of Port Valdez could cause a fairly deep (4 m) failure in the silt. Also, much of the silt is highly susceptible to failure during an earthquake.

In Resurrection Bay, a slide mass 15 to 120 m wide, along with docks and harbor facilities, moved into the Bay as a consequence of the 1964 earthquake. Submarine slopes are now steeper in some places than before the sliding occurred, implying the likelihood of failure during future large seismic events.

Kodiak Shelf

Geomorphology

General. The geomorphology of the Kodiak Shelf consists of a series of banks, generally 50 to 100 m deep, cut by transverse troughs up to 300 m deep. The banks are flat and dip gently seaward over broad areas, although many low hills and shallow depressions do exist (Turner, Thrasher, Shearer, and Holden 1979; Dunlavy, Childs, and von Huene 1980). Closed depressions also exist in the troughs. The sea floor is nearly horizontal on most parts of the banks and rarely exceeds 2° inclination on the flanks of troughs (Hampton 1983a). A notable exception is Sitkinak Trough, where the gradient reaches 10 degrees. The upper continental slope is also relatively steep, with typical gradients between 5 and 20 degrees.

Troughs on the Kodiak Shelf are similar to the troughs in the northeastern Gulf of Alaska. They have a broad, U-shaped cross section and contain closed depressions on the trough floor. Anticlinal folding in bedrock has uplifted the sea floor to form sills near the mouths of Kiliuda, Chiniak, and Stevenson troughs and across the mid-portion of Amatuli Trough. The sill in Stevenson Trough is deeply breached in two places; the other sills are breached to shallower levels. The anticlines also have sea-floor expression on the banks. They have relief of more than 60 m in places and have been eroded to expose bedrock. The series of anticlines that forms the sill across both Kiliuda and Chiniak troughs forms a ridge parallel to and near the shelf break of southern and middle Albatross Bank. The ridge extends landward adjacent to the southwest edge of Chiniak Trough. A similar ridge exists near the shelf break of Portlock Bank; it extends landward, along the northeast side of Stevenson Trough. Other uplifted exposures of bedrock occur on the banks (von Huene, Hampton, Fisher, Varchol, and Cochrane 1980) (Fig. 5–4). The bedrock is middle or late Miocene to Pleistocene age (McClellan *et al.* 1980).

The morphology of the troughs has been modified by sedimentation. Sediment eroded from the banks has been deposited as inclined strata that prograde laterally into the sides of the troughs, significantly narrowing them (Fig. 5–16A). The floor of the troughs is aggrading from the ongoing sediment deposition. The sill across the troughs is

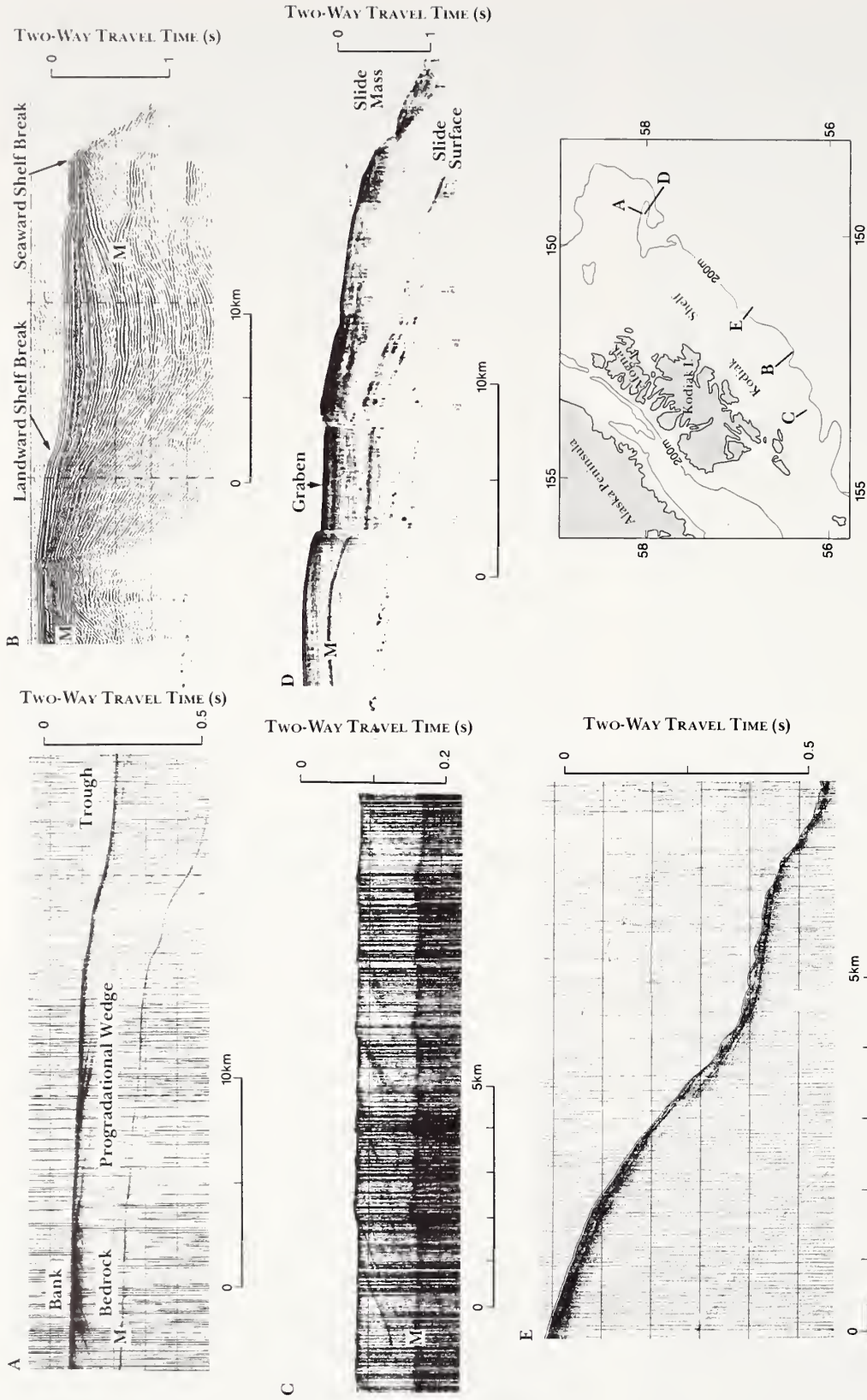


Figure 5-16. Seismic-reflection profiles of geologic features on the Kodiak Shelf area. M denotes sea-floor multiple reflection. A. Profile showing truncated bedrock at left and inclined strata of progradational wedge at right. B. Profile showing old landward shelf break and younger seaward shelf break. C. Profile showing hogback ridges on the sea floor in an area of bedrock outcrop. D. Profile showing large graben on the outer continental shelf and part of large sediment slide on the upper continental slope. E. Profile showing translational sediment slide on the upper continental slope.

capped by what appears to be Pleistocene glacial moraine (Thrasher 1979).

The shelf break along the Kodiak Shelf typically occurs on the seaward flank of the shelf-edge anticlines described above. Young anticlines actively growing seaward from the main shelf break are forming a new break off Portlock Bank, southwest middle Albatross Bank, and Kiliuda Trough (Hampton and Bouma 1977) (Fig. 5-16B).

Second-order geomorphic features on the shelf include bedrock ridges, sand waves, and fault scarps. Ridges (hogbacks) occur where steeply inclined bedrock crops out at the sea floor and has undergone differential erosion of sandstone and mudstone intervals (Fig. 5-16C). Maximum relief of these features is about 5 meters.

Fields of large sand waves appear at three locations: in Stevenson Trough, on northern Albatross Bank, and between Chirikof and Trinity islands. Wave heights reach 15 m, and wave lengths reach 300 meters. Some of these waves are asymmetrical with the steepest side facing seaward, but some in Stevenson Trough face landward. Many of the waves in the field between Chirikof and Trinity Islands appear symmetrical. Smaller sand waves, on the order of a meter high, have been noted on side-scan sonographs at various places on the banks, but their extent has not been mapped.

Abrupt scarps are abundant in fault zones that offset the sea floor. A major fault zone extends along the southeast coast of Kodiak Island, both onshore and offshore, and continues some 600 km to Montague Island (Fig. 5-6) (Capps 1937; Moore 1967; von Huene, Shor, and Malloy 1972). Fault lengths range up to 60 km, and perhaps reach 140 km (Thrasher 1979; von Huene *et al.* 1980). Fault planes in this zone are steep and have either landward or seaward dip. The maximum sea-floor offset is about 10 m, but it varies significantly along the length of a fault. In fact, some of the faults merge with folds along the strike. Less extensive fault zones are associated with the belt of shelf-break folds along Portlock Bank and southern and middle Albatross Bank (Figs. 5-6 and 5-16D). More than 250 m of sea-floor offset occurs in one graben. Faults in this shelf-break zone die out and folds become broad and subdued on the intervening area of northern Albatross Bank. Individual, relatively short faults occur outside the prominent zones (von Huene *et al.* 1980).

The steep continental slope, seaward of the shelf, extends to abyssal depths of nearly 5,000 m where it meets the Aleutian Trench just west of 144° West. The slope is smooth in its upper portion, benchlike in its middle portion, and rough and steep in its lower portion (von Huene 1972). Several canyons incise the slope, but few traverse it entirely. The Alaska abyssal plain is relatively smooth but is interrupted by the Alaska seamount chain, which runs in a northwesterly direction (Gibson 1960).

Sediment Slides. Indications of sediment slides are rare on the Kodiak Shelf, whereas they are abundant on the adjacent upper continental slope (Figs. 5-7 and 5-16D) (Hampton and Bouma 1977; Self and Mahmood 1977). One feature in Stevenson Trough appears as small hummocks on the sea floor and has been interpreted as a possible slide

(Hampton 1983a). Slides have been reported by Self and Mahmood (1977) on the steep flanks of unidentified troughs southwest of Kodiak Island and south of Sitkinak Island, but exact locations were not given.

Hampton and Bouma (1977) described two types of slides on the upper continental slope. Large rotational slides (Varnes 1978), some of which cover an area of more than 100 km², have a curved slide surface that underlies a slide mass of up to a few hundred meters thick (Fig. 5-16D). They occur where there is a well-defined shelf-break arch and relatively large-scale folding off Portlock Bank and southern and middle Albatross Bank.

Smaller translational slides on the continental slope are detected in single seismic-reflection profiles at apparently random locations (Fig. 5-16E). These slides are characterized by a planar slide surface (Varnes 1978). The thickness of the slide mass is on the order of a few tens of meters.

Sediment

Stratigraphy and General Distribution. The thickness of sediment cover in local basins on the Kodiak Shelf is up to 200 m, and more than 400 m in Sitkinak Trough (Fig. 5-4). Bedrock is exposed on the banks and has a discontinuous thin veneer of shelly material in the valleys between hogback ridges. Thrasher (1979) constructed a surficial geologic map based mainly on seismic stratigraphy and supplemented by sediment samples. A poorly stratified unit located in the transverse troughs is interpreted as moraine. A discontinuously stratified unit, presumed to be of glacial, glacial-marine, and glacial-fluvial origin, occurs on the banks. Well-stratified soft sediment was mapped in the troughs and is underlain by the glacial unit. A unit distinguished by the presence of sand waves was mapped on the banks and in Stevenson Trough.

Texture and Composition. Hampton (1981, 1983a) presented a method of sediment classification for sea-floor sediment samples from the Kodiak Shelf. His method was more comprehensive than the textural scheme shown in Figure 5-5. The method employs Q-mode factor analysis and includes composition as well as texture. Five end-member sediment types were defined: 1) gravelly terrigenous material; 2) mud with abundant clay minerals and significant volcanic ash, fine carbonate, and siliceous microfossils; 3) sand-size volcanic ash; 4) clean terrigenous sand; and 5) shelly sand. Many deposits consist predominantly of one end-member sediment type, whereas others are composed of mixtures.

Clay-sized material constitutes only a small portion of most sediment samples; however, two suites of clay minerals have been identified (Hein, Bouma, Hampton, and Ross 1979). One suite is relatively rich in chlorite and kaolinite, whereas the other contains a relative abundance of illite. Two distinct sources of clay minerals are implied, and they are inferred to be 1) local bedrock and 2) the Copper River.

Volcanic ash is a major component of two sediment (*i.e.*, factor) types that occur on the sea floor in Kiliuda Trough, Chiniak Trough, and on the banks. It has a refractive index (1.485 ± 0.002) that is unique in this area to outfall from the

1912 eruption of Katmai Volcano on the Alaska Peninsula (Nayudu 1964; Pratt, Scheidegger, and Kulm 1973; and Hampton, Bouma, Frost, and Colburn 1979). Buried layers of volcanic ash with a different refractive index (*i.e.*, chemistry) have been identified in sediment cores, attesting to previous major eruptive events (Nayudu 1964; Pratt *et al.* 1973).

Hydrocarbon gas is an important secondary constituent of sediment samples at several localities (Hampton and Kvenvolden 1981). A high concentration of methane-rich biogenic gas was measured in samples from Kiliuda, Chiniak, and Sitkinak Troughs and from the continental slope. Anomalous acoustic returns beneath the sea floor appear in seismic-reflection profiles at many of the locations of gas-charged cores, although there is not a one-to-one correspondence between the anomalies and the gas. Several types of acoustic anomalies were identified. Some are similar to those associated with gas-charged sediment in other geographic areas (Schubel 1974; Nelson, Kvenvolden, and Clukey 1978) and are explainable by the known acoustic behavior of sediment that contains bubble-phase gas (Hampton and Anderson 1974; Holmes and Thor 1982). Bubbles in the water column that indicate a possible gas seep from the sea floor were seen near the west margin of middle Albatross Bank along the extension of a fault that offsets the sea floor (Fig. 5-17) (Hampton and Kvenvolden 1981). This gas could be coming from a deep thermogenic source, although no samples have been collected for chemical analysis. In addition, acoustic anomalies occur beneath the sea floor at this locality. The wide distribution of gas-charged cores and acoustic anomalies implies that high concentrations of gas are spread out beneath the Kodiak Shelf.

Physical Properties. In addition to grain size and mineral composition, physical properties have been determined for three sediment types:

- 1) terrigenous sandy mud from Sitkinak Trough, Chiniak Trough, and the upper continental slope
- 2) diatom-rich terrigenous mud from Kiliuda Trough
- 3) sand-sized volcanic ash from Chiniak Trough (Hampton 1983b) (Table 5-2).

Properties are coherent within deposits of the three sediment types but show significant variation between types. Appropriate cores could not be collected from sediment types such as the gravelly terrigenous material and the shelly sand, so no physical-property determinations were made for them.

The cores of terrigenous sandy mud have physical properties that are generally within normal ranges for terrigenous marine sediment samples from elsewhere, except that several samples exhibit low compressibility (*cf.* Richards 1962; Richards and Hamilton 1967; and Keller, Lambert, and Bennett 1979). The reason for the low compressibility is not evident, but the implication is that the sediment would experience relatively small settlement when subjected to loads. The fine-grained sediment in Kiliuda Trough, with its mixture of terrigenous and siliceous-biogenic components, has high water content, low grain specific-gravity, and low bulk density. This indicates a small increase of overburden stress with depth of burial and a subsequent small increase of dependent properties such as consolidation state and shearing strength. However, compression index values are the highest measured on the Kodiak Shelf, which implies a relatively large amount of compaction under a static load. The sediment is highly plastic and, compared

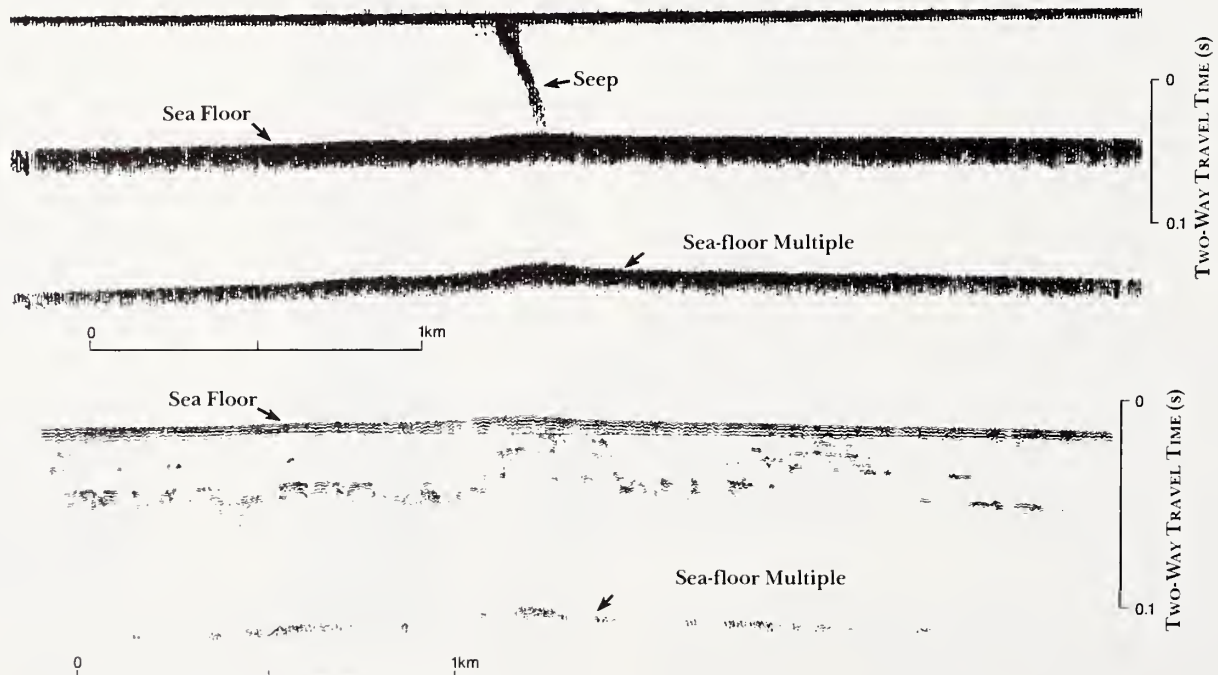


Figure 5-17. Seismic-reflection profiles at $57^{\circ}01.1'N$, $152^{\circ}10.3'W$ on the Kodiak Shelf showing gas seep from the sea floor (upper, 12-kHz profile) and acoustic anomalies in the form of offset, jumpy reflectors beneath the sea floor (lower, boomer profile). (Modified from Hampton and Kvenvolden 1981.)

Table 5-2. Summary values of geotechnical properties for three sediment types on the Kodiak Shelf. Range, average, and (number of values) are shown. (Compiled from Hampton 1983b.)

SEDIMENT TYPE	WATER CONTENT AT 1m (% dry wt)	PLASTIC LIMIT (wt %)	LIQUID LIMIT (wt %)	PLASTICITY INDEX (wt %)	GRAIN SPECIFIC GRAVITY (g/cm ³)	BULK DENSITY AT 1 m (g/cm ³)	VANE SHEAR STRENGTH AT 1 m (kPa)	COMPRESSION INDEX	S _u /σ' _o ^a	φ ^b (degrees)
Terrigenous	21-48	13-28	16-73	3-43	2.52-2.85	1.74-1.95	5-20	0.06-0.79	0.3-6.7	26-50
	37 (16)	22 (44)	39 (44)	18 (44)	2.72 (70)	1.85 (14)	12 (5)	0.28 (17)	1.2 (32)	38 (32)
Diatom-rich terrigenous	91-147	48-77	82-132	32-65	2.39-2.95	1.34-1.48	3-20	0.37-1.17	0.4-22.9	41.5-4
	115 (12)	60 (20)	106 (20)	45 (20)	2.58 (74)	1.40 (8)	14 (9)	0.70 (10)	4.8 (12)	46 (12)
Volcanic ash	67-93				2.17-2.35	1.39-1.53		0.07-0.12	2.9-16.1	46-62
	80 (6)				2.30 (21)	1.46 (3)		0.10 (2)	7.6 (3)	54 (3)

^a Strength to overburden ratio, determined from static triaxial shear tests.

^b Effective angle of internal friction, determined from static triaxial shear tests.

with other sediment of similarly high plasticity, it is relatively strong under conditions of undrained loading. These properties are similar to the properties of sediment in the northeastern Gulf of Alaska (Hampton 1983b; Lambe and Whitman 1969: p.307).

Physical properties values for the sand-sized ash in Chiniak Trough are different in most respects from the other sediment types. The clay content is low, so the sediment classifies as nonplastic. Its water content is lower than that of the fine-grained sediment from Kiliuda Trough, but due to the low specific gravity of the ash grains, the bulk density is comparable. In contrast to the samples from Kiliuda Trough, the Chiniak Trough material is incompressible, similar to the mixed terrigenous sediment type. High static shearing strength was measured for the ash-rich deposit, under conditions of both drained and undrained loading (*i.e.*, under loading conditions where the pore fluids were either allowed to escape or were prevented from escaping). These conditions correspond to both slow and rapid loading situations in the natural setting. However, cyclical loading causes severe strength degradation (up to 12% of the static undrained strength at 10 cycles of loading) (Fig. 5-18). This is representative of the number of load cycles experienced during a moderate earthquake (Hampton 1983b; *cf.* Lee *et al.* 1981; and Anderson, Pool, Brown, and Rosenbrand 1980).

Sedimentary Processes

Pleistocene glaciers eroded the broad banks on the Kodiak Shelf, and localized ice streams carved the transverse troughs—except perhaps in the case of the Sitkinak Trough, which does not connect with or extend to any reasonable source for an ice stream. This trough might have formed as a shelf-edge submarine canyon prior to ice advance and might have then been modified by glacial action. The hogback ridges on the banks are more easily explained by subaerial erosion than by ice erosion, so it is likely that portions of the banks were ice free and exposed to fluvial processes at some point.

Ice-related processes deposited poorly sorted and generally coarse-grained material on the banks and in the troughs. Thrasher (1979) mapped linear mounded deposits (that are lateral) and end moraines along the edges and across the mouth of the troughs, respectively. The blanket-like deposits that cover the banks and underlie the stratified soft sediment in the troughs were interpreted as ground moraine, glacial-marine, and glacial-fluvial deposits.

Glacial deposits were reworked during the Holocene transgression. Sediment that eroded from the banks moved laterally into the troughs, narrowing them considerably. The seismic-reflection profile in Figure 5-16A (similar to others collected elsewhere along trough margins) shows inclined reflectors of a prograding sediment wedge along

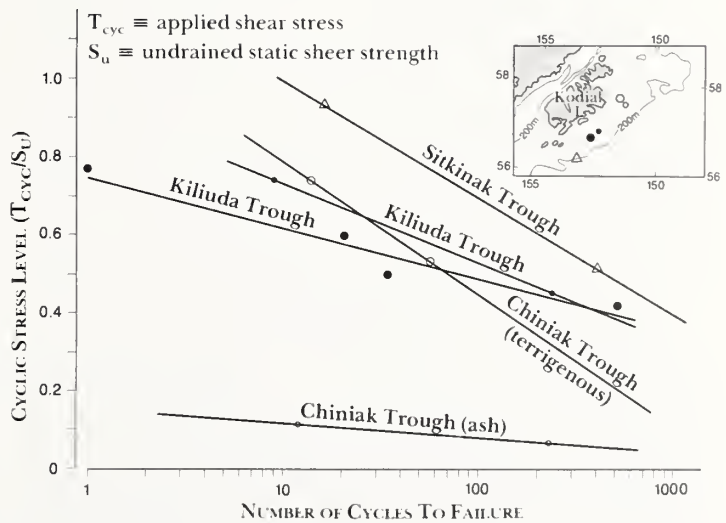


Figure 5-18. Cyclic stress level versus number of cycles to failure for tests run on sediment samples from the Kodiak Shelf. Cyclic stress level indicates the amount of strength degradation under conditions of repeated loading, compared with conditions of static loading. (Modified from Hampton 1983b.)

the edge of Chiniak Trough. The wedge appears to be composed of sediment that was derived from the thin veneer of glacial sediment above truncated bedrock on the adjacent bank.

The influx of sediment under present-day conditions is low, because no large rivers drain onto the Kodiak Shelf. Clay-mineral analysis suggests that the Copper River and local submarine outcrops provide minor clastic material. Layers of ash from strong volcanic eruptions such as the Katmai event in 1912 occasionally are deposited on the shelf. Biogenic sources provide some siliceous and carbonate shell debris. The sedimentary regime consists mainly of reworking, with large storm waves probably being a more important influence than the relatively weak geostrophic currents that impinge on the shelf. Fine-grained material is winnowed from the glacial material on the banks and, along with the siliceous biogenic and volcanic grains, is deposited in the quiet environments within the troughs and in the minor depressions on the banks (Hampton 1983a).

The geometry of these sedimentary deposits, as seen in seismic-reflection profiles, shows that sediment is being transported into the troughs mainly from the east. This must reflect the dominant sediment-transporting current direction of the shelf. A notable exception is Sitkinak Trough, where seismic-reflection profiles show that sediment is the thickest and the most steeply inclined on the west side. This is surprising, because the core of the swift Alaska Stream flows toward the west just seaward from where the profiles were collected. Perhaps a bathymetrically guided, contour-parallel current, such as the one in Chiniak Trough described by Lagerloef (1983), exists in Sitkinak Trough and controls sediment deposition. That is, the Alaska Stream might branch, flow up the northeast side of the trough, and return down the southwest side, depositing more sediment on that side.

The distribution of ash from the Katmai eruption reflects the original outfall pattern and post-depositional redistribution. The end-member sediment type composed of sand-sized ash occurs from middle Albatross Bank to Stevenson Trough (Hampton *et al.* 1979; Hampton 1983a). This distribution corresponds to the original atmospheric dispersal pattern, which was southwesterly across the shelf (Wilcox 1959). Finer-grained ash is a component of the mud end-member sediment type, which is widespread and occurs in quiet depositional settings such as the troughs. This material probably has been reworked from the original outfall and redeposited in low-energy settings.

The large sand waves are evidence of high-energy, bed-load transport, but they might have formed during an earlier time of strong currents (*i.e.*, the transgression). A layer of Katmai ash, buried about 10 cm beneath the sea floor, was sampled at one station in the Stevenson Trough sand-wave field, a fact that implies that some significant sediment transport has occurred recently in this area. This activity was probably induced by storm waves, because oceanographic observations show no indications of strong geostrophic current activity in this or the other fields of large sand waves (Muench and Schumacher 1980).

The scarcity of sediment slides indicates that sediment on the Kodiak Shelf is gravitationally stable. This stability is

accounted for by the presence of relatively strong, coarse-grained sediment on those sloping portions of the sea floor and by the gentle sea-floor slopes in general. The sediment beneath the steepest slopes of Sitkinak Trough is potentially unstable under both static and earthquake loads, according to an infinite-slope analysis by Hampton (1983b). The sediment slides identified in this general vicinity by Self and Mahmood (1977) confirm this. The sand-sized ash deposits in the Chiniak Trough are exceptionally weak under repeated loading conditions and could liquefy and lose bearing capacity during storms or earthquakes. But the sediment is unlikely to slide laterally because it rests on flat sea floor.

The sediment slides on the upper continental slope attest to unstable conditions there. Analysis by Hampton, Bouma, Carlson, Molnia, Clukey, and Sangrey (1978) indicates that earthquakes and faults that remove support are the likely causes of the large rotational slumps. The small translational slides have not been analyzed geotechnically, but the planar geometry of the slide surface implies that weak sediment layers control sliding, although earthquakes might act as a triggering mechanism.

Cook Inlet

Geomorphology

Cook Inlet is separated from the Kodiak Shelf by Kennedy and Stevenson Entrances (Fig. 5-1). A detailed bathymetric map by Bouma (1981) shows rugged sea floor both approaching and within these passages. The depth within individual basins reaches 200 meters. The rough topography appears to be partly due to faulting and partly due to glacial erosion. A sill at 120-m depth extends across the entrances.

Cook Inlet is 90 km wide across its mouth, which extends from Cape Douglas to the Kenai Peninsula. The overall length of Cook Inlet is 275 km, with two significant extensions, Knik and Turnagain Arms, reaching another 70 km to the north and east, respectively (Fig. 5-1). Kamishak and Kachemak Bays indent the west and east coasts, respectively, near the southern end of the Inlet. Insular Mount Augustine is located in Kamishak Bay, and elongate Kalgin Island is situated 30 km south of the Forelands. Cook Inlet is divided into two parts, upper Cook Inlet north of the Forelands and lower Cook Inlet south of the Forelands.

The sea floor at the mouth of Cook Inlet has a relatively deep trough (~170 m) that terminates northward against an arcuate ramp that rises to a water depth of less than 70 meters. A narrow channel extends northeast up the center of the Inlet. The channel is bordered on each side by a steep slope that in turn is bordered by a wide-to-narrow shelf adjacent to land (Bouma, Hampton, Frost, Torresan, Orlando, and Whitney 1978; Bouma 1981). The channel bifurcates around Kalgin Island and extends between the Forelands where the Inlet narrows to its minimum of 20 kilometers. North of the Forelands the Inlet is fairly uniform in width (30 km) and the sea floor is shallow, generally less than 40 m (Sharma and Burrell 1970).

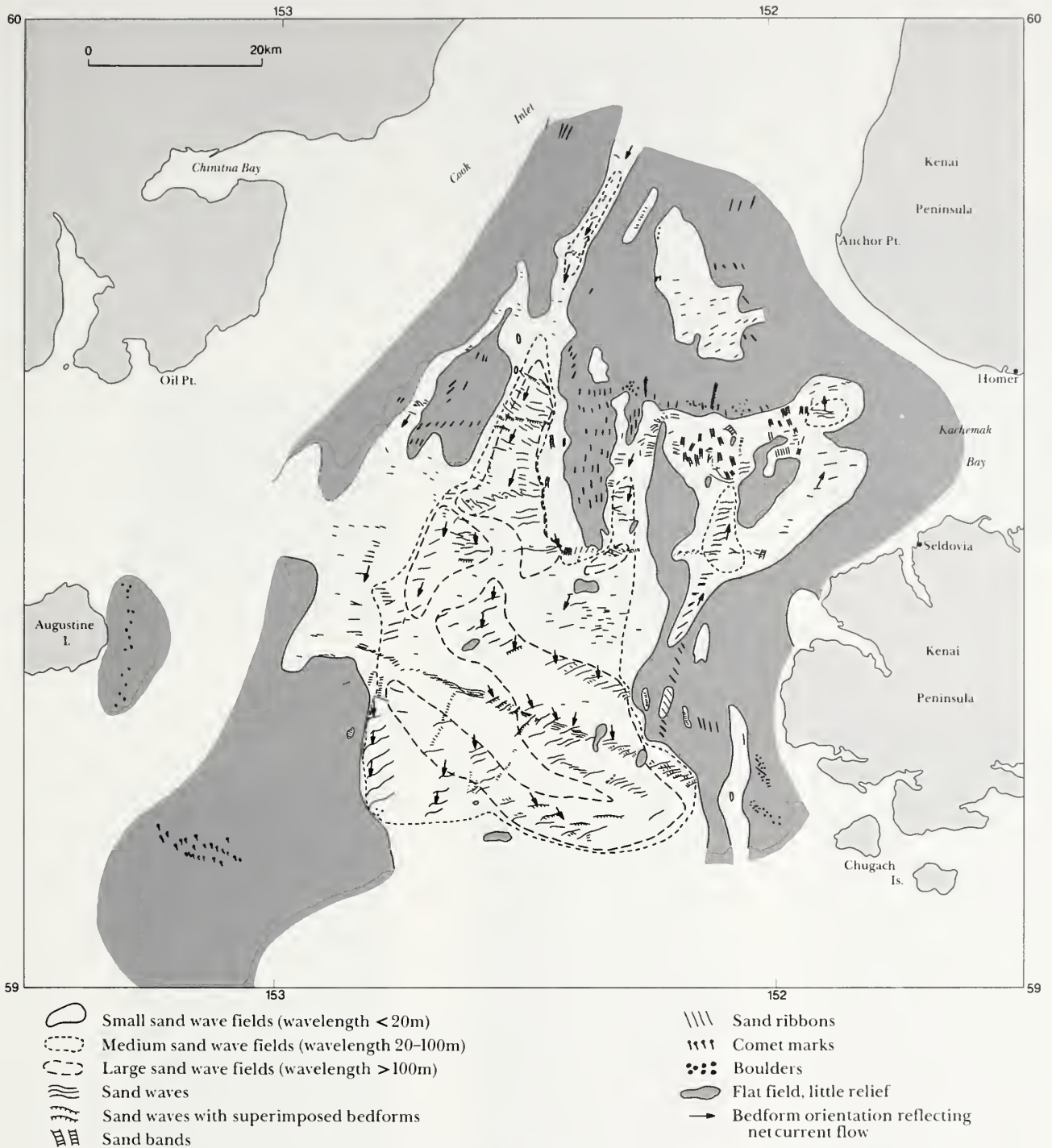


Figure 5-19. Distribution of bedforms in lower Cook Inlet. (Modified from Orlando 1984.)

The sea floor in the central part of lower Cook Inlet is covered by a variety of bedforms (Fig. 5-19). Numerous publications have reported on the classification, morphology, distribution, and dynamics of these features (e.g., Bouma, Hampton, and Orlando 1977; Bouma, Hampton, Wenekens, and Dygas 1977; Bouma, Hampton, Frost, Torresan, Orlando, and Whitney 1978; Bouma, Hampton, Rapoport, Whitney, Telaki, Orlando, and Torresan 1978; Bouma, Rapoport, Gacchione, Drake, Garrison, Hampton, and

Orlando 1979; Bouma, Rapoport, Orlando, and Hampton 1980; Whitney, Noonan, Bouma, and Hampton 1980; Mahmood, Ehlers, and Cilweck 1981; Rapoport 1981; and Orlando 1984).

Listed below are descriptions of the major bedform types that have been observed in lower Cook Inlet (Orlando 1984):

Sand waves (Fig. 5-20A) are wavy accumulations of sand with a straight or sinuous crest oriented perpendicularly to current flow. Wave height ranges to 14 m in lower Cook Inlet

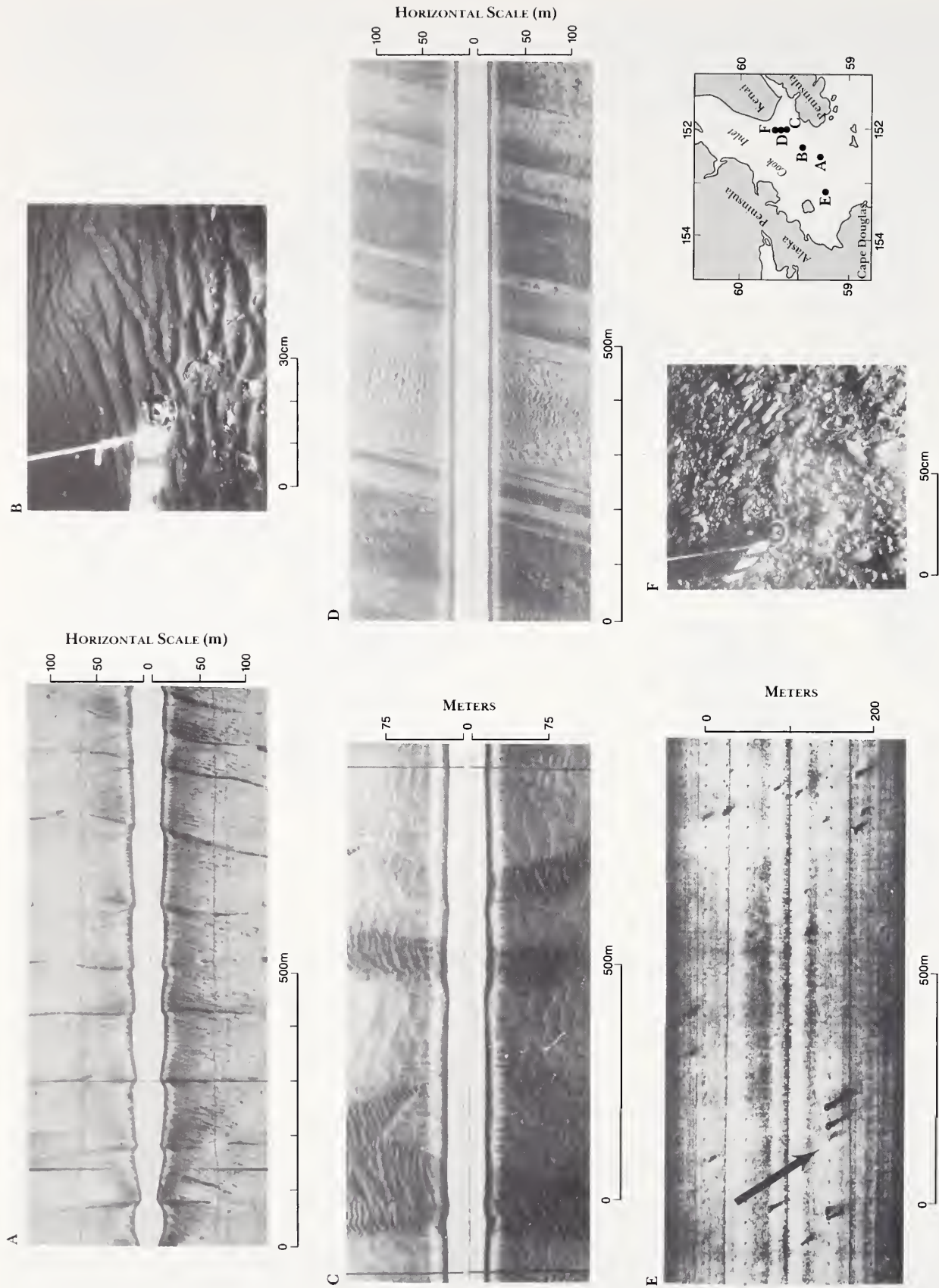


Figure 5-20. Side-scan sonographs and photographs in lower Cook Inlet (from Orlando 1984).

A. Sonograph of large sand waves with smaller superimposed sand waves.

B. Photograph of sea-floor ripples.

C. Sonograph of sand bands.

D. Sonograph of sand ribbons.

E. Sonograph of comet marks. Arrow denotes inferred current direction.

F. Photograph of sea-floor in area of hard bottom.

and wave length ranges to 950 meters. Sand waves are further classified as small (wave length <20 m), medium (wave length 20–100 m), and large (wave length >100 m). Length-to-height ratio typically exceeds 20 to 1, but a ratio as low as 10 to 1 has been reported (Rappeport 1981). Small and medium sand waves can be superimposed on large sand waves and other bedforms such as sand ribbons.

Ripples (Fig. 5–20B) are small wavy forms in sand with heights less than 10 cm and wave lengths less than 20 centimeters. These small bedforms are detectable only with photographic or television systems.

Sand bands (Fig. 5–20C) are fields of sand waves elongate in the direction of flow and relatively sharply bounded by fields of other sand waves of different size. A sand band may be straight and have parallel sides, but it also can bifurcate.

Sand ribbons (Fig. 5–20D) are narrow, typically thin (<1 m), current-parallel bodies of sand overlying hard bottom (see below). Sand within a ribbon commonly is formed into small, transverse- to oblique-trending sand waves.

Comet marks (Fig. 5–20E) are scour depressions extending down-current from obstructions to flow, such as large boulders.

Hard bottom (Fig. 5–20F) is more-or-less flat sea floor covered with a gravel pavement.

Sediment

Stratigraphy and General Distribution. The nature of the sediment on the sea floor of Cook Inlet is known from samples collected throughout the entire area (Sharma and Burrell 1970; Hampton 1982a). However, the features of the sedimentary units beneath the sea floor and above the regional unconformity are known only for lower Cook Inlet, where extensive seismic-reflection profiling has been done (Rappeport 1981).

Four seismic-stratigraphic units were identified in seismic-reflection profiles throughout lower Cook Inlet by Rappeport (1981):

- 1) The first (and lowest) unit is 75 m thick and is characterized by irregular and discontinuous reflectors. It was interpreted to be composed of unsorted glacial debris such as ground moraine.
- 2) The second unit is thin (<3 m) with a strong reflector at the lower boundary but with no other internal reflectors, and is interpreted to be a layer of outwash.
- 3) The third unit (up to 20 m thick) has large sand waves, both at the sea floor and buried beneath it. The sediment type is well-sorted sand with some shells, and occurs in areas of high-energy currents.
- 4) The fourth (uppermost) unit is up to 75 m thick, has well defined, continuous reflectors and was interpreted as glacial-marine, glacial-fluvial, or glacial-lacustrine deposits. Rappeport (1981) did not map the distribution of these units.

Texture and Composition. The coarsest sediment in Cook Inlet is in the area of the Forelands, where gravelly deposits occur that include boulders up to a few meters in

size (Geopfert 1969). The grain size decreases in both directions away from there. The sediment grades to sand that generally is fine-grained and well sorted in upper Cook Inlet (Sharma and Burrell 1970). South of the Forelands, in lower Cook Inlet, sand- and gravel-sized material is dominant (Bouma and Hampton 1976; Orlando and Martin 1981; and Hampton 1982a). Mean grain size generally decreases from north to south and shows certain associations with bathymetry and physiography. The most abundant size class is sand (0.0625–2 mm). Sediment covering the central area, including the trough and the ramp, contains more than 80% sand-sized grains. The greatest amount of gravel-sized sediment (>2 mm) occurs to the north, toward the Forelands. Mud-sized material (<0.0625 mm) occurs largely to the south, particularly in the deep water south of the ramp and along the Inlet's borders.

The textural classification map (Fig. 5–5) indicates that gravel with mud (gravelly mud, muddy sandy gravel, and gravelly muddy sand) blankets the borders of the Inlet. Sand with gravel (gravel, sandy gravel, and gravelly sand) occurs in the central area. Sand is found in and flanking the central trough and on the ramp. Silty sand was sampled at a few scattered locations, and sandy silt occurs in the deep water south of the ramp, along with some sand and gravelly sand.

Sediment along the coast of lower Cook Inlet has a wide range of grain size (Hayes and Michel 1982). Most beach sediment is a mixture of sand and gravel, but clasts up to several meters in size lie at the base of erosional scarps, whereas fine sand and silt occur on low-energy tidal flats.

The sand grains in lower Cook Inlet contain an abundance of microtextural features that are interpreted to be of glacial origin (Hampton, Bouma, Torresan, and Colburn 1978). These features either occur alone or are overprinted by inferred chemical and mechanical-impact features. Grains that exhibit glacial features are most common in the northern areas, while those exhibiting mechanical-impact features are most common in the central area of large wavy bedforms where high-energy bed-load transport occurs. Those grains exhibiting chemical features are dominant in southern areas and in protected areas around the edge of the Inlet, where current energy is relatively low.

Suspended Sediment. The distribution, the elemental composition, and the sedimentation patterns of suspended sediment in Cook Inlet have all been described using a variety of techniques, including: 1) satellite studies (Sharma *et al.* 1974; Gatto 1976; and Burbank 1977); 2) water-column process studies (Feely, Massoth, Paulson, Lamb, and Martin 1981; Feely and Massoth 1982; and Feely, Chester, Paulson, and Larrance 1982); and 3) sediment studies (Sharma and Burrell 1970; Bouma and Hampton 1976; Hein *et al.* 1979; and Atlas, Venkatesan, Kaplan, Feely, Griffiths, and Morita 1983). Hein *et al.* (1979) identified two end-member suites of clay minerals in one lower Cook Inlet sea-floor sediment. One suite is relatively rich in chlorite + kaolinite and the other is rich in illite. The former occurs in northern and western areas and is derived from rivers at the head of Cook Inlet, whereas the latter occurs in eastern and southern areas and is derived from the Copper River.

The suspended material from upper and western Cook Inlet has nearly the same elemental composition as the suspended sediment from the Susitna, Knik, and Matanuska Rivers that enter the head of Cook Inlet (Table 5-3). This is especially true for the major rock-forming elements (Al, K, Ti, and Fe), which are primarily associated with aluminosilicate minerals of terrestrial origin (Price and Calvert 1973).

The distribution of suspended matter throughout the water column is characterized by horizontal gradients that reflect both the estuarine and the embayment characteristics of the flow patterns in lower Cook Inlet (Fig. 5-21). On the eastern side of the Inlet, the concentration of suspended matter is relatively low, ranging from 0.5 mg/l near the tip of the Kenai Peninsula to about 5 mg/l off Cape Ninilchik. On the western side of the Inlet, the water properties are characterized by low salinity and very high suspended-matter concentrations that range to more than 50 mg/l just north of Tuxedni Bay. Throughout most of this region the water column is virtually unstratified, and tidal currents are sufficiently high to resuspend almost all fine-grained sediment (Fig. 5-22).

Sedimentary Processes

The Cook Inlet sedimentary environment is characterized by strong tidal currents and sediment reworking. The Susitna, Knik, and Matanuska Rivers at the head of the Inlet provide a large supply of sediment, much of which travels in suspension and bypasses the Inlet entirely.

Sand-sized grains from these sources, however, settle to the sea floor within about 25 km of the head of the Inlet (Sharma and Burrell 1970).

The gravelly sediment farther south and extending past the Forelands appears to be winnowed relict glacial material. The dominantly glacial microtextures on sand-grain surfaces support this idea. The currents are strong in this area because the Inlet is narrow and the net circulation is south. Therefore, most of the winnowed sediment moves into lower Cook Inlet where the coarser sand-sized grains are deposited in the central area of large sand waves (Fig. 5-19). Reflectors beneath the arcuate ramp incline to the south, attesting both to the net southerly transport of bed-load sand and to the southerly progradation of this sediment body (Hampton *et al.* 1978). Sand grains from the area

Table 5-3.

Averaged 1977-1978 chemical composition data (expressed as weight %, $\pm 1\sigma$) and elemental ratios for surface suspended-matter samples from selected regions in Cook Inlet and Shelikof Strait (data from Feely and Massoth 1982).

REGION	NUMBER OF SAMPLES	Mg	Al	Si	K	Ca	Ti	Fe	BIOGENIC Si	ESTIMATED ALUMINO-SILICATE
Susitna-Knik-Matanuska River Systems	13	3.73 ± 0.61	10.39 ± 2.03	33.41 ± 3.42	2.26 ± 0.63	1.98 ± 0.58	0.607 ± 0.059	6.39 ± 0.40	0.00	104
Kalgin Island-upper Cook Inlet	9	3.05 ± 0.61	8.59 ± 1.91	28.57 ± 6.05	1.95 ± 0.38	1.73 ± 0.38	0.505 ± 0.085	5.33 ± 0.90	0.94	86
Kamishak Bay	5	3.69 ± 0.59	9.84 ± 1.66	34.82 ± 3.76	2.09 ± 0.36	1.77 ± 0.25	0.483 ± 0.084	5.31 ± 0.79	3.15	98
Kachemak Bay	6	2.15 ± 1.02	4.85 ± 2.78	30.38 ± 8.72	0.81 ± 0.53	1.74 ± 0.95	0.287 ± 0.159	2.95 ± 1.68	14.75	49
Kennedy-Stevenson Entrances	9	1.68 ± 1.11	3.91 ± 2.55	27.82 ± 5.48	0.65 ± 5.48	1.36 ± 0.48	0.205 ± 0.55	2.03 ± 0.126	15.24 ± 1.58	39
NW Shelikof Strait	6	2.98 ± 0.73	7.02 ± 2.14	33.46 ± 4.01	1.32 ± 0.47	1.71 ± 0.55	0.353 ± 0.118	3.64 ± 1.32	10.87	70
Copper River	5	4.65 ± 0.17	9.25 ± 0.19	27.91 ± 0.54	1.78 ± 0.03	4.42 ± 0.09	0.638 ± 0.013	6.70 ± 0.16	0.00	93

REGION	Mg/Al	Si/Al	K/Al	Ca/Al	Ti/Al	Fe/Al	K/Ca
Susitna-Matanuska-Knik River System	0.359	3.22	0.218	0.191	0.058	0.615	1.14
Kalgin Island-upper Cook Inlet	0.355	3.33	0.218	0.201	0.059	0.621	1.13
Kamishak Bay	0.375	3.54	0.212	0.182	0.049	0.540	1.17
Kachemak Bay	0.443	6.26	0.167	0.359	0.059	0.608	0.47
Kennedy-Stevenson Entrances	0.430	7.12	0.166	0.348	0.052	0.519	0.48
NW Shelikof Strait	0.424	4.77	0.188	0.244	0.050	0.519	0.77
Copper River	0.503	3.01	0.192	0.478	0.069	0.724	0.40

NOTE: Excess (biogenic) Si% was determined relative to Susitna-Knik-Matanuska River System Si/Al value of 3.22. Estimated aluminosilicate % values were obtained by multiplication of respective regional Al% by 10 (after Sackett and Arrhenius 1962).

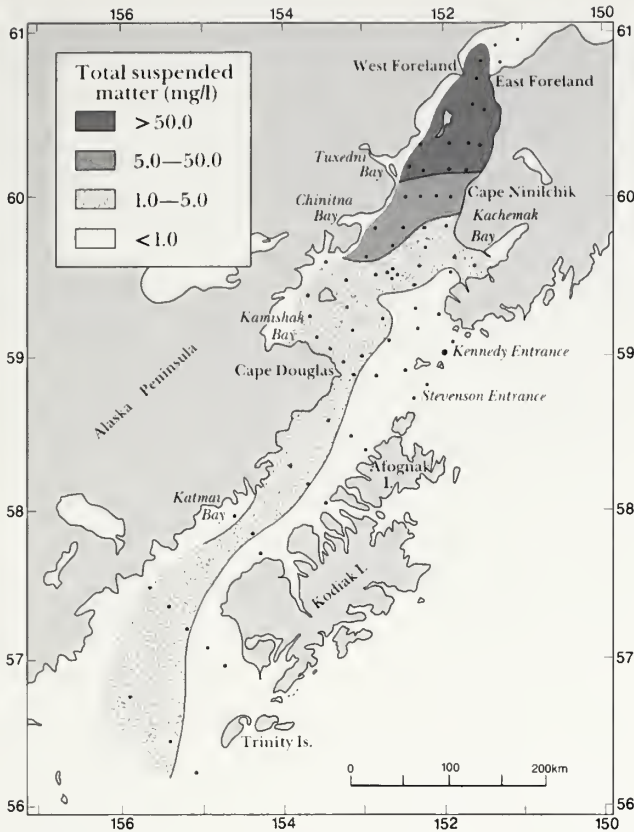


Figure 5-21. Distribution of total suspended matter in surface water of lower Cook Inlet and Shelikof Strait, 4 to 16 April 1977. (Modified from Feely and Massoth 1982.)

show abundant abrasional microtextural features acquired during this transport. Southerly transport is further indicated by the asymmetry of the large sand waves; the steep side of most waves faces south (Bouma, Hampton, and Orlando 1977; Orlando 1984).

Rappeport (1981) analyzed current velocities recorded over a three-month period in lower Cook Inlet during the summer of 1978. He reported that currents reached their maximum speed in the ebb direction. Also, current speeds near the sea floor were greatest at the crest of a large sand wave compared to speeds near the trough. Currents exceeded the theoretical threshold velocity necessary to initiate sediment transport about 35% of the time. This fact was supported by television observations made at the start of the study period, which showed that sediment movement took place only during 1 to 1.5 hours around peak ebb and flood currents (Bouma *et al.* 1979).

Rappeport (1981) also calculated sediment transport rates and deduced that the largest sand waves might migrate only 30 to 40 cm/yr, which equals one wave length every 500 to 600 years. This slow rate was corroborated in a study by Whitney *et al.* (1979), which compared sand-wave positions on side-scan sonographs taken four years apart over coincident tracklines. No net movement greater than 10 m (the precision of the comparison) could be detected.

Two alternative conclusions can be drawn from these studies: 1) the sand waves are virtually inactive under the present hydraulic regime and their morphology is relict

from a lower position of sea level, or 2) they move more today during periods of extreme current conditions, such as during large storms or spring runoff, but move at a slow rate that cannot be observed over a short period of years.

The protected areas around the boundaries of lower Cook Inlet have a relatively low sedimentation rate, and mud is deposited where the sea floor evidently is shielded from intense currents even though the water depth is shallow. Mud is also deposited in deeper areas south of the ramp where there is a higher sedimentation rate. Sand grains in these environments typically show chemically induced microtextures. A relatively low sediment accumulation rate is inferred in areas where glacial debris is still exposed on the sea floor (*e.g.*, gravelly mud, muddy sandy gravel, and gravelly muddy sand, Fig. 5-5). Higher accumulation rates are inferred where the glacial debris has been completely covered by a blanket of sediment. This sediment is made up of material in which the coarsest size grade is sand (*e.g.*, silty sand and sandy silt, Fig. 5-5).

A few geological studies have been conducted in coastal areas of Cook Inlet. Hayes, Michel, and Brown (1977) classified 1,216 km of the lower Cook Inlet coastline into three categories: 1) erosional (45%), 2) neutral (38%), and 3) depositional (17%). They conducted their studies as part of an effort to evaluate the oil-spill vulnerability of the coastal environments. Rocky headlands and other areas where there is evidence of coastal retreat were classified as erosional shorelines. Embayments that are backed by mountains or hills were classified as neutral shorelines. Depositional shorelines included spits, deltas, and bayhead zones.

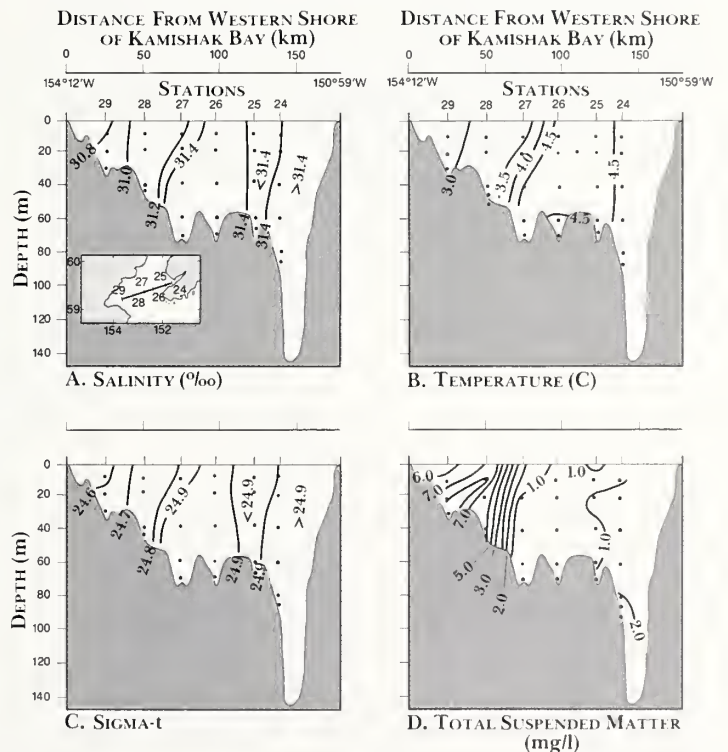


Figure 5-22. Vertical cross sections of salinity, temperature, density, and total suspended matter for six stations between Kamishak and Kachemak Bays in lower Cook Inlet, 4 to 16 April 1977. (Modified from Feely and Massoth 1982.)

Hayes and Michel (1982) concluded that sedimentation along depositional shorelines in lower Cook Inlet is related to the tectonic setting. High-gradient streams deliver abundant heterogeneous mixtures of sediment from actively rising, glaciated mountains northwest and southeast of the Inlet. Wave action is the most important process in shaping sedimentary deposits along the shoreline. Lobate fan deltas form where sediment-laden streams empty along sections of coast that are exposed to high wave energy. Arcuate-cuspate deltas form where similar streams enter areas of low wave energy. The effects of the large tidal range are not evident in the deposits of coarse-grained coastal sediment. Recurved and cuspate spits build along a few sections of shoreline where coarse sediment extends into deeper water.

Jordan (1962) analyzed repeated bathymetric surveys of the surface of a tidal flat near Anchorage. The studies were conducted from 1910 to 1959 and showed that significant net erosion and a 2.8-km retreat of the tidal flat occurred during that period. Tidal scour was proposed as a possible reason for the retreat, but earthquake-triggered slumping was mentioned as an alternative possibility.

The major controlling forces affecting suspended-matter distribution and transport in the Inlet are the strong semidiurnal tidal currents. These currents are augmented by estuarine and embayment circulation patterns. Clear, saline water transports chlorite-rich aluminosilicate material and biogenic matter from the Gulf of Alaska into the mouth of the Inlet along the east coast. Part of the material settles to the bottom in outer Kachemak Bay, and the rest is transported across the Inlet and eventually mixes with the outflowing turbid water (Fig. 5-21). The outflowing estuarine water that originates in upper Cook Inlet carries a large amount of suspended sediment and flows south along the west coast. The horizontal concentration gradient in this region is primarily due to dilution of the turbid estuarine water by the relatively clean oceanic water from the Gulf of

Alaska. Some of the sediment settles out in the Kamishak Bay region, and the remainder is transported past Cape Douglas into Shelikof Strait.

The elemental data for the suspended material provide more detailed information about the principal sources of suspended material in the Inlet (Table 5-4). The high concentration of the major rock-forming elements indicates that aluminosilicate minerals are the predominant phases in suspension, ranging from ~50% in outer Kachemak Bay to 98% in Kamishak Bay. The remaining material consists of organic material and biogenic tests of microscopic organisms. Furthermore, the K/Ca and Ca/Al ratios in the suspended matter provide further evidence that the Susitna-Knik-Matanuska River system is the principal source of the illite-rich aluminosilicate material in the Kalgin Island and Kamishak Bay regions, whereas the Copper River is the primary source of the aluminosilicate fraction in the suspended matter in the regions of Kennedy Entrance and outer Kachemak Bay.

Shelikof Strait

Geomorphology

The trough at the mouth of Cook Inlet continues into the parallel-sided Shelikof Strait (Fig. 5-2). The Strait itself is 200 km long and 50 km wide. The coastline on both sides of the Strait is indented with silled fjords. Adjacent to land are shallow (<50 m) shelves. Seaward, the sea floor slopes at between 1 and 4° to the bottom of the central trough.

The trough is 30 to 35 km wide. It extends the entire length of the Strait and then curves across the continental shelf to the shelf break west of Chirikof Island (Fig. 5-2). Morphologically, the floor of the trough consists of a plat-

Table 5-4.

Summary of the elemental composition of particulate matter from lower Cook Inlet and Shelikof Strait (R/V *Acona*-245, 28 June-12 July 1977). Precision is given at the 1 σ level (from Feely, Massoth, Paulson, Lamb, and Martin 1981).

ELEMENT	LOWER COOK INLET				SHELIKOF STRAIT			
	AVERAGE OF 50 SURFACE SAMPLES		AVERAGE OF 51 SAMPLES FROM 5 m ABOVE THE BOTTOM		AVERAGE OF 17 SURFACE SAMPLES		AVERAGE OF 16 SAMPLES FROM 5 m ABOVE THE BOTTOM	
C (wt%)	10.77 ±	11.0	6.18 ±	9.10	31.17 ±	11.2	8.40 ±	5.8
N (wt%)	1.98 ±	2.0	0.99 ±	1.4	4.89 ±	1.5	1.24 ±	0.8
Mg (wt%)	2.86 ±	1.41	3.59 ±	0.82	1.89 ±	0.91	4.01 ±	1.22
Al (wt%)	6.98 ±	4.24	8.88 ±	2.34	3.72 ±	2.46	9.49 ±	1.22
Si (wt%)	35.75 ±	5.56	38.09 ±	4.92	28.67 ±	10.10	44.71 ±	3.60
K (wt%)	1.86 ±	0.86	2.24 ±	0.45	0.89 ±	0.43	2.19 ±	0.63
Ca (wt%)	1.84 ±	0.63	2.23 ±	0.32	1.54 ±	0.35	2.08 ±	0.33
Ti (wt%)	0.46 ±	0.20	0.58 ±	0.10	0.27 ±	.09	0.53 ±	0.12
Cr (ppm)	99 ±	30	115 ±	24	75 ±	36	116 ±	29
Mn (ppm)	1138 ±	574	1460 ±	362	981 ±	709	4174 ±	7642
Fe (wt%)	5.14 ±	2.11	6.50 ±	0.95	3.15 ±	1.14	6.39 ±	1.71
Ni (ppm)	70 ±	25	81 ±	16	59 ±	19	77 ±	13
Cu (ppm)	99 ±	33	100 ±	31	94 ±	27	112 ±	30
Zn (ppm)	352 ±	158	343 ±	194	—	—	—	—
Pb (ppm)	65 ±	19	69 ±	13	60 ±	10	76 ±	22

form bordered by marginal channels. The platform is generally smooth and is gently inclined from 160 m at the northeast end of the Strait to 200 m at the southwest end. Two areas of major escarpments rise from the platform in the vicinity of 58°45'N, 153°00'W and 58°28'N, 153°28'W (Figs. 5-6 and 5-23A), with maximum sea-floor offset in excess of 100 meters. Both escarpments have a depression (moat) with a relief of 20 to 40 m adjacent to their southeast side.

The marginal channels are up to 300 m deep and have closed depressions. The southeast marginal channel extends the entire length of the Strait, whereas the northwest channel begins about 60 km down the Strait.

Bedforms and other small topographic features cover a limited area of the sea floor within the Strait. Only a single occurrence of small sand waves, covering an area less than

0.02 km², appears in side-scan sonographs. Comet marks, continuous with those in lower Cook Inlet, occur at the head of the Strait and trend southwest down the Strait. A few boulders, with no associated comet marks, appear in side-scan sonographs. Circular depressions (pockmarks), typically 50 m in diameter and 5 m deep, are dispersed over an area of 1,500 km² on the southwest part of the central platform.

Other than the features mentioned above, the sea floor of Shelikof Strait is remarkably smooth. Fields of the large wavy bedforms that exist in other areas of the Gulf of Alaska are not present here. Furthermore, high-frequency bathymetric profiles of the sea floor have none of the small hyperbolic reflections that indicate the presence of ripples, small sand waves, or furrows (Damuth and Hayes 1977).

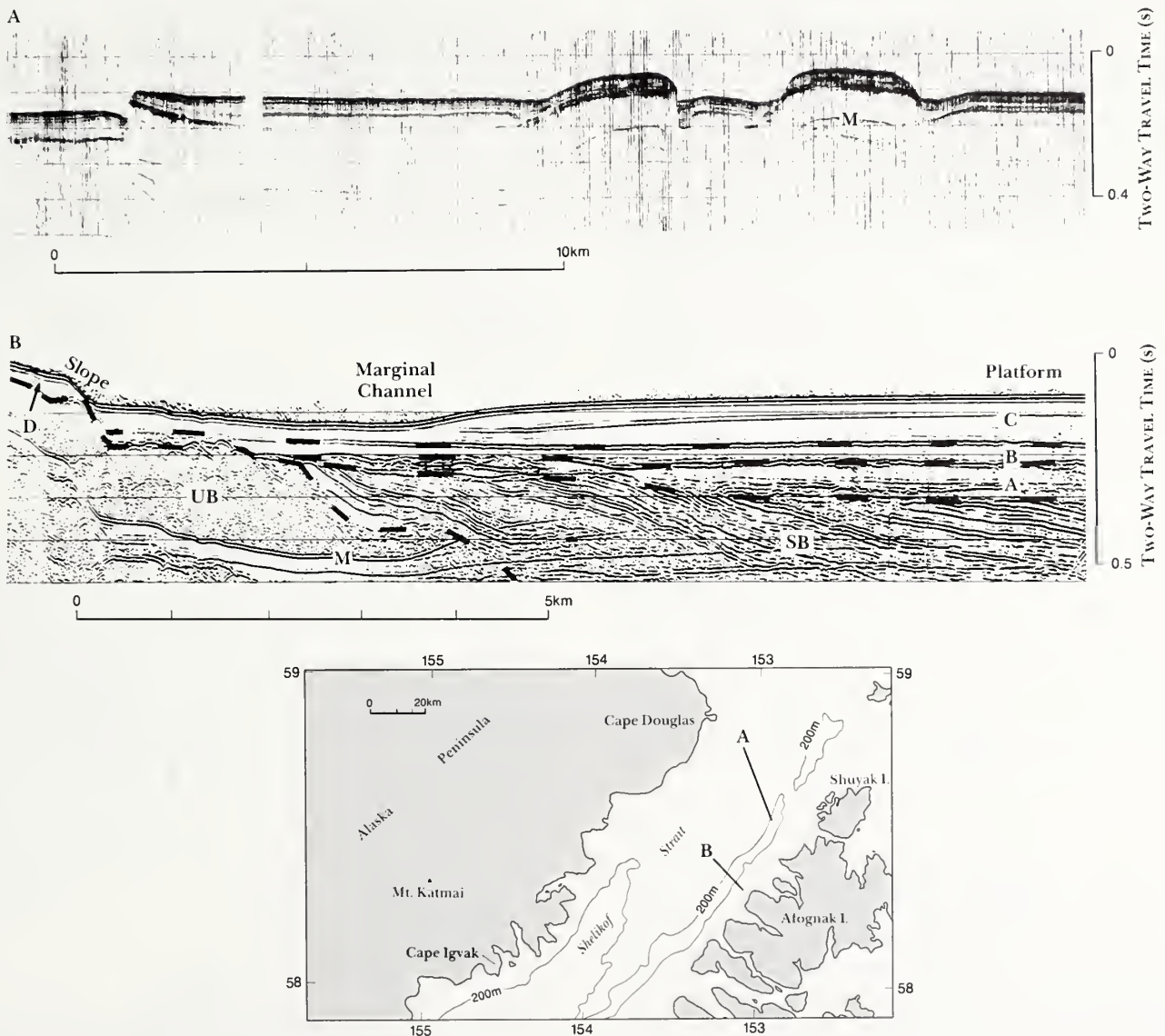


Figure 5-23. Seismic-reflection profiles of geologic features in Shelikof Strait. M denotes sea-floor multiple reflection.

- A. Seismic-reflection profile showing faults with large sea-floor offset.
- B. Seismic-reflection profile showing stratigraphic relation of acoustic units. UB and SB are unstratified and stratified bedrock, respectively. Stratigraphic contacts are emphasized by dashed lines. A, B, C, and D indicate four different sedimentary units above bedrock.

Sediment

Stratigraphy and General Distribution. The seismic stratigraphy of Shelikof Strait was analyzed in detail by Hampton (1985). He described and mapped four distinct units in the sedimentary section above bedrock (Fig. 5-23B). The section's thickness is about 80 m over much of the northeast half of the Strait, adjacent to Cook Inlet, but it reaches more than 800 m in the southwest half (Fig. 5-4). The first and lowermost unit (Unit A in Fig. 5-23B) has complex seismic stratigraphy, with intervals of a few strong reflectors separated by thicker intervals of weak, discontinuous reflectors. The reflectors have hummocky geometry in places, but their geometry ranges from planar to broadly folded in others. Although this unit occurs mainly in a deep erosional basin in the southwest half of the Strait, it also occurs in incised channels and other limited areas in the northeast half (Fig. 5-24A). It has an onlap-fill relation to the underlying bedrock and was inferred to be composed of glacial-marine deposits of late Pleistocene age.

The second, next highest unit (Unit B in Fig. 5-23B) is thin, typically less than 20 m but ranging to 60 m in places. It is spread over much of the central Strait, with a separate deposit near Cape Douglas (Fig. 5-24B). The unit has weak, continuous internal reflectors, and it is constrained within low areas in the underlying surface. The lateral margins of the unit are onlap-fill, whereas the leading, southwest margins are tapered. Mounded, fan-like buildups are located off Afognak and Shuyak Islands. This unit was inferred to have been deposited in a restricted marine environment that existed in early Holocene time, after ice retreated from the Strait but before onset of the modern circulation system.

The third, overlying unit (Unit C in Fig. 5-23B) blankets most of the present sea floor up to 200 m thick (Fig. 5-24C). Internal reflectors are strong and continuous, and strata drape the underlying topography. Many of the present topographic features of the sea floor reflect the morphology of this unit. The platform in the central trough is the main location of deposition. Strata underlying the platform pinch out laterally to form the seaward boundaries of the marginal channels, which themselves are underlain by blanket-like deposits at the base of the unit. Strata also pinch out toward the moat at the base of the fault blocks. This sedimentary environment evolved from the previous one when the modern circulation system became established.

The fourth unit (Unit D in Fig. 5-23B) occurs along the sides of the Strait, beneath the shallow shelves and adjacent slopes. The base of the unit cannot be seen in seismic-reflection profiles, but the stratigraphic range is that of Units B and C described above. The internal reflectors typically are short and discontinuous. Their inclination conforms closely to the sea floor: horizontal beneath the shelves and inclined beneath the slopes. Its lateral contact with other units is abrupt in some places and gradational in others. A distinct interfingering occurs prominently near Cape Douglas. The sediment for this unit has been emplaced by lateral progradation of sediment derived from the landmasses adjacent to the Strait. Although progradation appears to be limited today, it probably was more intense in the past when glaciers were more abundant.

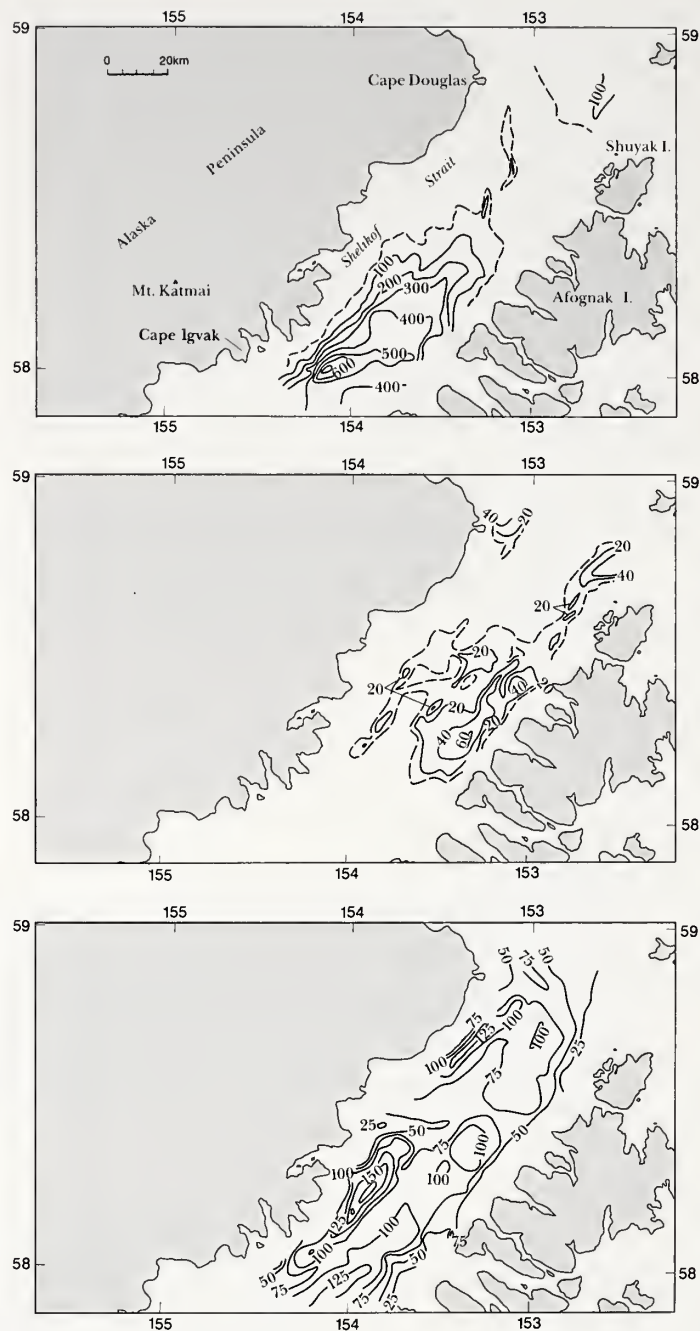


Figure 5-24. Thickness of seismic-stratigraphic units in Shelikof Strait. Isopleths in meters. Dashed line indicates approximate boundary of unit (from Hampton 1985).

- A. Unit A in Figure 5-23B.
- B. Unit B in Figure 5-23B.
- C. Unit C in Figure 5-23B.

Texture and Composition. Surficial sediment in the central trough of Shelikof Strait is derived mainly from Cook Inlet. It is progressively sorted starting with muddy sand at the boundary with Cook Inlet, and ranges to sandy mud at the southwest end of the Strait (Fig. 5-5). In addition, a detectable fining occurs across the Strait, from northwest to southeast. Detailed grain-size distributions show two dis-

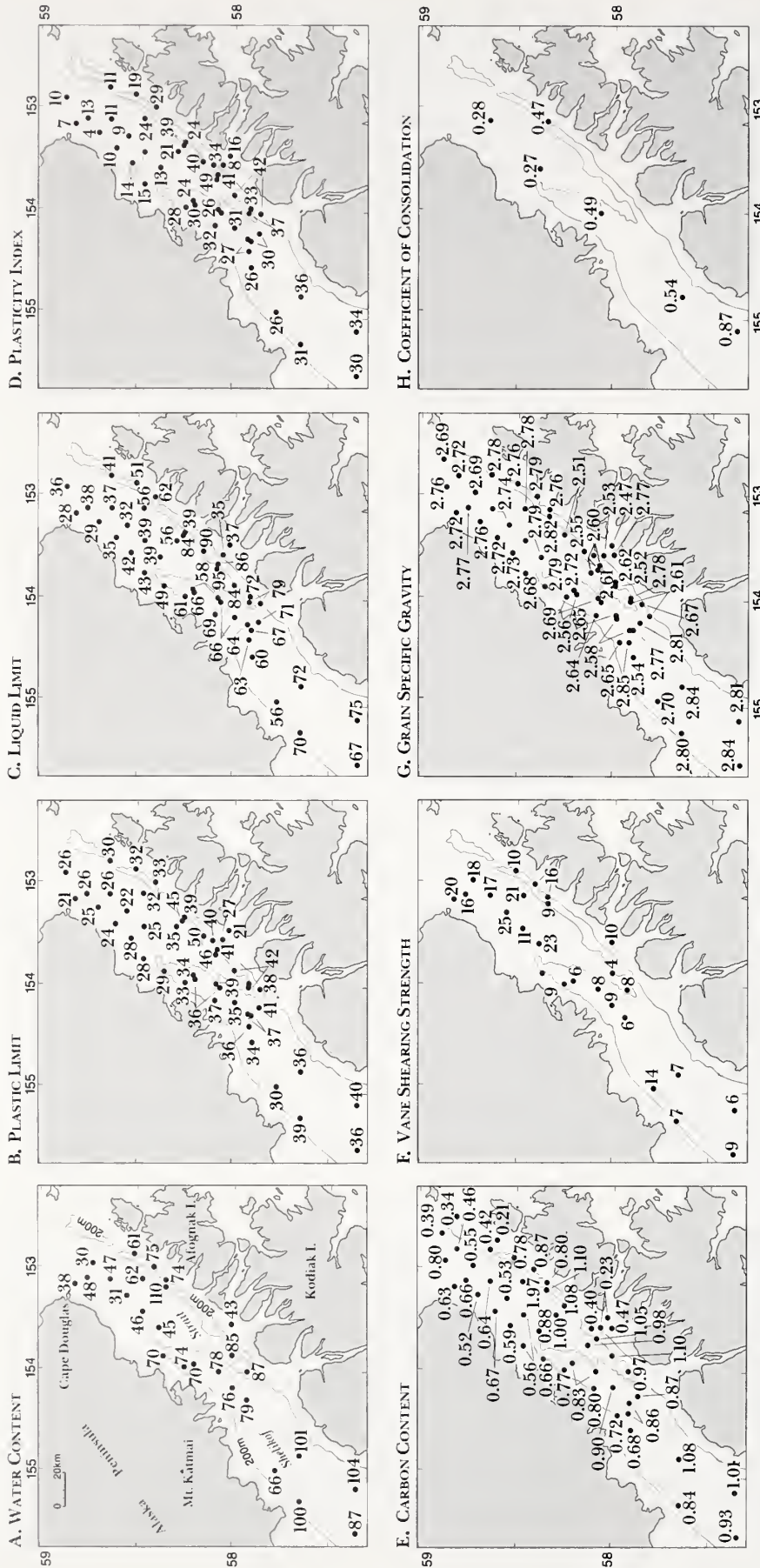
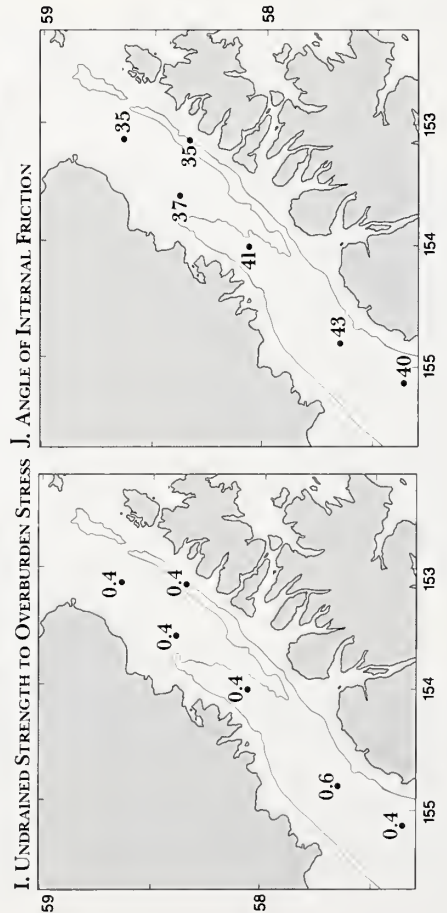


Figure 5-26. Physical properties of sediment in Shelikof Strait. (Modified from Hampton 1983c.)

- A. Interpolated value of water content (% dry weight) at 1-m depth in sediment cores.
- B. Average of plastic limit measurements in sediment cores (weight %).
- C. Average of liquid limit measurements in sediment cores (weight %).
- D. Average of plasticity index measurements in sediment cores (weight %).
- E. Organic carbon content in sea-floor sediment sample (weight %).
- F. Interpolated value of vane shearing strength (kPa) at 1-m depth in sediment cores.
- G. Average of grain specific-gravity measurements in sediment cores.
- H. Average of coefficient of consolidation measurements in sediment cores.
- I. Average of undrained strength to overburden stress measurements in sediment cores.
- J. Average of effective angle of internal friction (degrees) measurements in sediment cores.



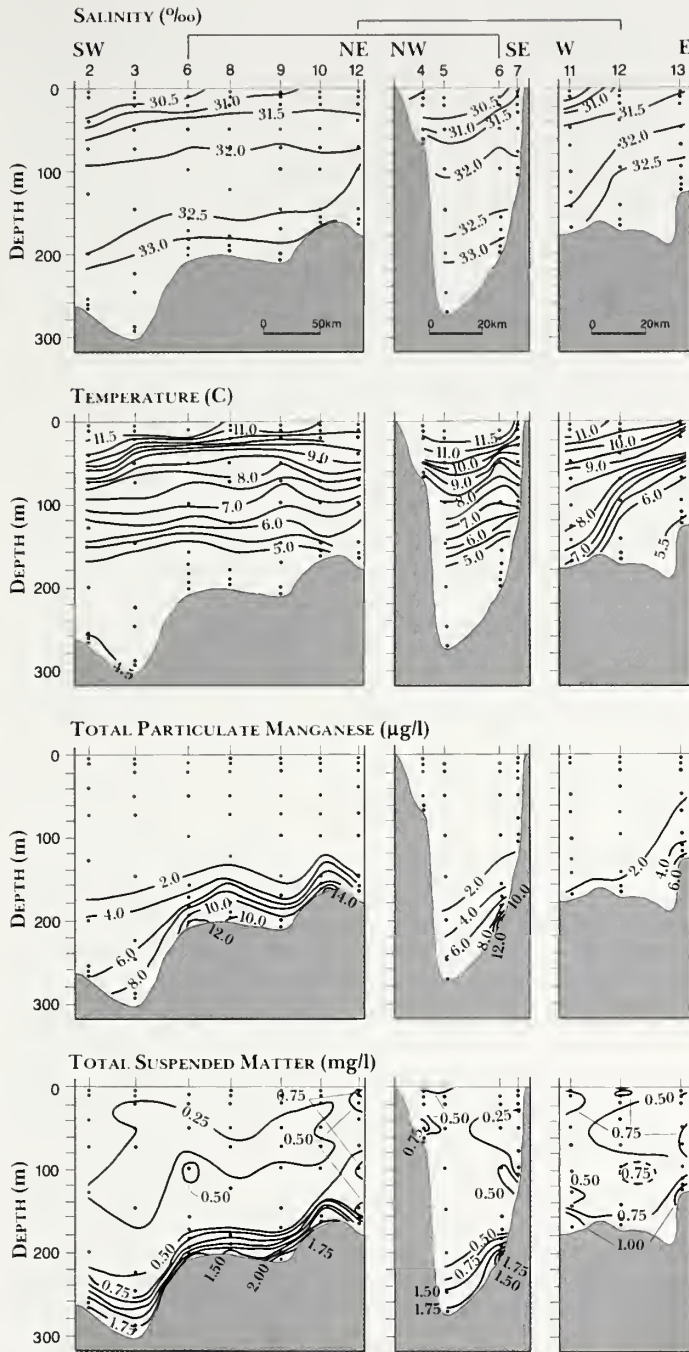


Figure 5-27. Vertical cross sections of salinity, temperature, particulate Mn, and total suspended matter for stations in Shelikof Strait. Stations 2, 3, 6, 8, 9, 10, and 12 represent a longitudinal section along the main axis of the Strait. Stations 4 through 7 and 11 through 13 represent transverse sections at mid-Strait and upper-Strait locations, respectively. (Modified from Feely, Massoth, Paulson, Lamb, and Martin 1981.)

bastions were formed where ice that was flowing down the valleys deflected the southward flow of the main ice mass, thereby shielding part of the basin margin from erosion.

Regional glaciation is believed to have commenced in Miocene time (Péwé 1975), and Shelikof Strait was last occupied by ice during the Naptowne glaciation, which

occurred 48,000 to 5,500 years B.P. (Karlstrom 1964). A continuous ice cover connected the Alaska Peninsula, Cook Inlet, Shelikof Strait, and the Kodiak Islands (Capps 1937). According to Karlstrom (1964), the surface of the ice sloped southward from an elevation of more than 600 m on the Alaska Peninsula to 300 m on Kodiak Island. Channels incised into the bedrock unconformity in the northeast half of the Strait suggest that the main ice mass flowed south from Cook Inlet and the adjacent Alaska Peninsula. As the ice was deflected by the islands of the Kodiak Archipelago, the major portion continued southwest down the Strait, but some flowed through Stevenson Entrance.

Erosion of the deep basin in southwest Shelikof Strait might have been due to either weak bedrock or to the addition of ice from the adjacent landmasses. The bedrock strata are clearly truncated at the margin of the basin, but there is no evidence of the downwarping or marginal faulting that would indicate a structural origin.

Glacial and glacial-marine deposits fill the deep basin and the incised channels in the bedrock surface. Deposits around the basin margin are mounded, hummocky, and chaotically stratified, particularly within and extending from the spur-bounded canyons. The deposits probably were emplaced near a grounded ice margin. Most of the basin fill has strong, continuous subparallel reflectors that are separated by thicker units of weak reflectors. These deposits probably were emplaced by remobilization and mass flow of the mounded-chaotic facies, by density flows associated with sediment-laden meltwater, and by the release of sediment from floating ice sheets or bergs (see Carey and Ahmad 1961; Drewry and Cooper 1981; Anderson, Brake, Domack, Myers, and Wright 1983; and Visser 1983). Deposits in the incised channels appear to be ice-contact or meltwater deposits.

After ice retreated from the Strait, restricted marine conditions prevailed during early Holocene time. Sediment prograded into the sides of the Strait to form the discontinuously stratified unit (Unit D in Fig. 5-23B), and a few feeder canyons funneled sediment to the floor of the central trough. Fan deltas formed at the mouth of these canyons, and sediment prograded beyond these fans in the form of bedload. The sedimentation continued on through shallow, sinuous low areas and was finally deposited as a weakly stratified unit (Unit B in Fig. 5-23B). Sediment also encroached into the Strait from Cook Inlet (Fig. 5-24B).

The contemporary sedimentary environment began rather abruptly when the Kenai Current (Schumacher and Reed 1980) breached the sill through Kennedy and Stevenson Entrances, flowed arcuately across the mouth of Cook Inlet, and encountered the sediment-laden estuarine outflow on the west side near Cape Douglas. Then, as now, the Cook Inlet sediment was dispersed throughout Shelikof Strait as suspension and intermediate-suspension load to accumulate as a sediment blanket across the floor of the Strait (Unit C in Fig. 5-23B). This sediment is constructing the platform on the floor of the trough. The marginal channels and the moat around the uplifted fault blocks resulted from flow distortions. The current is accelerated through these features, causing reduced deposition relative to adjacent areas (Hampton 1985).

Sedimentation in Shelikof Strait is progressing toward a state of dynamic equilibrium between the hydraulic conditions and the elevation of the sea floor. This means that the regime becomes purely transportational. The sediment accumulation rate (calculated from the burial depth of the Katmai ash layer) implies that in proximal areas at the northeast end of the Strait, the level of the platform has aggraded to a near-equilibrium elevation where current velocity nearly precludes deposition (accumulation rate is low) (Hampton 1985) (Fig. 5-25). In more distal areas to the southwest, sediment accumulation is more rapid (highest calculated rate is 122 mm/y), as sediment fills the low areas in the depositional surface that are farthest from equilibrium. The platform is prograding down the Strait to bring the entire sea floor closer to equilibrium.

Most of the sediment transported laterally into the Strait from the Alaska Peninsula and the Kodiak Archipelago is being deposited behind sills in the fjords, so the discontinuously stratified unit (Unit D in Fig. 5-23B) is not prograding significantly at the present time. Southwest of Cape Douglas, however, sills are absent, and the discontinuously stratified material is being dispersed across the shallow shelf to mix with the well-stratified deposits derived from Cook Inlet.

The Mn enrichment measured in the near-bottom suspended matter of Shelikof Strait has also been observed in other coastal areas. This phenomenon has been attributed to Mn remobilization from rapidly accumulating fine-grained sediment, with subsequent precipitation of the Mn on suspended matter in the water column (Graham, Bender, and Klinkhammer 1976; Aller and Benninger 1981; Yeats, Sunby, and Brewers 1979; Feely, Massoth, and Paulson 1981; Tefry and Presley 1982; and Feely, Massoth, Paulson, and Gendron 1983). Tefry (1977) showed that interstitial Mn flux from recent sediment in the Gulf of Mexico varies directly with the mass sediment accumulation rate. Massoth *et al.* (1979) found a similar relation for Mn flux from Shelikof Strait sediment. Figure 5-28 shows a plot of the relation between the calculated Mn flux at the sediment-seawater interface and mass sediment accumulation rate for both the Gulf of Mexico and Shelikof Strait data. The high degree of correlation indicates that a linear relation exists between the mass sediment accumulation rate and the Mn flux at the sediment-seawater boundary. This is primarily due to a corresponding increase in organic-matter accumulation that acts as a reducing agent for the manganese. Thus, the near-bottom Mn enrichment in Shelikof Strait is a direct result of diagenetic processes in the underlying sediment and therefore can act as a sensitive indicator of these processes. Indeed, near-bottom enrichment of particulate Mn has been observed elsewhere in the Gulf of Alaska and near the entrance to Prince William Sound where the sediment is accumulating at a rate that is similar to the rate along the main axis of Shelikof Strait. (R.A. Feely, NOAA/PMEL, unpubl. data). Because newly formed hydrous Mn oxides in suspended matter are known to have a major role in scavenging and removal of a number of different trace metals in natural waters (Longathan and Burau 1973; Feely, Massoth, and Paulson 1981; and Feely, Massoth, Paulson, and Gendron 1983), this process may be an important mecha-

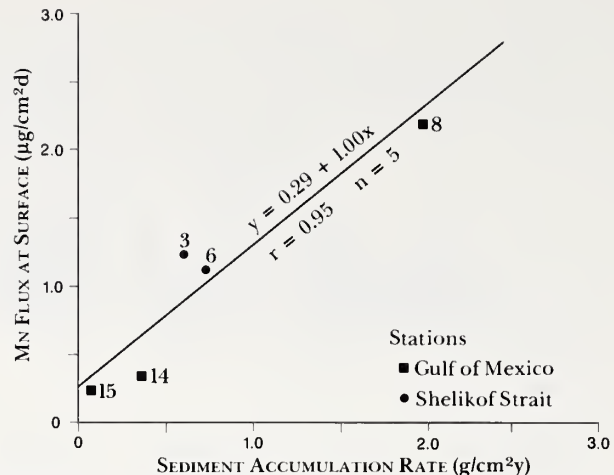


Figure 5-28. Relation between calculated fluxes of Mn from Shelikof Strait and Gulf of Mexico sediments, and sediment accumulation rates determined by ^{210}Pb geochronology.

nism for maintaining the low level of trace metal concentration in Shelikof Strait as well as in the Gulf of Alaska (Massoth, Feely, Appriou, Ludwig, and Gendron, NOAA/PMEL, unpubl. data; Heggie 1983).

Discussion and Conclusions

Extensive knowledge has been obtained about the geology of the Gulf of Alaska. The focus of the preceding discussion is the *surficial* geology, that is, the geology from the sea floor to a relatively shallow depth beneath it. Correspondingly, the time frame is small, extending back into the late Pleistocene. The *framework* geology of the Gulf encompasses a larger time frame and is concerned with the larger-scale aspects of structure, tectonism, and stratigraphy. This framework geology is well known as a result of a large body of literature that has been summarized in a companion paper by Jacob (Ch. 6, this volume).

Few data have been collected on the open shelf southeast of Cross Sound, between Montague Island and Amatuli Trough (the area between the northeastern Gulf and the Kodiak Shelf), or on the Shumagin Shelf southwest of Chirikof Island. The most significant knowledge gap in a specific subject area is in the nature of the subsurface sediment. Inferences from seismic-reflection stratigraphy have been used to outline the general nature of sedimentary deposits and processes, but drill sampling is necessary in order to obtain specific information about lithology and detailed stratigraphy.

In spite of these information needs, the evidence is clear for a consistent, though complex, interaction of tectonism, glaciation, and subpolar climate in controlling the surficial geology of the region. This includes important local contrasts in oceanography and the sedimentary environment, particularly during the Holocene, that serve to distinguish each geographic area.

The Gulf of Alaska Shelf (an area of intense tectonic force) lies at the margin of the Pacific and North America lithospheric plates. The present configuration of the Pacific

crust (that moves northwest relative to North America) became established in early Tertiary time (Byrne 1979; Engebretson, Cox, and Gordon 1984). The long-term geomorphic evolution of the sea floor has been primarily controlled by tectonic forces, which have formed deeply subsided basins and intervening uplifted highs (Fisher and von Huene 1980; Bruns 1982, 1985). Even today the sea floor is being actively deformed; as much as 15 m of uplift was documented after the Great Alaskan Earthquake of 1964 (Plafker 1972; Malloy and Merrill 1972; and von Huene *et al.* 1972).

The modern sea floor owes its geomorphology more to glaciation than to tectonism. Ice sheets have waxed and waned across the region since Miocene time, and have advanced out to the shelf break at least once (Karlstrom 1964; Thrasher 1979; and Carlson *et al.* 1982). While it occupied the shelf, the ice severely eroded bedrock into forms that are typical of glacial action. Seismic-reflection profiles in confined areas such as Nuka Bay (von Huene 1966) and Shelikof Strait (Hampton 1985) display deeply eroded basins far below the lowest sea level. On the open shelf, deformed strata that compose bedrock have been truncated along extensive flat surfaces that are liberally incised with broad, flat-floored valleys, most of which align with fjords and probably mark the position of ancient ice streams (Carlson *et al.* 1982; Hampton 1983a). Capping the erosion surface are linear moraines and blankets of other ice-contact and meltwater deposits (Thrasher 1979; Molnia and Carlson 1978, 1980).

At the beginning of Holocene time, ice retreated, the sea level rose, and the modern geologic, climatic, and oceanographic setting developed. The rugged, glaciated mountains throughout the area became an abundant source of sediment that is now deposited in coastal embayments or delivered to the sea by a few major rivers and glaciers. The sediment is dispersed by currents that tend to be sluggish on the open shelf except when driven by waves from fierce storms that frequent the area (Reed and Schumacher, Ch. 3, this volume). Certain current velocities in the area are relatively strong, both as a consequence of seasonally variable freshwater runoff from the rivers and as a result of modifying influences of the wind. Currents are particularly strong near the shelf break and throughout most of the Gulf, at the location of the Alaska Stream (Favorite 1967; Thomson 1972), and within baroclinic coastal currents that flow along the south side of the Kenai Peninsula (Schumacher and Reed 1980; Royer, Luick, and Johnson 1984).

The continental shelf in the northeastern Gulf of Alaska is characterized by large areal variation in sedimentation rate, from nil in areas of repeated strong storm currents (Tarr Bank) to extreme in some coastal embayments (Icy Bay) and the mouth of large rivers (Copper River and Alsek River) (Molnia 1979b; Molnia and Sangrey 1979). Much of the suspended sediment introduced by rivers is carried westward by regional currents (Reimnitz and Carlson 1975). The unconsolidated sediment on the shelf is unstable in many places; large sediment slides and flows have been triggered both by earthquakes and by waves (Schwab and Lee 1983).

The Kodiak Shelf is receiving only a small amount of modern sediment because it is isolated from major fluvial or glacial sources. Biologic and volcanic activity are providing

some material, and deposits of diatom tests and volcanic ash are important locally. The sedimentary environment is typified by material that has been reworked on the shallow banks and then redeposited in glacial troughs (Hampton 1983a). Tectonically uplifted areas are devoid of significant accumulations of unconsolidated sediment, but it is unclear whether this is because no material is deposited in these areas, or because of subaerial or submarine erosion.

Estuarine conditions with strong tidal currents exist in Cook Inlet. Also, the Alaska Coastal Current (locally called the Kenai Current) plays a major role in circulation in the lower Inlet (Muench *et al.* 1981). Sedimentation varies systematically throughout the Inlet. Coarse sediment from rivers that empty into the head of the Inlet is deposited near the source, whereas most of the suspended load is carried south into Shelikof Strait (Sharma and Burrell 1970). Strong currents in the constricted Forelands area cause winnowing of all but the coarsest sediment, and most of the winnowed material is carried south to the lower Inlet where there are large fields of sand waves in the central portions (Bouna *et al.* 1980). Fine sediment accumulates in the deep water at the mouth of the Inlet and in quiescent areas around the margin.

Circulation in Shelikof Strait is driven by the Kenai Current and the Alaskan Stream, and the net water and sediment movement is to the southwest. The major source of sediment is from Cook Inlet. Deposits of sandy bedload sediment decrease down the Strait, but intermittent-suspension and suspended-load deposits increase (Hampton 1985). Surficial sediment is progressively sorted from muddy sand adjacent to lower Cook Inlet to mud at the southwest end of the Strait.

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Seismicity, Tectonics, and Geohazards of the Gulf of Alaska Regions

6

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ABSTRACT

The Gulf of Alaska is one of the tectonically most active regions in the world. The Pacific Plate moves north–northwest at a rate of 5 to 7 cm/yr relative to the North American Plate. This motion controls the tectonics, seismicity, volcanicity, and much of the morphology of the Gulf of Alaska. Subduction is the dominant force along the Aleutian Trench where the Pacific Plate is outlined by dipping seismic zones that range to depths of 250 kilometers. The plate descends beneath the Alaska Peninsula, Cook Inlet, Prince William Sound, and the Chugach–St. Elias Range, while a right–lateral transform motion combines with a small component of convergence to dominate the tectonics of the plate boundary that runs along the Queen Charlotte–Fairweather Fault system in Southeast Alaska.

The overriding North American Plate is composed of distinct accreted terranes. The historic active accretion continues into the present by collision of the Yakutat Block with the Chugach terrane in the north eastern Gulf. Seismicity is concentrated on—but not limited to—the plate interface between the Pacific and North American Plates, with great earthquakes ($M_w \geq 7.8$) recurring at any given plate–boundary segment about once a century. Some of the great Alaskan earthquakes are among the largest recorded on Earth, measuring magnitudes of up to M_w equal to 9.2 (*e.g.*, the Great Alaskan Earthquake of 1964). Some great Alaskan earthquakes are highly tsunamigenic and thus can cause widespread devastation along Pacific coastlines in Alaska and as far away as Hawaii, California, and Japan. In addition, they cause regional damage as a result of shaking, faulting, subsidence, landslides, avalanching, seiches, and soil liquefaction both offshore and onshore. Moderate shallow earthquakes pose a more frequent risk, but except in localized cases, are generally less damaging to man–made structures. The Aleutian and Wrangell volcano chains pose additional hazards.

Tectonic, seismic, and volcanic activity pose unavoidable risks to development in the Gulf of Alaska region. The potential for damage from these hazards has—within certain limits—become spatially and temporally quantifiable. Although such assessments provide the public with new options for long–term hazard–mitigation, they also pose the dilemma of striking a balance between mitigation costs and the long–term benefits from those actions taken against rare but catastrophic losses.

Introduction

The Gulf of Alaska is tectonically one of the most dynamic environments on Earth. This chapter includes:

- an overview of the tectonic activity in the Gulf of Alaska
- the elements of the major tectonic processes (plate

motions, seismicity, crustal deformation, and volcanism)

- the hazards associated with the seismic and volcanic activity
- the challenges to human activity from tectonic hazards along the Pacific rim of Alaska.

The geographic region considered in this review extends from the Queen Charlotte Islands in the southeast to Unimak Pass in the northwest (Fig. 6-1). The discussion of hazards focuses on the coastal regions, but the plate-tectonic forces that drive the seismic and volcanic activities require a look beyond a narrow coastal strip.

Both in terms of method and discipline, this contribution relies more on geophysics than geology. Geologic data are commonly constrained to near-surface observations. The sources of the tectonic processes, and especially of the major seismicity in the subduction zone are, however, deep-seated. Geophysical methods, with their capabilities to monitor deep-seated crustal properties and deformations, are therefore well suited.

Yet, geologic and geodetic data and arguments can be crucial in removing ambiguities that are sometimes inherent in geophysical problems. For instance, some seismologists inferred from their analysis of global seismic data resulting from the giant 1964 Earthquake that a steeply southeast-dipping thrust fault had slipped. Plafker (1969), in a now classic paper, showed on the basis of geologic and geodetic data that a gently northwest-dipping thrust was the correct choice of the two possible solutions and equally compatible with the seismic nodal-plane information. In this report, the author relies on geologic input where helpful or necessary.

Because of the brevity of this survey we must select from the large number of topics covered in the literature. The object is to present a comprehensive rather than an exhaustive treatment of the topic. Omissions, whether inadvertent or as a result of some bias, are inevitable.

Overview of Tectonic Activity

The Earth is a thermodynamically convecting 'machine'. It owes its tectonic characteristics (which are rather unique among planetary objects), to a cold outer layer only 100 km thick which acts as a thermal boundary layer. This cold, rigid, yet mobile lithosphere forms plates which overlie a hot ductile asthenosphere.

Gravitational forces are the major forces that drive the dozen (or so) primary plates on Earth. The forces originate from mostly thermally controlled lateral density heterogeneities both in the plates and in the mantle. Cold slabs of lithosphere sink into the hot mantle along the oceanic trenches and try to pull the attached plates along behind them. In return, the hot, partially melted mantle wells up beneath mid-oceanic ridges which are located at the trailing edges of the mobile plates. The melt solidifies into a young oceanic lithosphere. The ocean floor of a hot young oceanic plate stands above the older, cooler, and denser ocean floor,

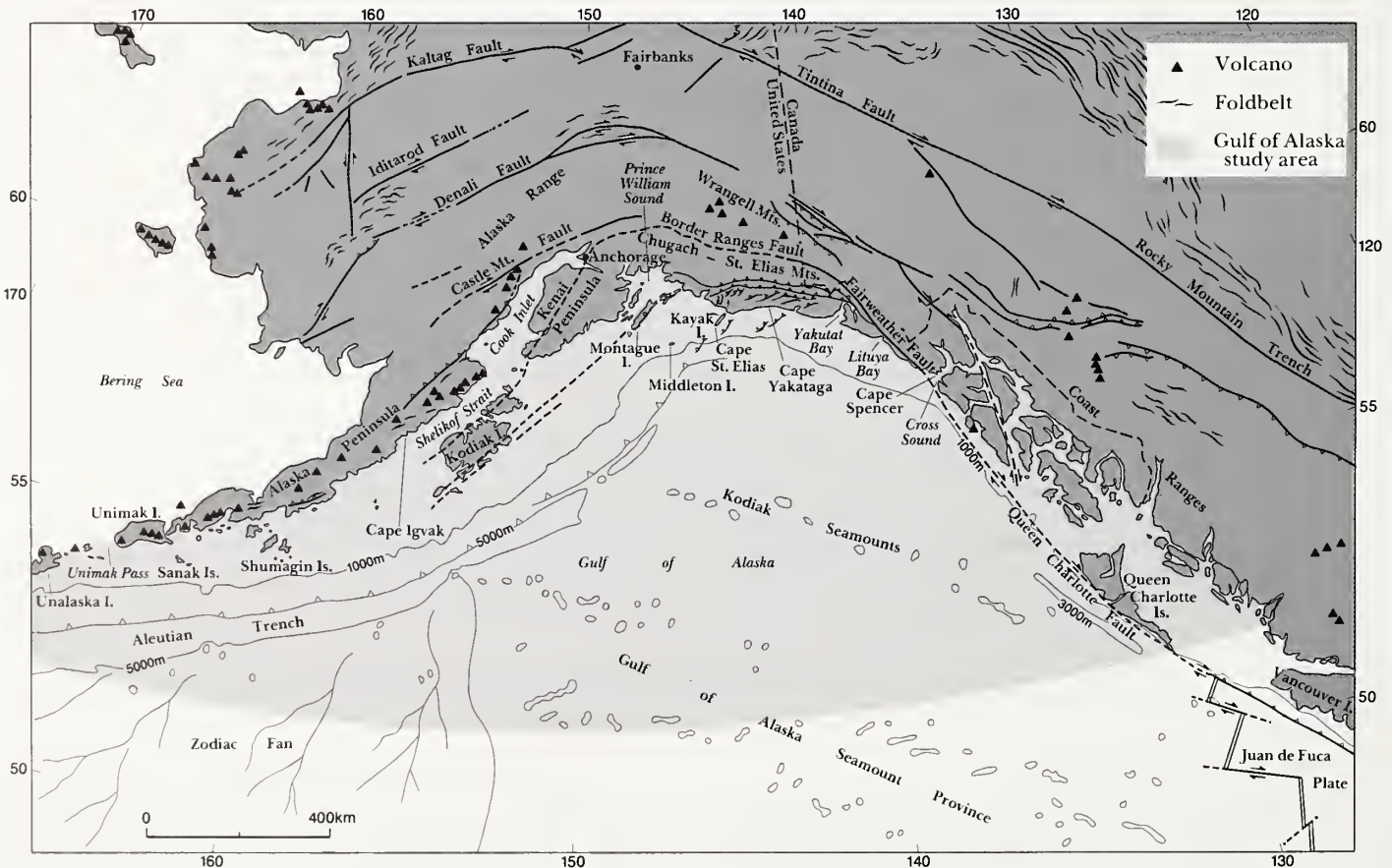


Figure 6-1. Tectonic map of the Gulf of Alaska and adjacent regions with modifications after King's (1969) Tectonic Map of North America. Note that truncated channels on Zodiac Fan are only schematical to indicate turbidite transport direction. For actual channel configurations, see Stevenson, Scholl, and Vallier (1983).

and thereby exerts a force in the direction of the age gradient that runs from young to old. The combination of ridge push and slab pull are the two most important driving forces for plate motions (Forsyth and Uyeda 1975; Chapple and Tullis 1977).

Besides the driving forces, the rheologies (stress–strain interactions) between the plate and the mantle are also thermally controlled (Kirby 1983). For example, the plates' long-term elastic properties are largely dependent on their thermal structure. In an oceanic plate, the depth to a certain isotherm (*e.g.*, 450C) increases as the square root of the plate's age (Fig. 6–2). The depth of this isotherm determines the elastic thickness of the plate. In materials with higher temperatures (at greater depths), stresses are released by ductile flow. At lower temperatures (shallower depths), stresses either cause elastic (reversible) strains, or else they are released by a sudden seismic failure when the shear strengths of the materials are exceeded. That is why earthquakes are confined to the low-temperature, elastic–brittle zones of plates.

In oceanic plates, the elastic zone thickness varies from about 10 to 40 km, whereas in continental plates, it can measure up to 50, or even 100 km in old cratonic shields. Seismicity thus delineates only the stressed zones within the lowest-temperature, brittle regions of the Earth. This is particularly visible for instance, at Wadati–Benioff zones where cold slabs subduct into normally aseismic ductile mantle.

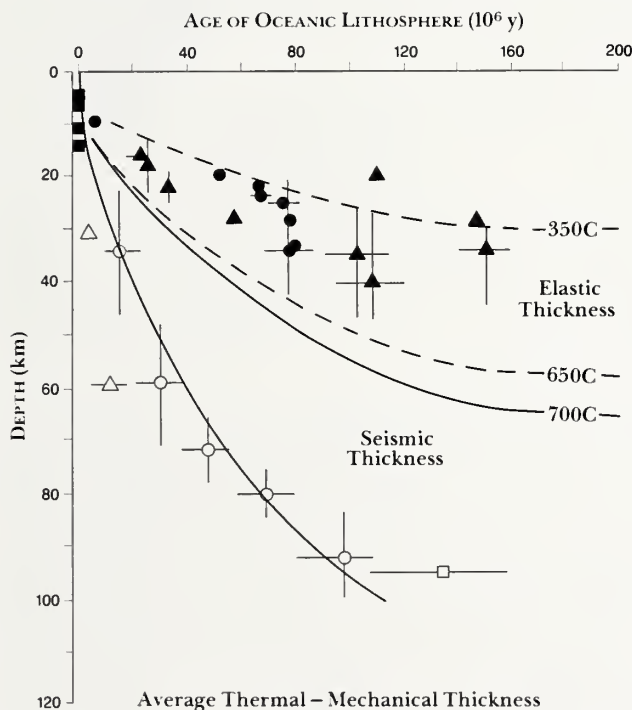


Figure 6–2. Thickness of oceanic lithosphere as a function of age (based on various geophysical indicators). Open symbols describe the mechanically coherent thickness of the lithosphere as determined by seismic-velocity studies. Solid symbols define the depth of the elastic portion of the lithosphere. Superimposed on the data are computed isotherms. The elastic thickness approximately tracks a 450C isotherm. (Modified from various sources after Kirby 1983.)

In addition to the thermally induced density heterogeneities in the Earth, there are a number of heterogeneous conditions based on contrasts in compositional density. When an oceanic plate is converging with a continental plate, the more mafic, denser oceanic plate almost always plunges beneath the more silicic, lighter continental plate. Once the oceanic lithosphere has started to subduct, it becomes colder and thus denser than the compositionally similar but hot asthenosphere. The resulting gravitational pull on the slab reinforces further subduction. In contrast, the subduction of the continental crust to any considerable depth is resisted because of the buoyancy caused by its inherent lower density.

If an oceanic plate contains low-density bodies (*e.g.*, continental fragments, ocean plateaus, island arcs, or other low-density loads such as thick sediments), then these bodies also tend to resist subduction because of their buoyancy. Often they are sheared off from the denser portions of the subducting plate, then transferred and accreted to the overriding continental plate. This action leads to the accretion and the growth of continents. If light fragments embedded in the oceanic plate are large enough, they may cause collisional tectonics and orogenic mountain-building.

All these processes play a prominent role in the present tectonics of the Gulf of Alaska, and have done so during the evolution of the entire formation of continental Alaska.

Elements of the Tectonic Process

Plate Motions

The instantaneous motion of any rigid plate on a sphere (McKenzie and Parker 1967) can be described by a vector of rotation that has a pole position (latitude, longitude) and a rate (degrees/my). The motion of all the major tectonic plates on the Earth (about a dozen) can be described in an absolute frame of reference, or on the basis of the relative motions of pairs of plates. Minster and Jordan (1978) inverted seismic slip directions as well as magnetic and transform lineation data on a global scale for a set of major plates that were assumed to be virtually rigid. Their model (RM2) has been widely accepted as one of several that can approximate plate motions for the last five million years.

Another model (RMI) is referred to later in this chapter (Minster, Jordan, Molnar, and Haines 1974). Figure 6–3 outlines the three principal plates in the northeast Pacific along with the motion for those plates. The three plates discussed here are the North American (NAM), Pacific (PAC), and the Juan de Fuca (JF) Plates. Minor plates or platelets are omitted for the sake of simplicity. The three plates join in a triple junction (ridge/trench/transform) off the Vancouver–Queen Charlotte Islands shelf. The relative motion of the PAC–NAM along the Queen Charlotte–Fairweather Fault system (at rates of about 6 cm/y) is dominantly a right-lateral transform movement coupled with a small convergence component. At the Aleutian Trench, convergence dominates at rates reaching more than 7 cm/y near the Shumagin and at Unimak Island. There is a transition region in the northeastern Gulf of Alaska where motion changes from transform motion to convergence. This leads to the complex tectonics discussed below.



Figure 6-3. Plate-tectonic map of the Gulf of Alaska showing the Pacific, North American, and Juan de Fuca plates, their absolute plate-motion vectors (solid arrows), and vectors of relative plate motions (open arrows). Large numbers next to arrows indicate motion rates (in cm/y) of model RM2 (see text). Fine lines on the PAC plate are magnetic anomaly patterns, offset by major fracture zones. The time scale (in millions of years) for the numbered magnetic anomalies is shown at upper right. Shaded areas represent the subducted oceanic lithosphere (note the fingering of subducted plates). The basemap is modified from Drummond (1981) with new data added.

The Pacific Plate. Age Distribution. The ages of the Pacific Plate can be inferred from the magnetic lineations shown for the Gulf of Alaska in Figure 6-3. Magnetic lineations are remnant lines of equal magnetic-field components that were frozen into the oceanic crust as it formed at mid-oceanic ridges. Once these magnetic-field anomalies or polarity reversals are dated in a few places (*e.g.*, by dating the oldest sediments overlying the oceanic basalts), then the magnetic patterns provide an excellent means to date any piece of ocean floor on the Earth that has this clear magnetic signature.

The Pacific Plate presently forms along ridges shared with the Juan de Fuca Plate (Riddihough 1984), resulting in a young ocean floor off the Queen Charlotte Islands. Ages increase towards the northwest, reaching more than 50 million years near Unimak Island. Several fracture zones strike east to west off Southeast Alaska and offset the generally N-S magnetic anomalies and isochrons. Note the change to E-W trending isochrons in the western Gulf, a feature

known as the 'magnetic bight'. This feature is related to a former ridge/ridge/ridge triple junction (Byrne 1979).

This pattern of isochrons reveals that, in general, the ages of the Pacific Plate in the Gulf of Alaska decrease from the open ocean towards the margin with the Alaskan continent. The pattern implies that the ridges that formed the Pacific Plate have long been absorbed into its northern and eastern margins (Atwater 1970; Byrne 1979). The leading edges of subducted Pacific slabs in the Gulf are younger than their up-dip portions. In fact, areas of close-to-zero-age Pacific Plate must have been subducted in the geologic past in a manner similar to that now occurring near the PAC/NAM/JF triple junction off Queen Charlotte and Vancouver Islands.

Seamount Chains. Riding on the Pacific Plate are chains of sea mounts (Fig. 6-1) that seem to originate near the triple junction in the southeast and trend north-northwest, the direction in which their age systematically increases (Turner, Jarrard, and Forbes 1980; Silver, von Huene, and Crouch 1974). Whether these seamount chains record the

'absolute' motion of the Pacific Plate with regard to a fixed 'hot spot' depends on just how 'fixed' those generating hot spots were through time.

Sediments and Zodiac Fan. Much of the Pacific Plate ocean floor in the Gulf of Alaska is blanketed with layers of terrigenous sediments (Fig. 6-4). These layers resulted from the erosion of the coastal ranges on the adjacent North American continental margin, and they are transported and deposited as turbidites. At the base of the continental slope of South east Alaska they can be up to 2 km thick (Ludwig and Houtz 1979).

The origin of the voluminous sediments of the Zodiac Fan (see Fig. 6-1 for location) has been a persistent enigma. Their origin is difficult to reconstruct (Byrne 1979; Stevenson, Scholl, and Vallier 1983) because reconstructions depend on placing past configurations of the mobile borderlands of North America relative to the ocean floor, which has been subducted beneath or accreted to the North American continent. Few data, therefore, exist to constrain the earlier configurations (von Huene, Keller, Bruns, and McDougall 1985).

Subducted Portions of the Pacific Plate. In the northwestern, central, and northeastern Gulf, subducted portions of the Pacific Plate dip into the upper mantle (see Fig. 6-3). Their configurations to depths of 250 km can be determined by the presence of well-defined Wadati-Benioff zones of seismicity that will be discussed later. In cases where descending slabs are suspected, but if present, behave aseismically, they can be only vaguely inferred from plate motions and sometimes from associated volcanic arcs.

The subduction zone in the Gulf of Alaska, beneath Cook Inlet, is characterized by one of the most gently dipping slabs in the world for depths shallower than 50 km (Jacob, Nakamura, and Davies 1977; Davies and House 1979). Below that depth, the dip of the slab increases and is comparable to global averages. The descending Pacific Plate may be torn into fingered segments. For instance, one segment is dipping northwest beneath Prince William Sound and Cook Inlet, while another appears to dip northeast beneath the St. Elias and Wrangell Mountains (Stephens, Fogleman, Lahr, and Page 1984). Perez and Jacob (1980a) speculate that some subduction of the Pacific Plate may be initiated near the Queen Charlotte Islands, very close to the PAC/NAM/JF triple junction. There, if model RM2 is to hold true, a small component of convergence is required (see Fig. 6-3). If that convergence exists, a very obliquely subducting slab could be continuous at depth from near the triple junction in the vicinity of the Queen Charlotte Islands to beneath the Wrangell volcanoes. However, so far only the northernmost portion of the dipping slab has been observed seismically.

The North American Plate. Accreted Terranes. One of the most important results of geologic research on the North American continent in the last decade is the realization that much of Cordilleran western North America—including most of continental Alaska—is made up of distinct terranes. Each has its own characteristic stratigraphy and tectonic history (Jones and Silberling 1979; Coney, Jones, and Monger 1980; and Churkin and Eberlein 1977). Paleomagnetic data demonstrate that some of these ter-

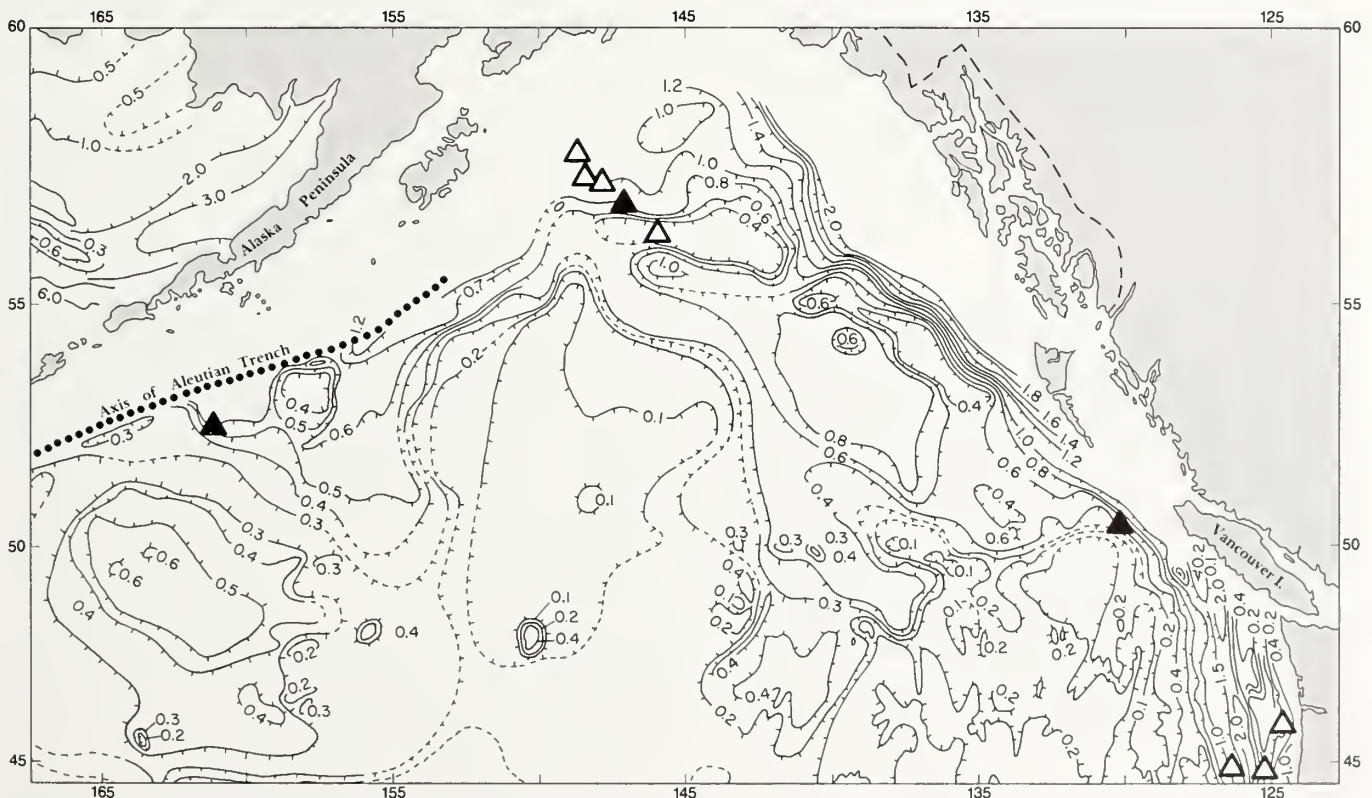


Figure 6-4. Isopach map of sediments in the abyssal portions of the Gulf of Alaska. (Modified from Ludwig and Houtz 1979.) Triangles indicate sites drilled by the Deep Sea Drilling Program. Barbed lines are on the side of lesser sediment thickness. Numbers indicate thicknesses in kilometers. For sediments on shelves, see compilations by Hampton, Carlson, Lee, and Feely (Ch. 5, this volume).

ranes have traveled thousands of kilometers—sometimes from near equatorial latitudes—at velocities compatible with present plate tectonic rates (Stone, Panuska, and Packer 1982; Irving 1979). In fact, the Wrangellia terrane in Alaska was one of the first terranes for which this discovery was made (Hillhouse 1977).

Biostratigraphic studies have shown that sediments on now adjacent terranes originated in ocean basins with distinctly different faunas and climatic affinities. Docking times of terranes can be inferred from overlapping stratigraphic sequences, common igneous piercing or metamorphic events, and rock magnetism that reveals periods of joint polar wanderpaths that follow times of separate paths. The Alaskan continental crust, despite a flurry of recent research, is far from thoroughly probed. Yet, studies are already revealing a bewildering number of complexly assembled terranes. Figure 6-5 shows some of the larger terranes identified in the Gulf of Alaska borderlands. Most of the terranes are bound by clearly identifiable faults, and some, but not all, are active or reactivated. In fact, seismicologic data show (see later sections in this chapter) that active accretion currently occurs. The Yakutat Block (Fig. 6-5) is being accreted to the North American continent by collision with the Chugach terrane (Lahr and Plafker 1980; Perez and Jacob 1980a; Bruns 1983, 1985; and von Huene *et al.* 1985).

Recent Volcanism. In almost every segment where the North American Plate overrides the subducting Pacific Plate, the upper plate is pierced by volcanic activity that geometrically aligns closely with the 100-km iso-depth line of the Wadati-Benioff zone (where the latter is defined). The basaltic-to-andesitic magmas following tholeiitic to calc-alkaline differentiation trends appear to be fractionated from a parental magma very similar to the mid-ocean ridge basalts (MORB). However, in contrast to MORB, their geochemistry suggests that they fractionate from finite, closed-system batches of rising magma rather than from an open system with a replenishing supply of mantle material (Kay,

Kay, and Citron 1982). It appears that magma is generated at a depth of about 100 km because at that depth, the advecting asthenospheric mantle comes in contact with volatiles emanating from the hydrothermally altered crust of the subducting oceanic plate. Melting temperatures of mantle rocks are lowered by the presence of volatiles such as water.

The most prominent subduction-related volcanic chains at the margins of the Gulf of Alaska are the eastern Aleutian arc and the Wrangell Mountains (Kienle and Swanson 1983a; Jacob *et al.* 1977; and Simkin, Siebert, McClelland, Bridge, Newhall, and Latter 1981). In Figure 6-6, the former can be seen to stretch from Unimak Island at the tip of the Alaska Peninsula into Cook Inlet where it straddles the Inlet's northwest shoreline. St. Augustine volcano actually emerges from within Cook Inlet. More than twenty Quaternary or historically active volcanoes lie in this continental portion of the Aleutian arc. There are no volcanoes northeast of and beyond either Mount Spurr or Mount Hayes along the Cook Inlet segment, although the Wadati-Benioff zone at depth continues for another 300 km to a point beyond Mount McKinley and the Denali Fault.

The Wrangell Mountains in the borderlands of the northeastern Gulf contain at least five major volcanic edifices (Mounts Drum, Sanford, Wrangell, Blackburn, and Regal) plus the unnamed source of the White River ash near Mount Bona (Lerbekmo and Campbell 1969). These volcanoes seem to be related to the subduction of a separate slab of the Pacific lithosphere (see Fig. 6-3). The tectonic origin of the Mount Edgecumbe volcano—which is seated so closely to the Fairweather-Queen Charlotte transform fault—is uncertain (Perez and Jacob 1980a). It consists of bimodal mafic and felsic volcanic rocks rather than the andesites and basalts that characterize the Aleutian and Wrangell volcanoes.

There is considerable volcanic activity in the coastal regions of British Columbia, in the interior of continental Alaska, and on the Bering Sea shelf. Some of the activity in southwest British Columbia is related to both the present and the past subduction of portions of the Juan de Fuca Plate system, but hot-spot and extensional tectonics may be involved for those volcanoes with alkali-basaltic magma affinity (Souther 1977). Extensional tectonics has also been proposed as associated with the widespread volcanic activity in the western interior of Alaska and the Bering Sea shelf (Nakamura, Jacob, and Davies 1977).

Internal Deformation and Diffuse Plate Boundary. In contrast to the rather rigid oceanic Pacific Plate, the North American continental plate bordering the Gulf of Alaska seems to undergo substantial internal deformation. Most aseismic deformation occurs in two places: 1) in the accretionary prism (Fig. 6-7), and 2) in young subduction complexes at the leading edge of the plate up to several tens of kilometers north of the Aleutian Trench (von Huene 1979; House and Jacob 1983). However, some segments of the eastern Aleutian Trench do not have extensive accretionary prisms at present (Plafker, Bruns, Winkler, and Tysdale 1982).

Internal deformation of the more mature (>20 km-thick) portions of the accreted fore-arc crust in the hanging wall above the main thrust zone often occurs coseismically, although Pavlis and Bruhn (1983) argue that aseismic ductile

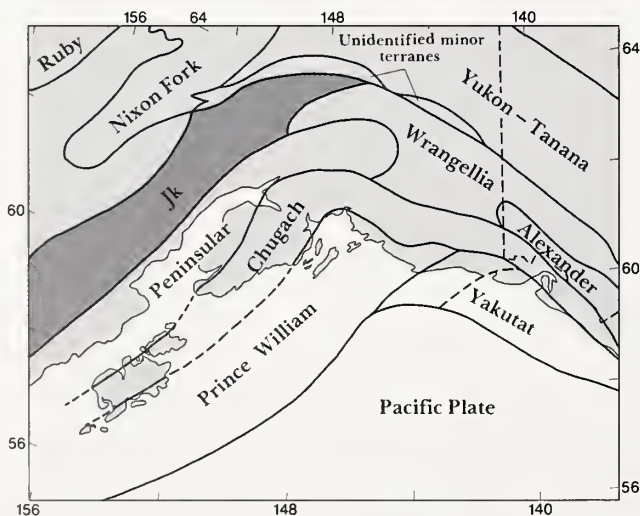


Figure 6-5. Simplified terrane map of portions of southern Alaska (see text for sources). Shaded area labeled Jk is a region that is dominated by extensive Jurassic-Cretaceous flysch.



Figure 6-6. Map of Quaternary volcanic centers in the Aleutian arc and southern Alaska. (Modified from Kienle and Swanson 1983a.)

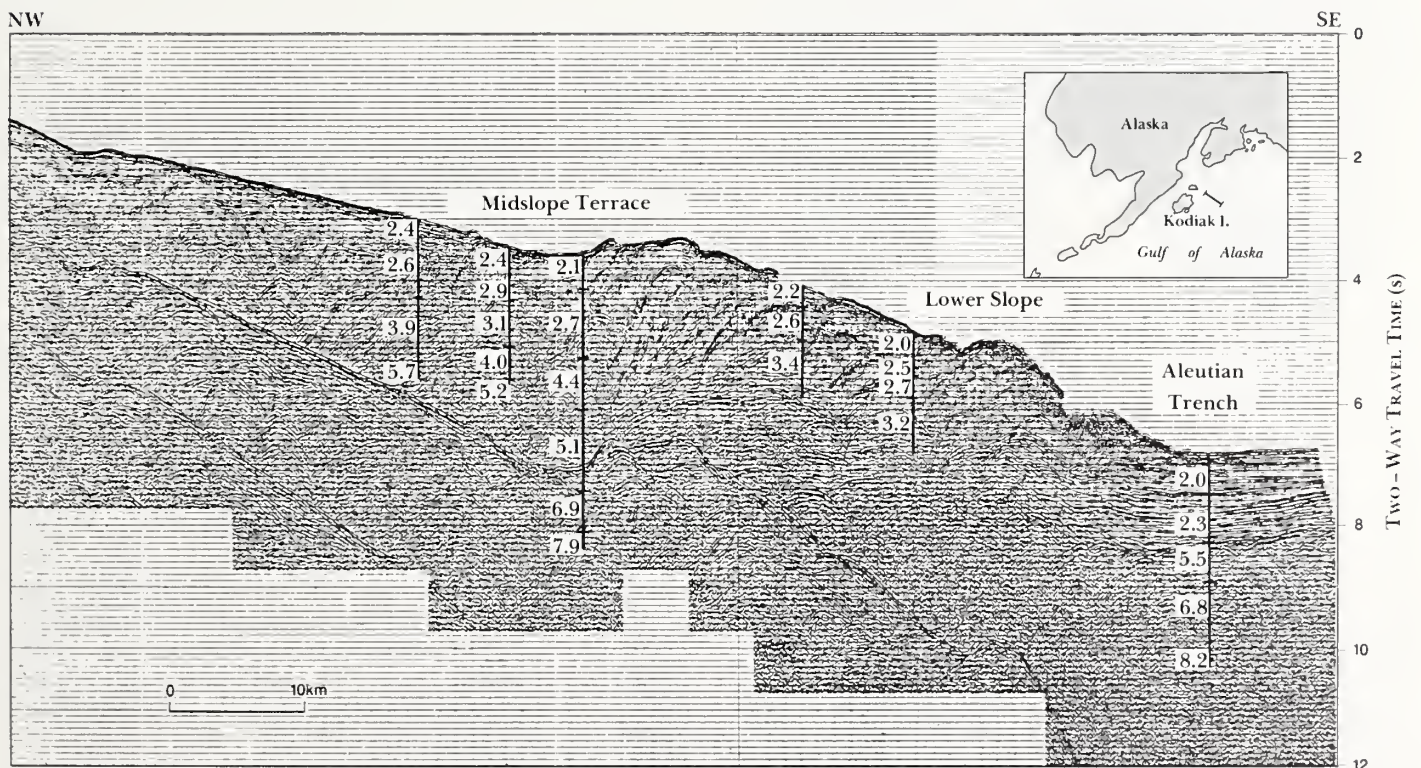


Figure 6-7. Multi-channel seismic reflection record (time section) across the trench slope northeast of Kodiak Island (see inset for profile location). Note the folds and the faults near the Lower Slope, at the leading edge of the accretionary prism. Numbers near vertical bars indicate layer velocities (km/s) derived from refraction studies. Vertical exaggeration is $\times 5$ at the sea-floor. (Modified from von Huene, Fischer, and Bruns 1979.)

flow plays an important role. For instance, Plafker (1969) reports subsidiary faulting on Montague Island during the March 27, 1964 Alaskan earthquake. Internal deformation in submarine basins on the continental shelf of the northernmost Gulf of Alaska are documented by Bruns (1979, 1985). The Chugach–St. Elias Range is internally folded, faulted, and uplifted (Plafker 1967) as a result of its collision with the Yakutat Block that rides partly with the Pacific Plate (Lahr and Plafker 1980; Perez and Jacob 1980a; and Bruns 1983).

Farther inland (see Fig. 6–1), recent strike-slip and/or some dip-slip motion is observed on the Castle Mountain, Denali, Totschunda, and several lesser faults in the Alaska/Canada border regions (Plafker 1985, 1986; Plafker, Hudson, and Richter 1977; Brogan, Cluff, Korrington, and Slemmons 1975; Sieh 1981; Detterman, Plafker, Hudson, Tysdale, and Pavoni 1974; Richter and Matson 1971; Eisbacher and Hopkins 1977; and Clague 1979). Therefore, the entire relative motion of the PAC/NAM Plates cannot be attributed to a single sharply defined plate boundary. Lahr and Plafker (1980) have taken this fact into account and proposed a model that incorporates a secondary plate boundary that extends as far north as the Denali Fault and the Alaskan Range (Fig. 6–8). In reality, however, strain relief may be even more widely distributed in southern and central Alaska.

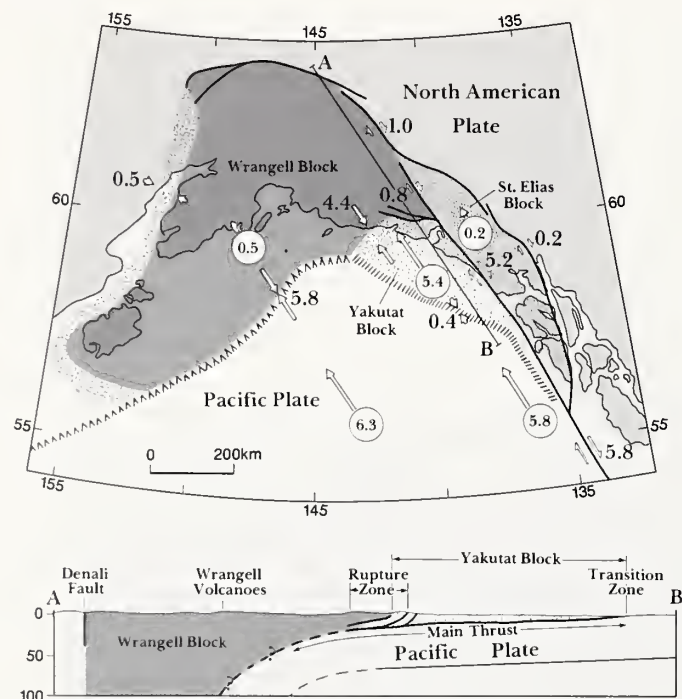


Figure 6–8. Model for present-day crustal deformation along PAC–NAM Plate boundary in southeastern Alaska (after Lahr and Plafker 1980). Top: Map view with estimates of plate-motion rates (circled numbers, in cm/y) of the Pacific Plate, Yakutat Block, and Wrangell Block relative to the North American Plate. Numbers next to paired vectors represent plate-motion rates across the indicated zones. Dot patterns are zones of surface outcrops of deformation and faulting. Bottom: Diagrammatic profile of section A–B across northeastern Gulf of Alaska. Rupture zone is that of the St. Elias earthquake of February 28, 1979. No vertical exaggeration.

No one understands from a quantitative standpoint why the overriding North American Plate apparently deforms internally more readily than the underriding oceanic plate. The higher heat flow from ongoing volcanism, inherited weaknesses along the boundaries of accreted terranes, and the differences in yield strength of silicic (continental) versus the more mafic (oceanic) crust may all play an important role. Another, less likely possibility is that internal deformation rates in the continental and oceanic plates are comparable, but only on land can one readily observe the cumulative slip integrated over long periods of time. On the oceanic plate, it is not observable because evidence is sooner or later either subducted or obliterated by continuous sedimentation.

Seismicity

Major Seismicity and Seismic Gaps. Most of the relative motion between the Pacific and the North American Plates in the Gulf of Alaska is relieved intermittently either by great thrust earthquakes along the Aleutian Trench or by strike-slip faulting along the Fairweather–Queen Charlotte Fault system. The largest recorded Alaska–Aleutian earthquake occurred in 1964 in the Prince William Sound–Kodiak region and measured M_w equal to 9.2 on the moment–magnitude scale. The horizontal slip component for this thrust measured ~ 20 m (based on geodetic data that resolved only part of the total displacement field). The dip-slip component on one of the steeply dipping subsidiary faults (in Henning Bay on Montague Island) measured 7.9 meters. Dislocation–model calculations indicate that the combined horizontal and vertical components of motion on the main thrust zone may have amounted to an average slip of between 20 and 30 meters. Great Alaskan earthquakes generate tsunamis and seiches that in special circumstances produce coastal run-up heights of 30 meters. In one extreme case in 1958, a huge seismically induced landslide displaced a large amount of water in Lituya Bay, creating a vertical run-up that measured in excess of 500 meters! (Miller 1960).

The locations where major plate–boundary earthquakes have occurred in Alaska since 1938 are shown in Figure 6–9 (from Sykes, Kisslinger, House, Davies, and Jacob 1981). During this period of almost 50 years, major earthquakes have broken all but perhaps five segments along the entire 4,000 km plate boundary in the northern Pacific between Southeast Alaska and Kamchatka. The dimensions of the rupture zones for all pre-1972 events were determined by Sykes (1971) by relocating the aftershocks of each main shock (Fig. 6–10). He pointed out that the aftershock zones closely abut each other with little overlap, and also noted that there are a few gaps in recent seismicity for major earthquakes. He suggested that these gaps should be likely sites for future large strain-relieving earthquakes.

Since Sykes' 1971 study, two moderately large earthquakes have occurred in two of the identified gaps. The 1972 Sitka earthquake ($M_s = 7.6$) almost completely filled the gap left between the 1958 Fairweather–Lituya Bay earthquake in the north and the northernmost possible extent of the 1949 Queen Charlotte earthquake in the south. (There remains a

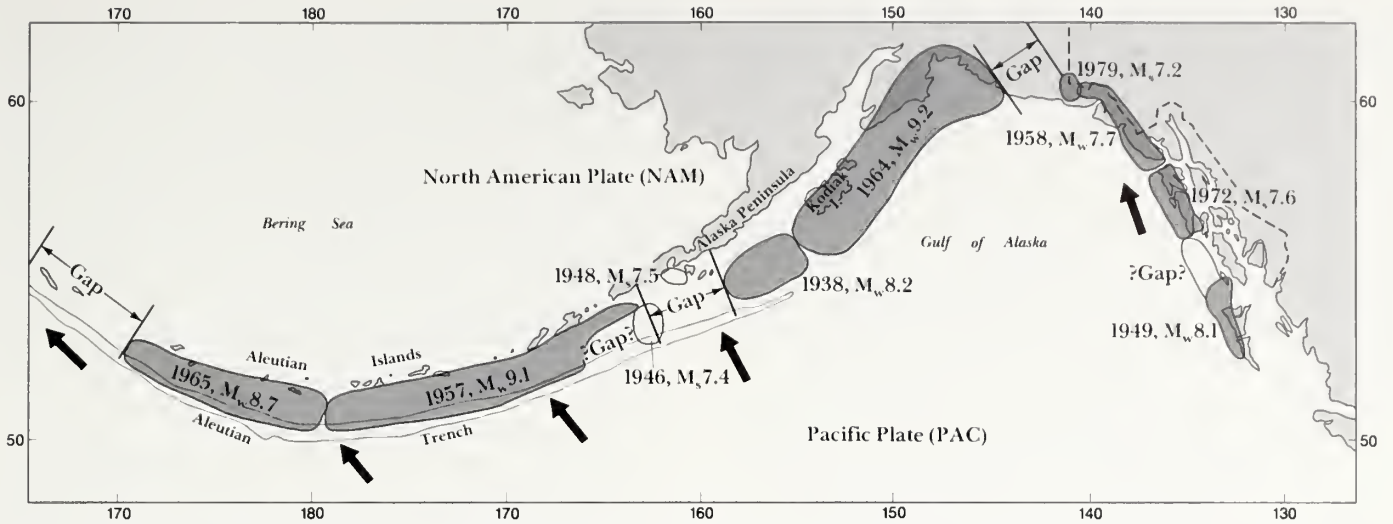


Figure 6-9. Rupture zones of large earthquakes and seismic gaps in the Aleutians, southern Alaska, and off British Columbia for the period 1938 to 1984. (Modified from Davies, Sykes, House, and Jacob 1981; Sykes 1971.) Three well-identified seismic gaps and two possible seismic gaps are illustrated for recent occurrence of large earthquakes. Arrows indicate PAC-NAM relative plate motions.

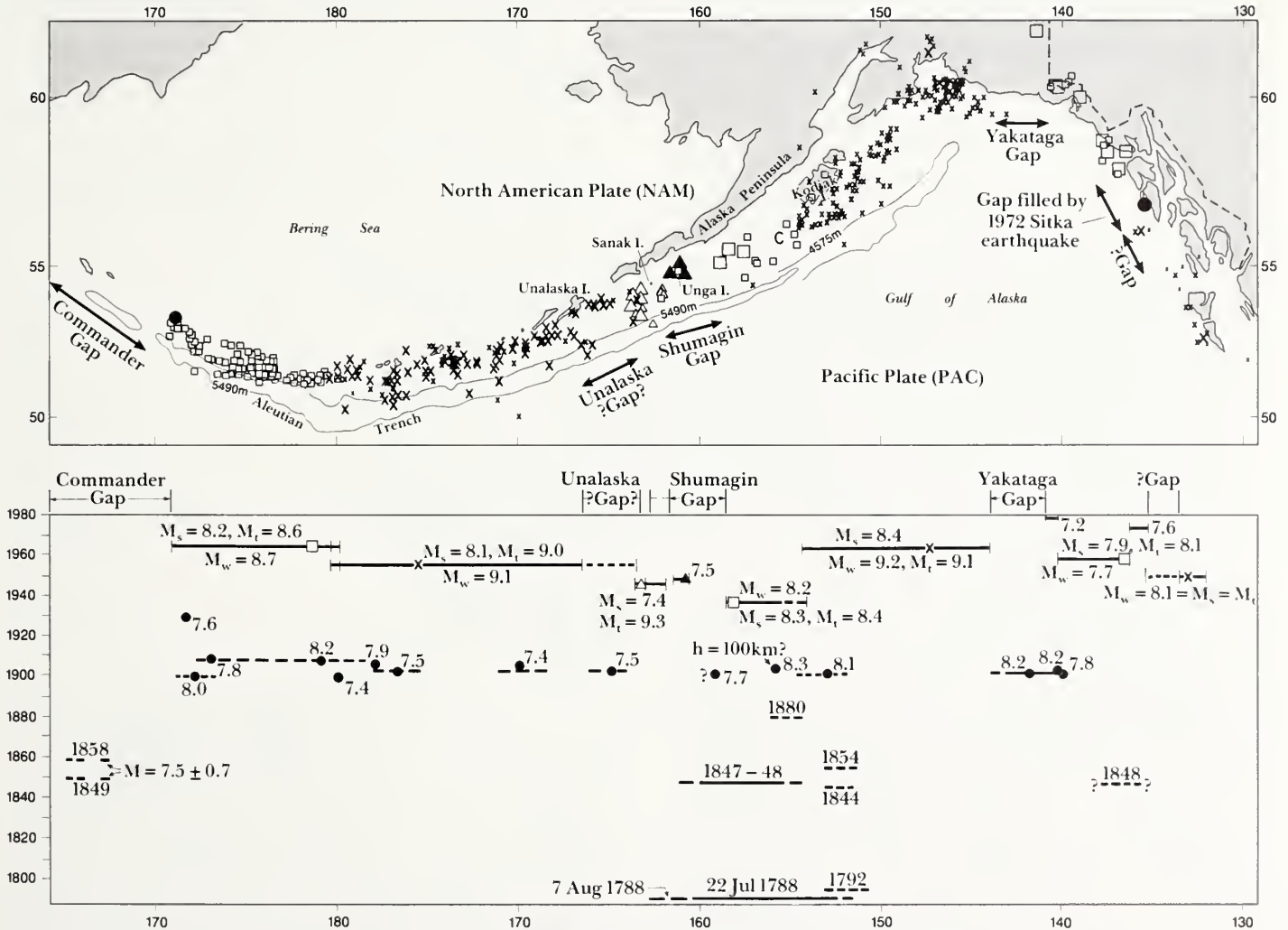


Figure 6-10. Top: Aftershock zones of earthquakes with $M \geq 7.4$ for the period from 1925 to 1971 along the Alaska-Aleutian portion of the PAC-NAM plate boundary. (Modified from Sykes 1971.) Bottom: Space/time diagram of known historic and instrumental great earthquakes along the Alaska-Aleutian arc since 1788 (after Davies, Sykes, House, and Jacob 1981). The time intervals between earthquakes at the same segment are the recurrence times used in Figure 6-11. M_s , M_w , and M_t refer to surface wave, moment, and tsunami magnitudes, respectively.

possible unbroken northern portion in the 1949 aftershock zone where the main shock may not have fully ruptured the plate boundary. There were only a few isolated moderate-sized aftershocks that occurred in the north, but these were south of the after shocks of the later 1972 Sitka earthquake.)

The other major event since 1971 occurred in the Yakataga seismic gap. The gap was only partly filled by the February 28, 1979 St. Elias earthquake of magnitude M_s equal to 7.2 ($M_w = 7.5$) (Buland and Taggart 1981; Lahr, Stephens, Hasegawa, and Boatwright 1980; McCann, Perez, and Sykes 1980; and Perez and Jacob 1980b). Thus a major seismic gap presently exists in the northeastern Gulf of Alaska, between the 1979 St. Elias rupture in the east and the 1964 rupture zone of the great ($M_w = 9.2$) Prince William Sound earthquake (see Fig. 6-9) in the west. This Yakataga seismic gap stretches across the 150 km from Icy Bay to Kayak Island. Part of this gap ruptured last in 1899 (Fig. 6-10) and is thought to be capable of supporting a future earthquake with a likely magnitude (M_w) of about 8.0 to 8.5 if restricted to a single rupture in the gap (McCann, Perez, and Sykes 1980; Perez and Jacob 1980a).

The other major seismic gap in the Gulf of Alaska is located near the Shumagin Islands between the 1938 rupture ($M_w = 8.2$) in the northeast and the 1946 earthquake ($M_s = 7.4$) in the southeast (see Fig. 6-9). The 1946 event was highly tsunamigenic ($M_t = 9.1-9.3$) and its rupture zone and mechanism are poorly constrained. The history of great earthquakes and tectonic setting of the Shumagin seismic gap and vicinity have been discussed in detail by Davies, Sykes, House, and Jacob (1981). They conclude that this gap has a high potential for a great earthquake within the next few decades. The historic and instrumental data are not fully conclusive, but the Shumagin gap may not have ruptured in a truly great earthquake since 1788 or 1847. A future great earthquake filling the entire gap is estimated by Davies *et al.* (1981) to measure about M_w equal to 8.4. An unlikely and extreme scenario would be if the rupture extended into the partly reloaded 1938 rupture zone and/or into the Unalaska segment, in which case these authors estimate that an event with a maximum magnitude of about M_w equal to 9.0 could occur.

Great thrust earthquakes in the Aleutians rupture the plate boundary seismically to depths of probably not more than 40 or at most 50 kilometers. Inter-plate slip at larger depths is ductile on a time scale that may range from minutes to decades. In contrast, the brittle-seismic rupture propagates usually at speeds of about 2.5 to 3 km/s, just below S-wave velocities. Thus, for example, the duration of propagation of the rupture front for a distance of more than 600 km during the 1964 Prince William Sound earthquake was of the order of three to four minutes. Of course, regional shaking lasted longer.

Recurrence Periods for Large Earthquakes. Figure 6-10 (bottom) shows the space-time diagram of known earthquakes with magnitudes M_s equal to or greater than 7.4 for the instrumental (1897 to present) and historic (since 1788) periods. Before 1900, this record is perhaps complete only for the largest events and for the segment between the Shumagins and Kodiak that was sufficiently densely settled by

Russian traders whose records have survived (Sykes *et al.* 1981; Davies *et al.* 1981).

Excluding all events east of 140°W , near the transform segment of the plate boundary, Jacob (1984) used a subset of this historic and instrumental seismicity since 1788 to calculate a probability density distribution for recurrences of events (on the same plate boundary segment) with magnitudes M_w equal to 7.8 and larger. He found that for these great events, recurrence times may be log-normally distributed with an average recurrence of ~ 80 and a range (± 1 SD) that stretches from about 40 to 140 y (Fig. 6-11). These recurrence periods, especially for giant earthquakes (with moment magnitudes larger than $M_w = 8.5$), are highly uncertain.

For the 1964 rupture zone, Plafker and Rubin (1978) used geologic studies to suggest recurrence periods of between 500 and 1,350 y for great thrust earthquakes large enough to form uplifted marine terraces on Middleton Island. The average slip during the 1964 event may have been on the order of 20 to 30 meters. If the average plate-convergence rate of about 6 cm/y for this plate margin is correct, it should take only about 300 to 500 y to restore the stresses on the 1964 rupture zone to essentially their pre-1964 levels. This forecast ignores any aseismic slip or the effects from lesser seismicity.

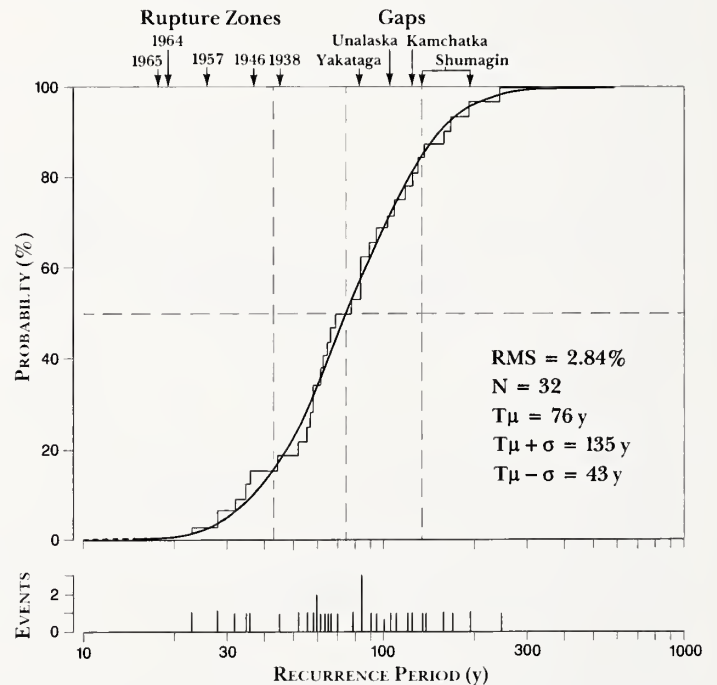


Figure 6-11. Cumulative probability (top) for observed recurrences of great earthquakes ($M \geq 7.8$) in the Alaska-Aleutian arc between Kamchatka and Yakutat Bay since 1788 (incremental curve) and fit of log-normal probability distribution to the data (smooth curve). Discrete probability density of the recurrence periods is shown below. The mean recurrence period is 76 y; the range (based on ± 1 SD) is 43 to 135 years. Note the probabilities that respective segments attained (in 1983) for rerupturing in a new great event; e.g., $\sim 60\%$ in the Yakataga Gap, $\sim 70\%$ for the Unalaska Gap, $\sim 90\%$ for the Shumagin Gap, but only less than 5% for the 1964 and 1965 rupture zones. (Modified from Jacob 1984.)

Sykes and Quittmeyer (1981) and Perez and Jacob (1980b) suggest that if terrace formation is linked to nearby imbricate faulting in the thrust wedge above the main thrust zone, then not every great event on the main thrust will form a discernible marine terrace. This is because different imbricate thrusts may be activated by successive slip events on the main thrust. Despite the contrary evidence summarized by Plafker (1986), these authors maintain that recurrence times that are derived from marine terraces in such subduction environments may be overestimated when compared with actual recurrence periods for great earthquakes. Alternatively, the historic seismic record for Alaska may be too short to provide accurate estimates for when to expect recurrence periods for the largest earthquakes.

Recurrence periods for great earthquakes that have predominantly right-lateral slip on the Fairweather Fault are estimated to vary between 60 and 100 y (Plafker, Hudson, Bruns, and Rubin 1978). These estimates were based on Holocene geomorphic features and the slip during the 1958 ($M_s = 7.7-7.9$) Lituya Bay earthquake.

Occurrence-frequency relationships for moderate- and small-magnitude earthquakes (*i.e.*, $M_w \leq 7.8$) in various source regions near the PAC-NAM Plate boundary in Alaska are discussed by Woodward-Clyde Consultants (1978, 1982) and by Jacob and Hauksson (1983). The data for these smaller events are consistent with the globally observed trend that as the magnitude decreases one unit, the earthquake occurrence-frequency increases by a factor of nearly 10 (corresponding to a so-called 'b-value' of ~ 1).

Teleseismic Patterns. Earthquakes with magnitudes of M_1 equal to or greater than four are usually recorded at teleseismic distances and reported by various agencies in catalogs such as the Preliminary Determination of Epicenters (PDE) published by the U.S. Geological Survey's National Earthquake Information Service (NEIS). Figure 6-12 shows an epicenter map for teleseismically located earthquakes since 1964. This map was taken from the PDE catalogs and indicates the following patterns:

- 1) A subdued activity persists in Southeast Alaska along the Queen Charlotte-Fairweather Fault zone. This seismicity is restricted to shallow depths (< 40 km) consistent with little or no subduction.
- 2) Near the eastern edge of the Yakataga seismic gap (McCann *et al.* 1980) which is centered on $143^\circ\text{W} \pm 1^\circ$, a cluster of seismicity is associated with the St. Elias earthquake ($M_s = 7.2$) of February 28, 1979 (Stephens, Lahr, Fogleman, and Horner 1980).
- 3) West of 145°W , both a strong activity level increase and an increase in the width of the seismogenic zone are associated with both the rupture and the after shock zones of the Prince William Sound earthquake of 1964 ($M_w = 9.2$) (Plafker 1969; Sykes 1971). There, the width of brittle contact between the two plates, as defined by shallow seismicity (< 50 km deep), extends for more than 300 km landward of the trench (Jacob *et al.* 1977).
- 4) Down-dip of this wide, brittle, plate contact, a dipping

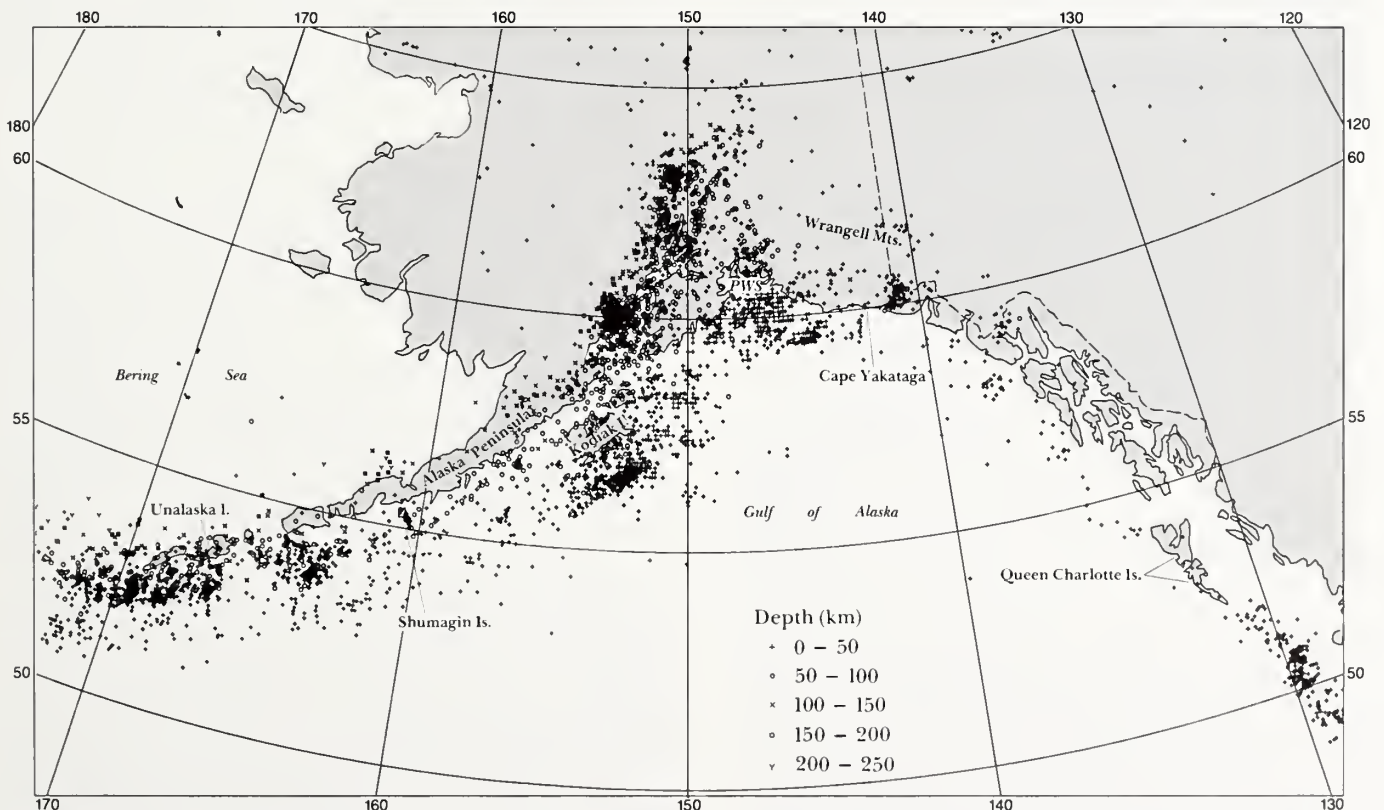


Figure 6-12. Teleseismic epicenter patterns for seismicity in the Gulf of Alaska between 1964 and 1984 for earthquakes with $M \geq 5$ and with epicenters at all depths (data from USGS-PDE files).

seismic (Wadati–Benioff) zone extends from depths of 50 km to ~150 km beneath the central Alaska Range (Agnew 1980), increasing to about 250 km beneath the Alaska Peninsula (Hauksson, Armbruster, and Dobbs 1984).

- 5) West of the 1964 rupture zone near 155°W, the seismicity since 1964 has been low in the 1938 rupture zone (Sykes 1971). The width of the shallow–plate contact narrows from 250 to 150 km (Davies and House 1979) and seismicity in the Shumagin seismic gap is restricted to a ring–like feature surrounding the gap (Davies *et al.* 1981; Hauksson *et al.* 1984).
- 6) A similar, but less well–developed pattern of low seismicity is repeated near Unalaska Island, in a possible seismic gap between the great earthquakes of 1946 and 1957 (House, Sykes, Davies, and Jacob 1981).
- 7) West of the continent–ocean transition (165°W) in the North American Plate, the brittle plate contact, as defined by shallow seismicity, narrows to a width of less than 100 km, which remains more or less constant for most of the oceanic portion of the Aleutian Island arc (House and Jacob 1983). The deepest earthquakes in the Alaskan arc occur at depths slightly less than 300 km (House and Jacob 1983).
- 8) A few scattered seismic events occur south and seaward of the trench. These events are associated both with flexural strains in the Pacific Plate as it approaches the trench, and with the load of the overriding plate.
- 9) Scattered shallow seismicity in south–central Alaska occurs near the Denali, Totschunda, Castle Mountain, and less prominent faults, as well as in the regions surrounding the Wrangell Mountains and the Canadian border.

The major shallow–depth teleseismic patterns on the primary boundary between the NAM and PAC Plates reflect both the occurrence of aftershocks to recent great earthquakes, and the quiescences that precede great earthquakes in seismic gaps. Thus, the shallow–seismicity patterns vary temporally with the earthquake cycle (Sykes 1971; McCann, Nishenko, Sykes, and Krause 1979). In contrast, the patterns of seismicity for the intermediate depth range (50 to 300 km) seem to correlate mostly with the presence (or absence) of dipping slabs of Pacific lithosphere (Fig. 6–3). Therefore, they suggest spatially more stationary patterns, although the possibility of temporal variations has been pointed out (House and Jacob 1983). The deep seismicity (300 to 750 km) that is present in many other island arcs is absent in both the Gulf of Alaska and the Aleutian arc. This restriction of Alaska/Aleutian seismicity to depths shallower than 300 km is consistent with models that predict the thermal assimilation of the lithosphere into the mantle, given the rates of subduction (<7.5 cm/y) and ages (<50 my) of the subducted Pacific Plate in the Gulf of Alaska (Molnar, Freedman, and Shih 1979).

Teleseismic hypocenter locations have random errors of about ± 20 km, and in subduction zones, they also often have an additional systematic mislocation bias of 20 to 40 km arcward, and tend to down–dip towards the descending slabs

(Fujita, Engdahl, and Sleep 1981; House and Boatwright 1980; and Hauksson 1985). Because of these errors, it is advantageous to use data from local seismic networks to resolve detailed tectonic features in the seismicity. The next section discusses the results from several such networks that have been operated in the Gulf of Alaska during the last decade.

Seismicity from Locally Operated Seismic Networks. Except for short periods of aftershock observations (Page 1973, 1975), there have been very few local seismic stations operating in Southeast Alaska that could improve the seismic coverage beyond the coverage already available through teleseismic methods. During OCSEAP–sponsored studies, extensive local seismic monitoring was carried out by the USGS (Lahr and Stephens 1983) in the northeastern Gulf of Alaska, by the University of Alaska in the Kodiak–Shelikof Strait–Lower Cook Inlet region (Pulpan and Kienle 1981; Pulpan and Frohlich 1985), and by Lamont–Doherty Geological Observatory in the Shumagin Island–Alaska Peninsula region (Jacob and Hauksson 1983). Other networks, not discussed here, have been operated farther west in the Aleutian arc on Unalaska Island (Jacob and Boyd 1985), and on Adak and Amchitka Islands (Frohlich, Billington, Engdahl, and Malahoff 1982; Engdahl 1977).

NEGOA–Wrangell Seismic Zone. Seismicity detected by the USGS–operated network (centered on the Yakataga seismic gap in the northeastern Gulf of Alaska [NEGOA]) has revealed an important tectonic feature that had not been previously discernible from teleseismic data: a seismic Wadati–Benioff zone that dips beneath the Wrangell Mountain volcanic chain (Stephens *et al.* 1984). Figure 6–13 (top) shows a subset of the hypocenters located by this network, and Figure 6–13 (bottom) displays the vertical section along the hinged profile A–A'–A". This section clearly reveals a band of seismicity that starts at the base of the continental shelf at depths between 10 and 30 kilometers. It reaches depths of 25 to 35 km beneath the crest of the Chugach–St. Elias mountain range (beneath A'), steepens its dip northeast of the surface trace of the Border Ranges Fault, then moves down to depths of 85 km beneath the southeast edge of the Wrangell volcano. A down–dip extension of the center of the inclined seismic zone would reach a depth of about 100 km beneath the crest of the Wrangell volcanoes. These features strongly suggest that a dipping slab of lithosphere descends with a northeast dip beneath the Wrangell mountains. The far–reaching tectonic implications of this important finding are discussed later in this chapter.

Another significant feature visible in Figure 6–13 (top) is the shallow– and intermediate–depth seismicity that was located by the regional seismic network both in the upper Cook Inlet and in the Prince William Sound segment of the Aleutian arc–trench system. This seismicity is sharply truncated towards the northeast along a line labeled RMI. This line is a segment of a small circle around a pole of rotation for the relative motion of both the PAC and NAM Plates (Minster *et al.* 1974). It could be visualized as a trajectory of a point fixed to the PAC Plate as it moves north–northwest and down beneath the edge of NAM Plate. The sudden drop–off in seismicity to the northeast of this line opens the

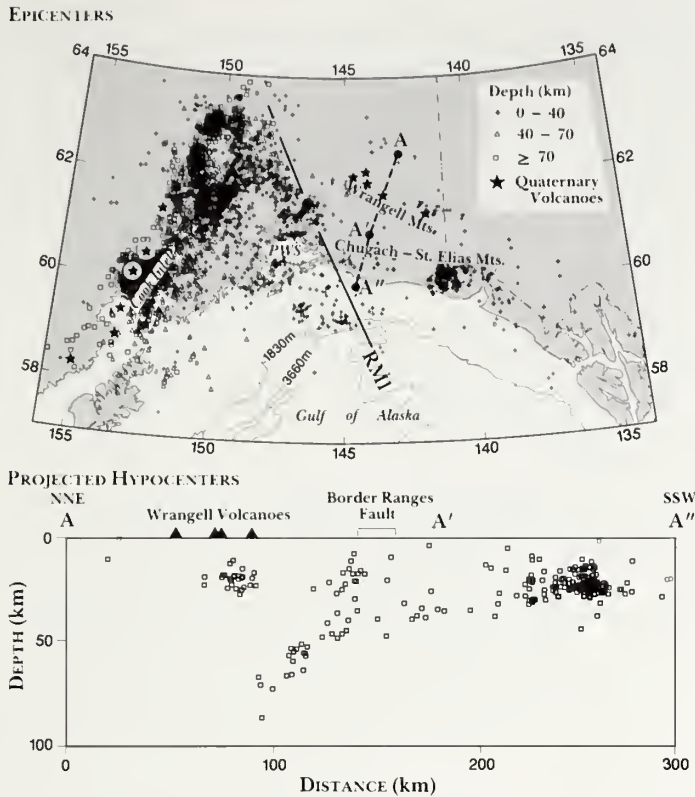


Figure 6-13. Seismicity located by the USGS regional seismic network in the Gulf of Alaska for the period 1980 to 1982 for magnitudes equal to or greater than 2. (Modified from Stephens *et al.* 1984.) Top: Map of earthquake epicenters at three depth ranges. See text for information on RMI line. Bottom: Projected earthquake hypocenters along a section (A-A'-A'') through the Wrangell Benioff zone. No vertical exaggeration.

possibility of a tear (see Fig. 6-3) or of some other discontinuity (*e.g.*, a compositional, thermal, or age contrast) in the descending plate—a discontinuity whose origin is intriguing but as yet unexplained (Stephens *et al.* 1984).

For later comparison with other seismic cross sections farther west in the Gulf, we note the position and depth of the so-called aseismic front. This aseismic front is the locus at which the dipping seismic zone peels away from the brittle seismogenic portion of the overriding plate, leaving a wedge of the mantle aseismic between the two plates. In the NEOGA-Wrangell section of the PAC-NAM plate boundary, this aseismic front is at a depth of only 30 km, just north of and beneath the Border Ranges Fault (Fig. 6-13 bottom).

The Cook Inlet-Kenai-Kodiak Sections. The University of Alaska operated a regional seismic network on portions of the Alaska Peninsula, on Kodiak Island, in lower Cook Inlet, and on the Kenai Peninsula with some overlap and sharing of stations with the USGS network to the east. Published analyses of these network data (Pulpan and Kienle 1979; Kienle, Swanson, and Pulpan 1983; Kienle and Swanson 1983a; and Pulpan and Frohlich 1985) focus both on seismotectonics and volcano seismicity.

Various hypocenters (Fig. 6-14) and three cross sections (A-A', B-B', and C-C') (Fig. 6-15) traverse the Kenai Peninsula as well as Afognak and Kodiak Islands, respectively.

These are the major geographical features in the center of each section. The sections are oriented normal to the local strike of the Wadati-Benioff zone. The direction of the profile nearly coincides with the PAC-NAM plate-motion vector for the Kodiak section C-C', but trends more westerly (rotated counterclockwise by about 24°) for the Kenai section A-A'. The salient seismotectonic features can best be seen on the three vertical sections.

A seismic Wadati-Benioff zone is well developed in all these sections to depths of about 200 kilometers. The thickness of the dipping seismic zone is about 30 to 40 km, with no clear double-planned seismic zone (as discussed later for the Shumagin Islands section). The aseismic wedge is best defined in the Kenai section and shows the depth of the aseismic front at 40 km beneath the northeastern edge of the Kenai section—beneath Cook Inlet.

The brittle thrust contact dips at a shallow angle between the two plates from the trench to the aseismic front. This contact is about 300 km wide in the Kenai, 280 km in the Afognak, and 250 km in the Kodiak section. Assuming that the initial depth of the thrust contact at the trench is at 10 km and that its final depth at the aseismic front is 40 km, then the average dip angles of the oceanic plate are only 5.7°, 6.1°, and 6.8° as it descends beneath the tapered accretionary prism of the fore-arc region. Even if we raise the initial

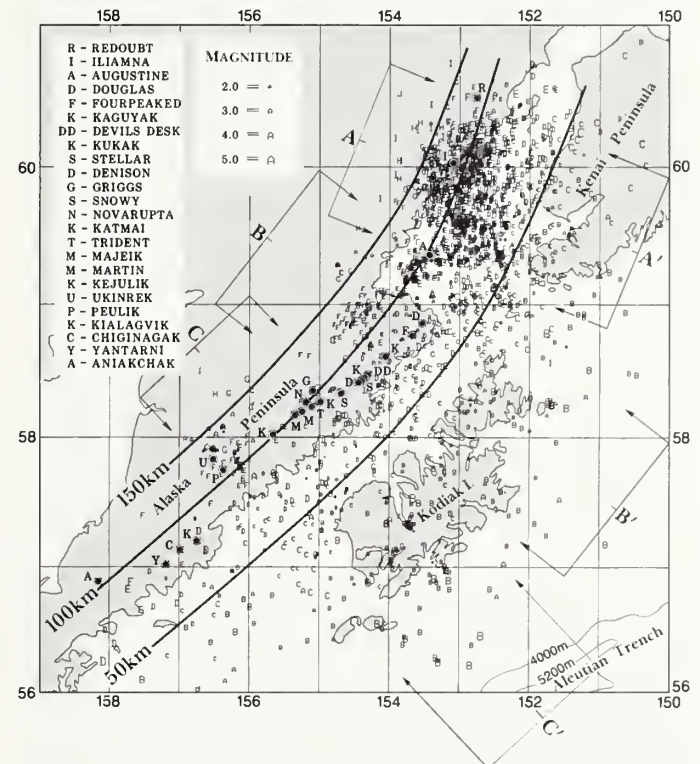


Figure 6-14. Seismicity located by the University of Alaska regional seismic network in the Cook Inlet/Kodiak/Kenai region for the period July 1977 to June 1981. Depth coding of earthquakes is A: 0 to 25 km; B: 26 to 50 km; C: 51 to 100 km, etc., in 50-km steps. Contours of upper surface to Benioff zone show the northwest dip of the descending Pacific lithosphere. Note the deviation from the 100-km depth contour of volcanoes (bold face letter symbols) in the Katmai region. (Modified from Kienle *et al.* 1983; Kienle and Swanson 1983a.)

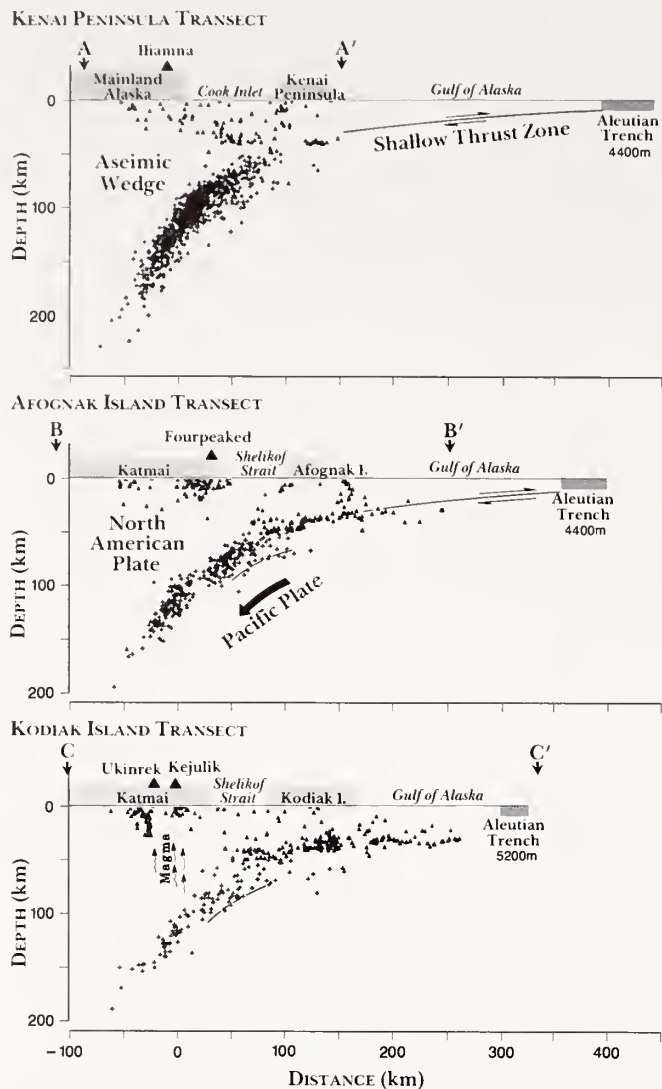


Figure 6-15. Cross sections A-A' (Kenai), B-B' (Afognak Island), and C-C' (Kodiak Island) with hypocenters projected onto sections (refer to Figure 6-14 for section locations). The absence of seismicity on the main thrust zone is partly real and partly due to poor station distribution toward the trench. No vertical exaggeration.

depth of the thrust zone at the trench to 5 km (*i.e.*, to the top of sediments, rather than of the oceanic basement), the average dip-angle of the thrust contact (to a depth of 40 km) would still only be 6.1° , 7.1° , and 8.0° , respectively, for sections A-A' through C-C'. These values are in remarkable agreement with, albeit slightly lower than, the 9° dip of the thrust fault derived by Savage and Hastie (1966) when they interpreted geodetic measurements of crustal deformation during the 1964 Earthquake.

This very shallow dip makes the Gulf of Alaska one of the widest subduction zones in the world. Since the moment of earthquakes is a function of their widths (Sykes and Quittmeyer 1981), this zone is capable of truly giant thrust earthquakes as exemplified by the M_w equal to 9.2 earthquake of March 27, 1964, which probably broke up-dip for the full 250- to 300-km-wide thrust zone.

A peculiarity of the Kenai section (A-A') is the very high level of seismicity in the Wadati-Benioff zone beneath Iliamna volcano, compared with the segments of Wadati-Benioff zone located to the southwest, beneath Katmai. This high activity also stands out on the epicenter map (Fig. 6-14). These activity level differences persist into the higher teleseismic-magnitude range (Fig. 6-12), and last for longer periods of time. The teleseismic activity spans almost two decades, while the network data cover only the four years from July 1977 through June 1981.

During periods of volcanic quiescence, few shallow crustal earth quakes are associated with volcanoes. In section C-C' we note some shallow crustal activity, which coincides in time and space with the sudden formation of the Ukinrek Maars in 1977 (Kienle, Kyle, Self, Motyka, and Lorenz 1980).

Shumagin Islands Section. A seismic network has been operated by the Lamont-Doherty Geological Observatory in both the Shumagin Islands and the outer Alaska Peninsula since 1973. The network is centered on the Shumagin seismic gap (Davies *et al.* 1981). Salient results from the analyses of network data were as follows:

- 1) A double-planed dipping seismic zone at depths below 70 km was found with an unusual pattern of down-dip tensional focal mechanisms in the upper plane.
- 2) Strong compression across the arc can be inferred from strike-slip mechanisms in the overriding plate; both these results imply strong compressive coupling between the converging PAC-NAM Plates (Reyners and Coles 1982).
- 3) The locked main thrust zone, which is expected to rupture in an impending great Shumagin earthquake, is at present seismically rather quiescent.
- 4) Very high stress concentrations are found at a depth of 40 km near the aseismic front. This was indicated by a few high-stress-drop events with magnitudes of about M_b equal to 6 (House and Boatwright 1980).
- 5) A burst of subcrustal seismicity was associated with a geodetically detected slip event and an unusual paucity of eruptive activity from the nearby Pavlof volcano, all consistent with an inferred ~ 80 cm downward slip of the descending Pacific Plate at depths of between 25 and 80 kilometers. The unusual event took place over a one- to two-year period during the period 1978 to 1980 (Beavan, Hauksson, McNutt, Bilham, and Jacob 1983; Beavan, Bilham, and Hurst 1984). This deep-seated event is inferred to have brought the locked shallower portion of the main thrust zone closer to failure.

The spatial distribution of the Shumagin network seismicity is shown in map view (Fig. 6-16) and in two cross-sectional views (Fig. 6-17) (from Hauksson *et al.* 1984). The figures show 1) the concentration of seismicity next to the aseismic front, 2) the down-dip end of the shallow thrust zone, and 3) the relative quiescence of the shallowly dipping portion of the thrust towards the trench. The width of the thrust zone between the trench and aseismic front at 40 km depth is about 140 km; hence the dip of main thrust is 12 to

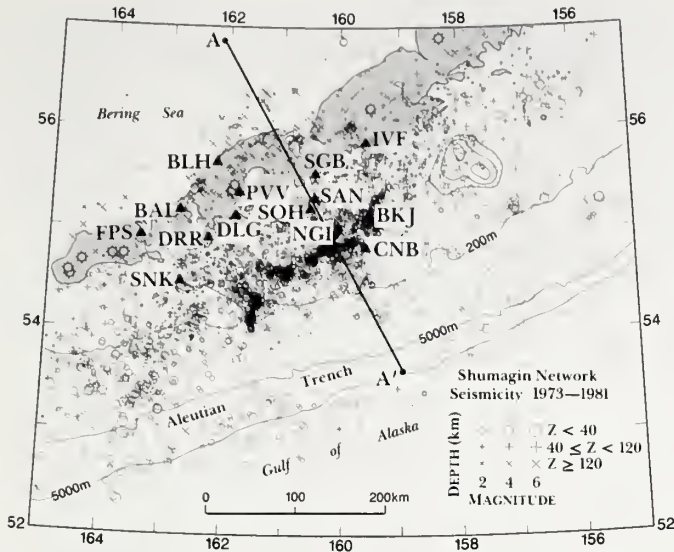


Figure 6-16. Seismicity located by the Lamont-Doherty regional seismic network in the Shumagin Islands and vicinity of the eastern Aleutian arc for the period 1973 to 1981. Three-letter symbols and triangles indicate network stations, sun symbols represent volcanoes. Section A-A' is used for projecting hypo-centers in Figure 6-17. (Modified from Hauksson, Arnbruster, and Dobbs 1984.)

14°, depending on either a 5- or a 10-km starting depth at the trench. These dip values are almost twice those for the Kenai section of the 1964 rupture-zone, and the width of the thrust is almost half of that for the Kenai section of the same zone.

More recently, Hauksson (1985) used 3-dimensional seismic-ray tracing to correct the systematic hypocenter mislocation of events in the deeper portion (> 100 km deep) of the Wadati-Benioff zone. He found that at depths from 80 to 250-300 km, the Wadati-Benioff zone dips at a constant angle of 45° and the associated cold slab of dipping lithosphere has a 7% higher P-wave velocity than the surrounding hotter mantle.

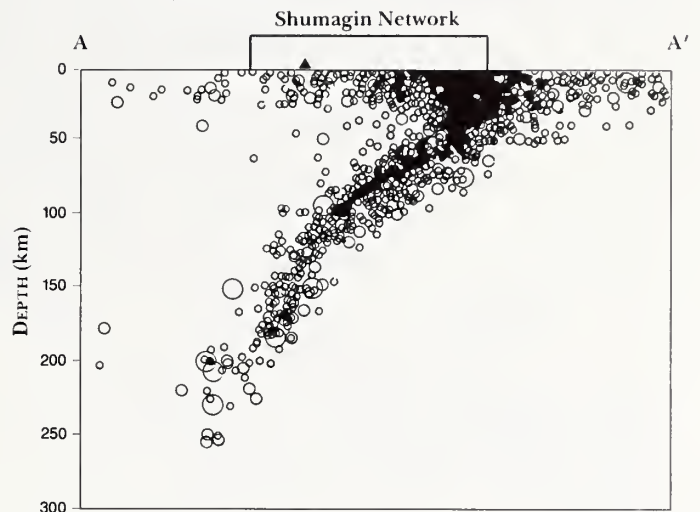
Crustal Deformation

Focal Mechanisms. An earthquake releases strain by slip across a fault under stress, resulting in a four-lobed radiation pattern for the seismic compressional (P) waves. The polarities of P waves can be separated into four quadrants by a set of two orthogonal nodal planes. Two quadrants contain compressional (outward directed) P-wave motions and the other two quadrants contain dilatational (inward directed) motions. A projection of a focal hemisphere (lower or upper) is known as a focal mechanism (Fig. 6-18). The quadrants with compressional-wave arrivals contain the T (tensional) axis, while those quadrants with the dilatational arrivals contain the P (pressure) axis. To determine which of the two nodal planes is the fault plane, one must use circumstantial evidence, such as aftershock alignments, or kinematic and geological arguments (see Introduction).

The lower-hemisphere projections of focal mechanisms for a set of teleseismic earthquakes in the Gulf of Alaska are shown in Figure 6-18 (after Jacob and Perez 1981). The solid quadrants contain compressional arrivals (and the T axis), open quadrants contain the dilatational arrivals (and the P axis). Mechanisms with half-tone shading are for Wadati-Benioff zone events (≥ 50 km deep). All others are for shallower events. There are essentially four types of mechanisms in this set:

- 1) *Normal faults* associated with flexure in the downgoing shallow portion of the Pacific Plate, both at or near the trench, and beneath Kodiak Island and the Kenai Peninsula (nos. 1,2,3,14,17,18).

ALL HYPOCENTERS 1973-1981



BETTER LOCATED EVENTS

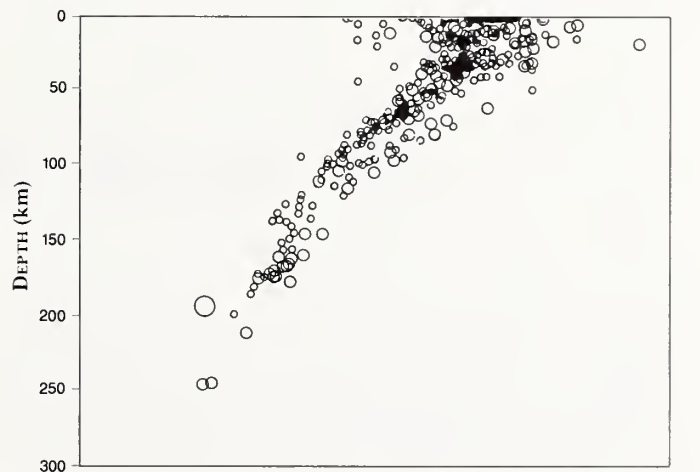


Figure 6-17. Depth profile along section A-A' showing hypocenters in the Shumagin Islands region. Symbol size is keyed to magnitudes. Top: All hypocenters recorded between 1973 and 1981. Bottom: Only better located events are plotted. Note double-planned seismic zones at depths between 60 and 120 kilometers. Lack of events toward trench is real and appears related to relative seismic quiescence of main thrust zone in the Shumagin Seismic Gap (see Figure 6-16 for location of section and data source).

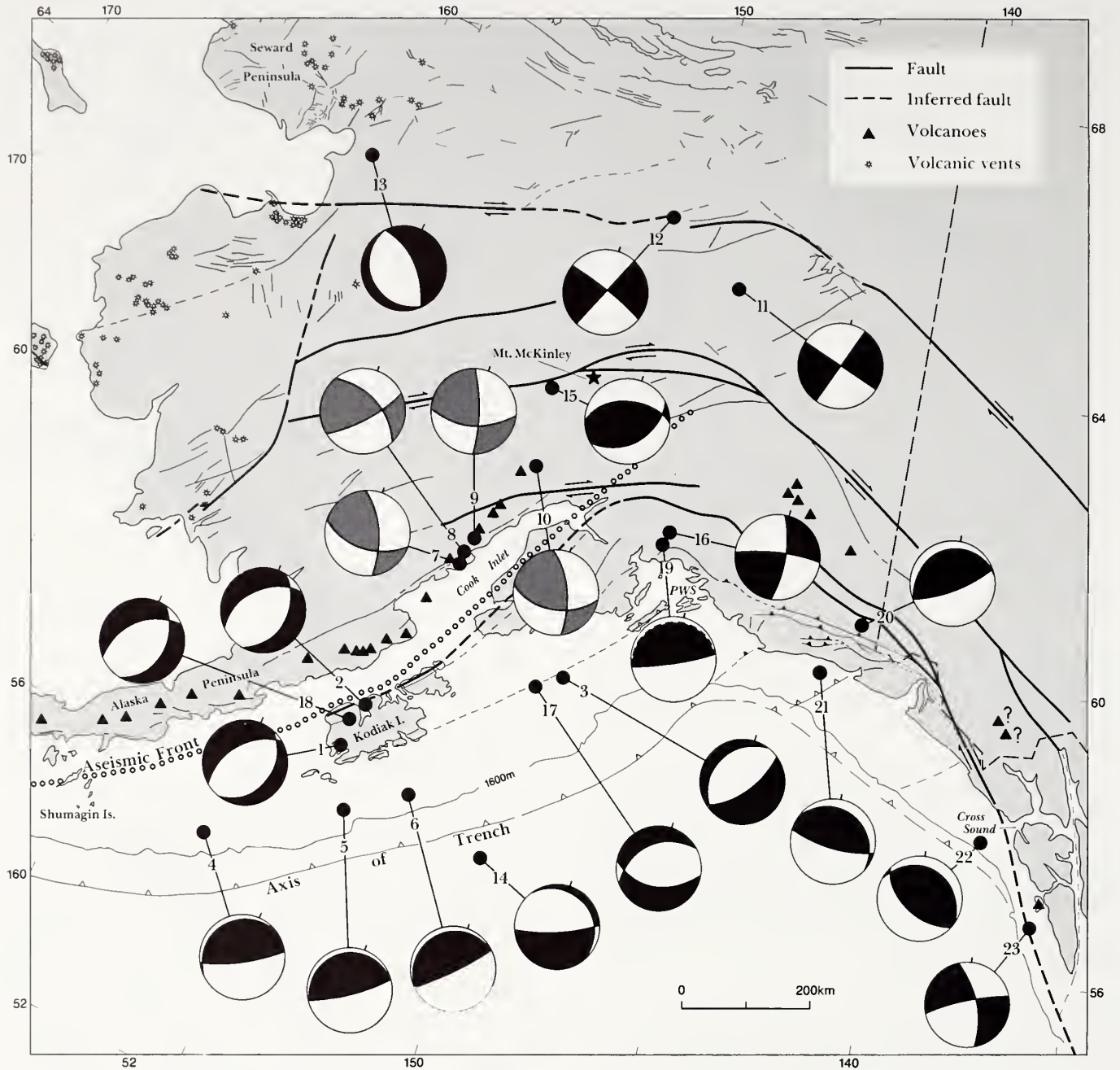


Figure 6–18. Earthquake focal mechanisms in the Gulf of Alaska and adjacent interior Alaska. Lower hemisphere projections; shaded quadrants contain ray directions with compressional P arrivals, open quadrants contain dilatational P arrivals. Solutions with solid shading are for shallow events (depths ≤ 60 km), those with tonal shading are for events with depths equal to or greater than 60 kilometers. Note strike-slip solutions (nos. 11, 12, 16, and 23); thrust solutions (nos. 4–6, 15, and 19–22); normal faulting (nos. 1–3, 13, 14, 17, and 18) and down-dip tensional solutions in the descending slab (nos. 7–10). Based on unpublished data by Jacob and Perez (1981) and Suarez *et al.* (1984).

2) *Thrust faults* in which the subhorizontal nodal plane is assumed to be the plane of faulting. These events occur on the main thrust zone beneath the active margin anywhere between Cross Sound (57°N , 136°W) and the Shumagins. These thrust solutions reflect, with few exceptions (nos. 21, 22), the basic PAC–NAM convergence (nos. 4, 5, 6, 19, 20).

3) *Right-lateral strike slips* (in Southeast Alaska along the Queen Charlotte–Fairweather Fault) reflect the PAC–NAM transform motion (no. 23).

4) *Down-dip tensional stresses* in the descending Pacific lithosphere (nos. 7, 8, 9, 10) found in the Wadati–Benioff zone beneath the upper Cook Inlet and adjacent volcanic arc.

In the Alaska interior, we note a south-to-north transition that runs from thrusting (no. 15) near Mount McKinley, to a strike slip near and around Fairbanks (nos. 11,12), to dominant normal faulting (no. 13) associated with apparent extension and alkali basalt volcanism on the Seward Peninsula, in western Alaska, and on portions of the Bering Sea shelf.

The above examples are only a representative subset of a large number of fault-plane solutions obtained during many different studies using teleseismic data (Tobin and Sykes 1968; Chandra 1974; Perez and Jacob 1980a,b; Hasegawa, Lahr, and Stephens 1980; Gedney 1970; Stauder and Bollinger 1966; Stauder 1968; and House and Jacob 1983). Other fault-plane solutions were derived using microseismic earthquake data (Stephens *et al.* 1980; Reyners and Coles 1982; and Hauksson *et al.* 1984). The tectonic inferences from these focal mechanisms are discussed next.

Seismic Slip Vectors and Tectonic Implications.

Earthquakes both delineate active faults and reveal the sense and direction of slip on those faults. Figure 6-19 shows the slip vectors for a set of earthquake mechanisms in the Gulf of Alaska in comparison with slip vectors inferred for PAC-NAM Plate motions. The comparison demonstrates how well seismic slip on the Queen Charlotte-Fairweather Fault system during earthquakes (nos. 1-4) coincides with

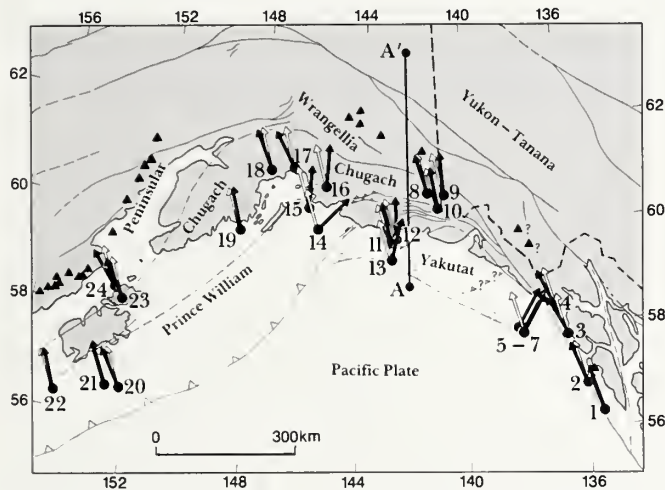


Figure 6-19. Seismic slip vectors (determined from focal mechanisms illustrated in Figure 6-18; Perez and Jacob 1980a) plotted on a tectonic sketchmap showing major tectonic terranes. Seismic slip vectors (solid arrows) show the direction of motion of the crust that is attached to the overriding Pacific Plate (relative to the crust attached to the overriding North American Plate). Note the general coincidence of the seismic slip directions with computed slip directions (open arrows) inferred for the PAC-NAM plate motion model RM2 of Minster and Jordan (1978). Right-lateral strike slip (nos. 1-4) occurs where slip vectors parallel the plate margin, and regular thrusting (nos. 8-10 and 18-24) occurs where vectors are at a high angle to the strike of the plate margin. Oblique thrusting (nos. 5-7 and 11-17) often occurs near the region where the motion of the Yakutat block complicates the slip patterns. Profile A-A' indicates the location of the section shown in Fig. 6-20.

the slip expected for PAC-NAM right-lateral motion. Similarly, the thrust earthquakes along the Alaska-Aleutian subduction zone (nos. 8-10 and nos. 18-24) show slip vectors that are close to those vectors for globally computed plate motions. In the northeastern Gulf, the terrane of the Yakutat Block both collides with and accretes to the North American continental margin (Lahr and Plafker 1980). There, some mismatch occurs between the seismically observed slip vectors and those slip vectors calculated for PAC-NAM Plate motions. These misorientations imply (Perez and Jacob 1980a) that the Yakutat Block is no longer attached to the Pacific Plate, but has started to thrust onto the oceanic portion of the Pacific Plate in a southwest direction. The forces responsible for this thrusting may be very recent. The buoyant, semi-continental Yakutat Block may have started resisting further subduction beneath the Chugach-St. Elias ranges of the Alaskan Plate margin only during the last million years.

Section A-A' (Fig. 6-20) illustrates the collision tectonics that characterize this continental margin. Subhorizontal detachment faults dip gently for distances of ~100 km beneath the deformed margin. Near the seaward edge of the thrust belt, the subhorizontal detachment faults curve upward into more steeply dipping, imbricate, listric thrust faults. Inland, beneath the surface trace of the Border Ranges Fault, the detachment at depths of ~30 km curves downward into a steeply dipping master thrust. This curve coincides with what is most likely the crust-mantle boundary (Moho) of the subducting slab of Pacific lithosphere. The cross section suggests (based on limited data) that the Pacific Plate is presently underthrusting the Chugach-St. Elias range. The leading edge of the Pacific Plate is apparently plunging beneath the Wrangell volcanoes, whose Quaternary activity is related to deep magma generation resulting from a release of volatiles from the dipping slab into the adjacent, advecting mantle. The volatiles lower the melting point of the mantle rocks.

It is uncertain whether the slab dipping beneath the Wrangell Mountains is genuine *oceanic* Pacific Plate that has underridden the Chugach-St. Elias range and/or the Yakutat Block. If it is not a regular oceanic plate, the subducted portion of the Pacific Plate could once have belonged to a transitional *continental* lithosphere similar in structure to the present combination of Yakutat crustal block and its poorly known subcrustal lithosphere (Bruns 1983, 1985). In the former model, it is implied that both the Chugach-St. Elias range and the Yakutat Block are allochthonous to the Pacific lithosphere (Lahr and Plafker 1980; Perez and Jacob 1980a; and Stephens *et al.* 1984). The latter model, however, implies that the Yakutat Block (at least until recently) was autochthonous to, and an integral part of, the Pacific Plate (Bruns 1983, 1985). If Bruns' model applies, this Yakutat Block may only now be in the initial process of being detached from the subducting Pacific Plate (mechanisms no. 22 of Fig. 6-18; and nos. 5,6,7, and 13 of Fig. 6-19) because the block is colliding with the continental edge in the Chugach-St. Elias range. Figure 6-18 reflects a bias for the first model, but needs to be verified by future work.

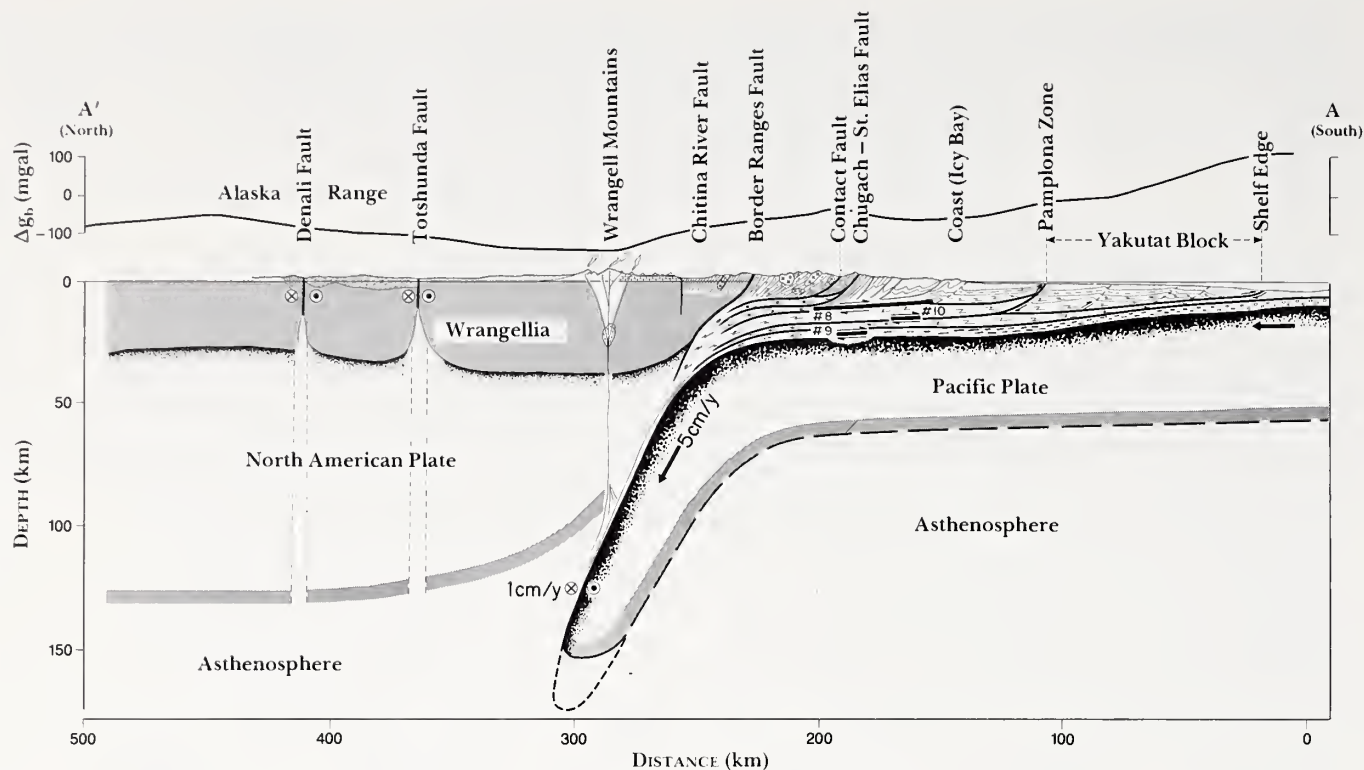


Figure 6-20. Schematic tectonic profile (section A-A' on Figure 6-19; Perez and Jacob 1980a) across the northeastern Gulf of Alaska from the abyssal Pacific (A) to the Yukon-Tanana terrane in the north (A'). Note that thrust solutions 8, 9, and 10 (same labeling as in Fig. 6-19) occur where the Pacific Plate and a down-dip extension of the Yakutat Block slip on a possibly multi-planed detachment beneath the Chugach/St. Elias mountain range which forms the leading edge and collisional boundary of the North American Plate. This tectonic profile assumes the oceanic Pacific Plate descends beneath the Wrangell volcanoes, a hypothesis which at this time is not proven (see discussion in text).

Plate Slip Versus Plate Deformation. If plates were perfectly rigid, they would slip steadily past each other without any deformation of either plate. If the two slipping plates were each perfectly elastic, they would still slip past each other without any permanent long-term deformation. But between slip events (earthquakes), the plates would take up elastic deformation that would completely rebound during earthquakes. For example, a plate boundary with 5-cm/y long-term motion would experience 10,000 earthquakes (of great magnitudes), each with ~ 5 -m slip to move the two plates 50 km past each other in one million years (the duration of the Pleistocene). Still, the two plates would be virtually undeformed internally if they behaved perfectly elastically throughout the 10,000 great earthquakes. Obviously, this is not the case. The slip between the plates is not neatly confined to a single master fault, because the finite strength of the rock in either plate causes secondary faulting.

It is this secondary faulting, associated with folding and ductile shearing, that creates the tectonic styles and much of the land forms. Magmatism, erosion, redeposition, and isostasy do the rest. The more that plate slip is diffused away from a single master fault between plates, the more tectonics is imprinted into the plate margin. As more plate slip is confined to a single plate-boundary fault, there is an increase in elastic recovery during the interseismic times between great earthquakes. However, deformation on secondary faults in either plate is not generally recoverable. This distinction is

important in understanding the tectonic significance of the crustal deformations that occur during great Alaskan thrust earthquakes. Figures 6-21 and 6-22 illustrate this case for the Prince William Sound earthquake of 1964. Figure 6-21 (from Plafker 1969) shows in map view the regions of mostly recoverable uplift southeast of Kodiak Island and the Kenai Peninsula and the regions of mostly recoverable subsidence northwest of Kodiak Island and the Kenai Peninsula. Profile A-A' (insert) shows that the co-seismic vertical deformations were largely opposite in polarity to that of the preexisting topography/bathymetry. The long-wavelength surface deformation represents largely elastic (recoverable) strain. Figure 6-22 shows models that can satisfactorily explain the elastic long-wavelength deformations at the surface (away from the fault) in terms of slip (with amplitudes between 3 and 18 m) on the main thrust at depth.

Superimposed on these major patterns are short-wavelength secondary patterns that reveal steep-angle subsidiary thrusting that cuts the surface of the fore-arc prism. The mostly irreversible deformation within the North American Plate during the 1964 event occurred as thrust motion both on the steep-angle Patton Bay Fault on Montague Island and on comparable offshore faults. Most other effects on the NAM Plate are elastic rebound, and therefore do not represent permanent internal deformations within NAM. These are related to the slip on the master fault between the NAM Plate and the PAC Plate.

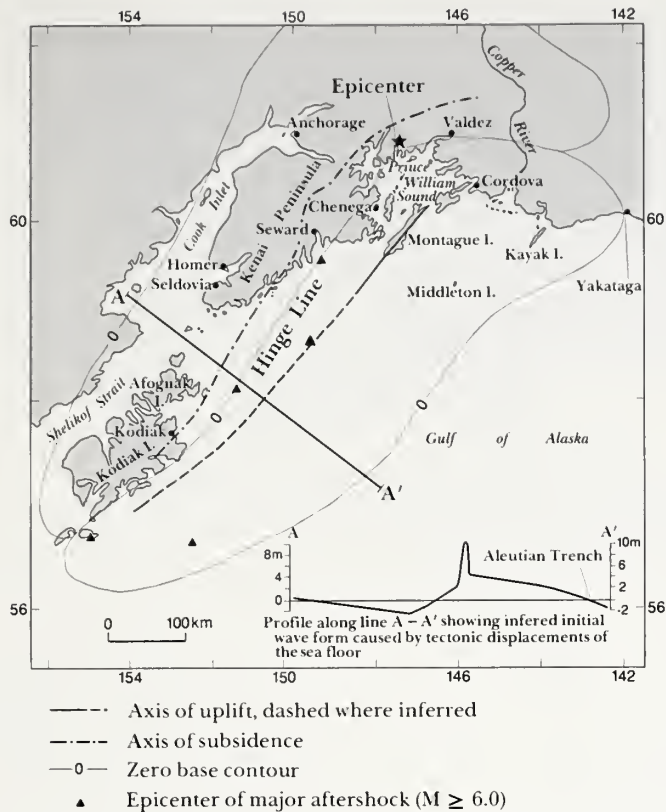


Figure 6-21. Vertical crustal deformation associated with the Great Alaskan Earthquake of 1964 (Prince William Sound). Note hinge line of zero vertical motion straddling the southeast shores of Kodiak Island and the Kenai Peninsula that separates an area of uplift in the southeast from an area of subsidence to the northwest. (Modified from Plafker 1969.)

The cumulative effects of irreversible deformation (by internal faulting in the NAM Plate) were exemplified in 1964 by the Patton Bay Fault. These effects can be seen elsewhere, as in the structures described by Bruns (1979, 1985) in the Yakutat shelf of the northeastern Gulf of Alaska (Fig. 6-23). Note the extensive offshore fold-and-thrust-belt with deeply infilled interfold basins (some have up to 5 km of thick young sediments). This offshore fold-and-thrust belt is formed above a main detachment by the internal shortening of the overriding NAM Plate. The folding is driven by the underplating and collision of the Yakutat Block that, in turn, is partly attached to and driven by the Pacific Plate (Figs. 6-18 through 6-20).

Faulting and crustal deformation are not restricted to the leading edge of the NAM Plate, however. Lesser faulting and crustal deformation occur as far north as central Alaska (Figs. 6-1 and 6-8), with motion documented for the Castle Mountain, Denali, Totschunda, and several lesser faults. Present slip rates on these interior faults are believed to be less than 1 cm/y, although they were probably more active at one time. A new compilation of active faults of Alaska is presently being prepared (G. Plafker, U.S. Geological Survey, pers. comm., 1985). When completed, it will constitute an important quantitative update of the older, mostly qualitative studies of crustal deformation in the Alaskan portions of the North American Plate.

Indicators of Tectonic Stress. A regional compilation of the directions of maximum horizontal compression (σ_{hmax}) based mostly on volcanic stress indicators is shown in Figure 6-24 (Nakamura *et al.* 1977; Nakamura, Plafker, Jacob, and Davies 1980). A few data points are based on surface faulting. The figure shows that along the eastern Aleutian volcanic arc, the maximum horizontal stress is closely aligned with the azimuth of relative PAC-NAM Plate motion. This result is in close agreement with the previous observation that at least the eastern portion of this arc-trench system is under considerable compression, both from the accretion of terranes and from underthrusting across the unusually wide plate contact at the leading edge of the overriding plate. Along the Fairweather transform-fault system, both fault data point No. 1 and Mount Edgecumbe volcano data point No. 186 (Fig. 6-24) indicate a 45° clockwise-rotated trend of σ_{hmax} with regard to both the northwest-trending plate boundary and the slip vector. This trend is to be expected for this right-lateral strike-slip regime. In central Alaska, a strike-slip regime dominates, with the σ_{hmax} direction fanning symmetrically out east and west from the 148° meridian. Nakamura *et al.* (1977, 1980) point out that in west central Alaska as well as on the Bering Sea shelf, this fanning takes on a more westerly trend for σ_{hmax} . There, σ_{hmax} coincides with the intermediate stress axis (σ_2), implying a dominantly (north-south)

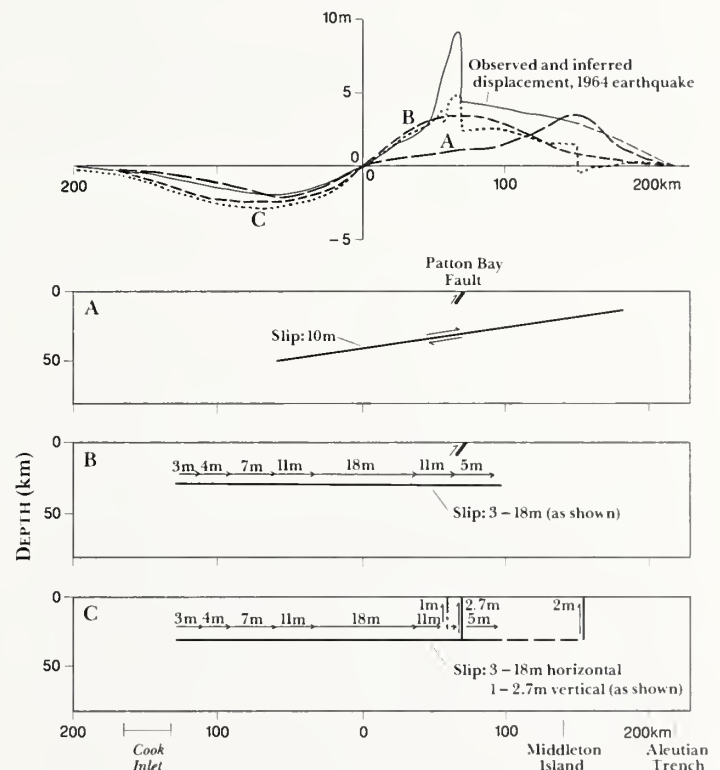


Figure 6-22. Comparison of observed and inferred profiles of surface displacements for the 1964 rupture zone. (Modified from Plafker 1969.) Three models (A, B, and C) are shown that try to explain the surface deformation with slip that is modeled on faults at depth. Model A is from Savage and Hastie (1966), and models B and C are from Stauder and Bollinger (1966). Note steep-angle subsidiary thrust emerging at Patton Bay.

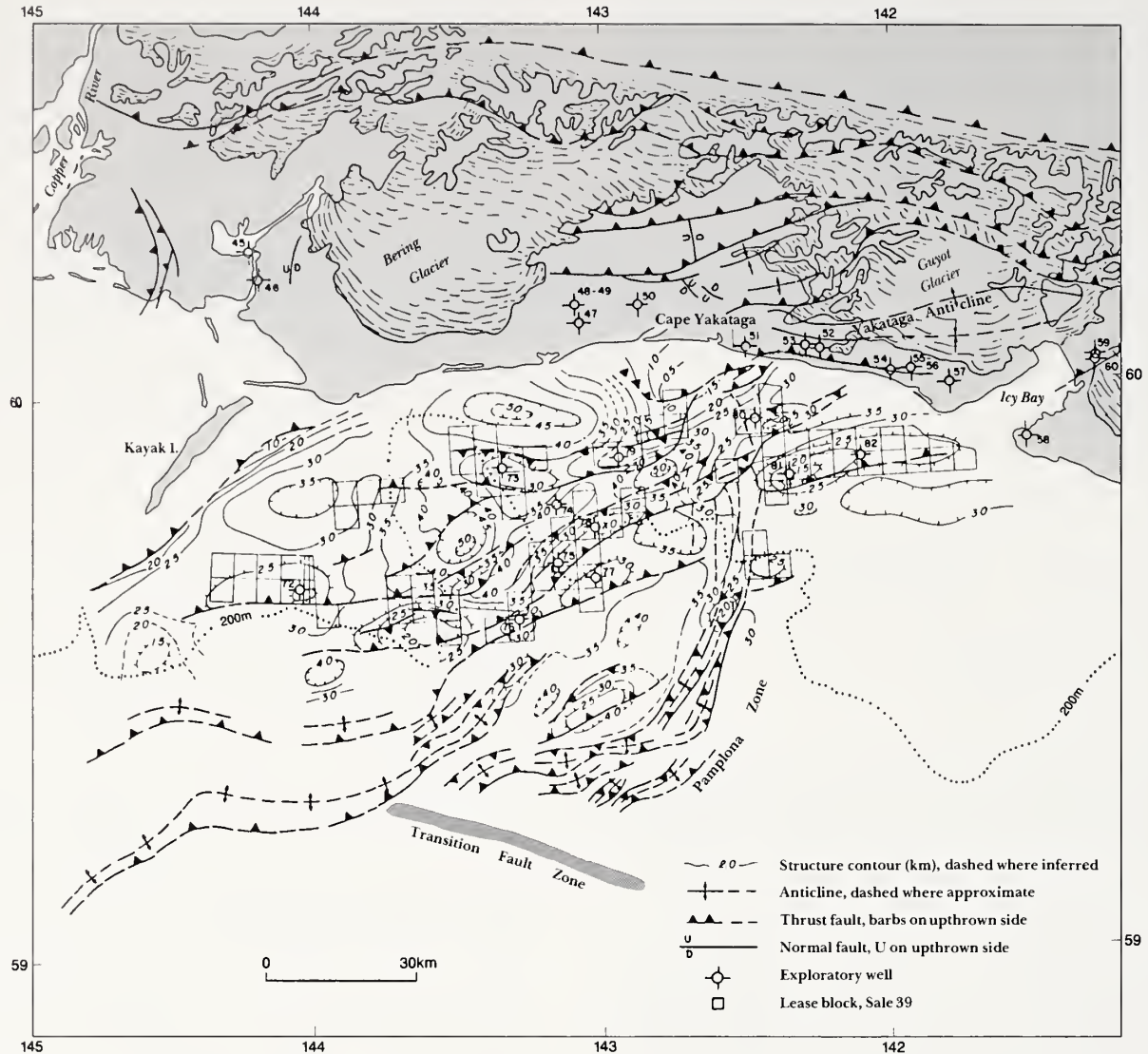


Figure 6-23. Structures and basins of the thrust and fold belt in the Yakataga area of the northeastern Gulf of Alaska. (Modified from Bruns 1979.) Contours are based on multichannel seismic data and show configurations of isopachs of presumed Pliocene (?) strata.

extensional regime favoring east-west trending normal faults (e.g., on the Seward Peninsula and Bering Sea shelf).

The side projections of pressure (P) and tension (T) axes of earthquake focal mechanisms in the Gulf of Alaska are shown in Figure 6-25 along a northwest-southeast profile that crosses Kodiak Island. Note that for earthquakes at depths of 20 km and deeper, located on or near the main thrust zone, the P and T axes are not oriented vertically. Moreover, thrust and normal faulting solutions are very closely interspaced both in depth (Fig. 6-25) and in map view (Fig. 6-18—solutions 1,2,3,17, and 18 are normal faults; most other nearby events represent thrust faults).

Detailed seismic body-wave modeling (Suarez, Jacob, Perez, and Ghosh 1984) suggests that virtually all the normal faulting events are located ~ 5 km beneath the main thrust and inside the subducting oceanic Pacific Plate. The normal-fault events are located where downward bending of the plate creates tensional stresses in the upper portion of the downgoing slab. They are therefore equivalent to the

extensional, normal-fault events commonly observed at the flexures of trenches and outer rises.

The tectonic and rheologic implications of the close spatial coexistence of thrust events and normal-faulting events in the Gulf of Alaska subduction zone are not yet fully resolved. We surmise, however, that the normal-faulting, bending events beneath the thrust zone should not preclude the fact that net horizontal compressive stresses are being transmitted across this plate margin.

Seismic and Volcanic Hazards

Hazards are generated by both seismic and volcanic events. Seismic hazards originate either from direct seismic effects such as ground shaking, faulting, and subsidence or from indirect earthquake effects such as tsunamis (seismic sea waves), soil failure and liquefaction, landslides, avalanching, and seiches in semi-closed or closed bodies of

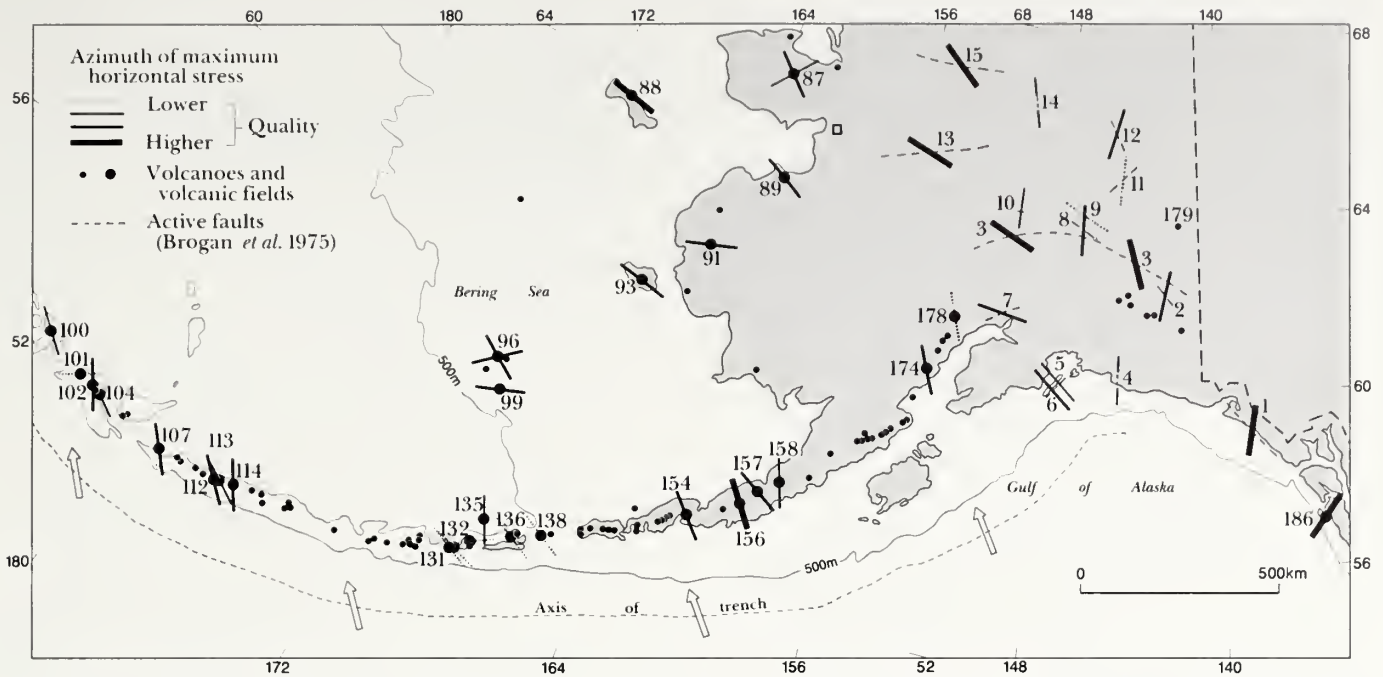


Figure 6-24. Orientations of maximum horizontal stress derived from volcanic-stress indicators and recent surface faulting. (Modified from Nakamura *et al.* 1977.) Note the parallel orientation of maximum horizontal stress with PAC-NAM plate-motion vector (open arrows) for most of the Aleutian arc. Also note fanning pattern in central Alaska (for details, see text). Numbers refer to identification of stress indicators as used by Nakamura *et al.* (1977).

water. Volcanic hazards originate from lava-, pyroclastic-, and mud flows; debris avalanches; air-borne projectiles and ash; toxic rains and gases; explosive shock waves; and volcanically induced earthquakes and sea waves.

Seismic Hazards (I): Earthquake Recurrence Periods

Great earthquakes are destructive but rare, occurring only about once a century at any given arc segment (Fig. 6-11). Smaller earthquakes pose a more frequent risk, generally with less significant effects. Since a wide range of magnitudes can contribute to seismic hazards, it is necessary to know the probability of earthquake occurrence as a function of magnitude in any given area.

The most common way to describe earthquake occurrence frequencies is as a function of magnitude (illustrated by an example in Fig. 6-26). The description has the form $\log N = (A - bM_w)$, where N is the cumulative number of earthquakes for all magnitudes M_w and larger. In order for this type of representation to be meaningful, it is assumed that earthquakes occur randomly, *i.e.*, they are spatially and temporally independent of each other and thus conform to a Poisson distribution.

The magnitude data for the Aleutian arc ($M_w \geq 7$) and for the period 1898 to 1982 are plotted as a function of M_w in Figure 6-26. The data show that ~ 100 events with M_w greater than or equal to 7, but only two events with M_w greater than 9, occurred during 85 years within a 3,600 km arc between Kamchatka and Yakutat Bay. If the slope ('b-value') is preserved, and the A-value is scaled down according to both the arc-length and the period of consideration, one would expect that in a 360-km-long arc (cen-

tered on Cook Inlet or Anchorage) one event with a magnitude of 7 or larger should occur every 8.5 years. But none has occurred there since 1964. In fact, no earthquake with a magnitude of 7 or larger has occurred within a distance of more than 1,000 km along the arc between Kayak Island and Adak (in the central Aleutians) for the 20-year period from 1966 to 1985. This is a quiescence for M_w events equal to or greater than 7 that falls a factor ~ 30 short of expected activity levels—if complete randomness did apply.

An alternative model assumes that although earthquakes are not purely randomly distributed in time, a random component of background seismicity for both small- and moderate-magnitude earthquakes is superimposed on a non-random component for great earthquakes in each plate-boundary subsegment. In this model, the probability for the non-random great earthquakes (and related fore- and after shocks) is a function of time or phase within the seismic cycle. This means that probabilities for the occurrence of great events are related to the time since the last great earthquake occurred at the plate-boundary segment in question. To define such a model, one needs to know the average periodicity of events, some statistical measure of deviation from this average, and the time since the last event. Such data were previously discussed in Figure 6-11 for various Aleutian arc segments.

Taking both these data and the theoretical relationships (Jacob 1984), one can calculate the conditional probabilities for the occurrence of great earthquakes during the next x years in each previously ruptured zone or seismic gap. Figure 6-27 displays the results of such calculations for the Aleutian arc, excluding the southeastern Alaska transform segment of the PAC-NAM Plate boundary. It shows the

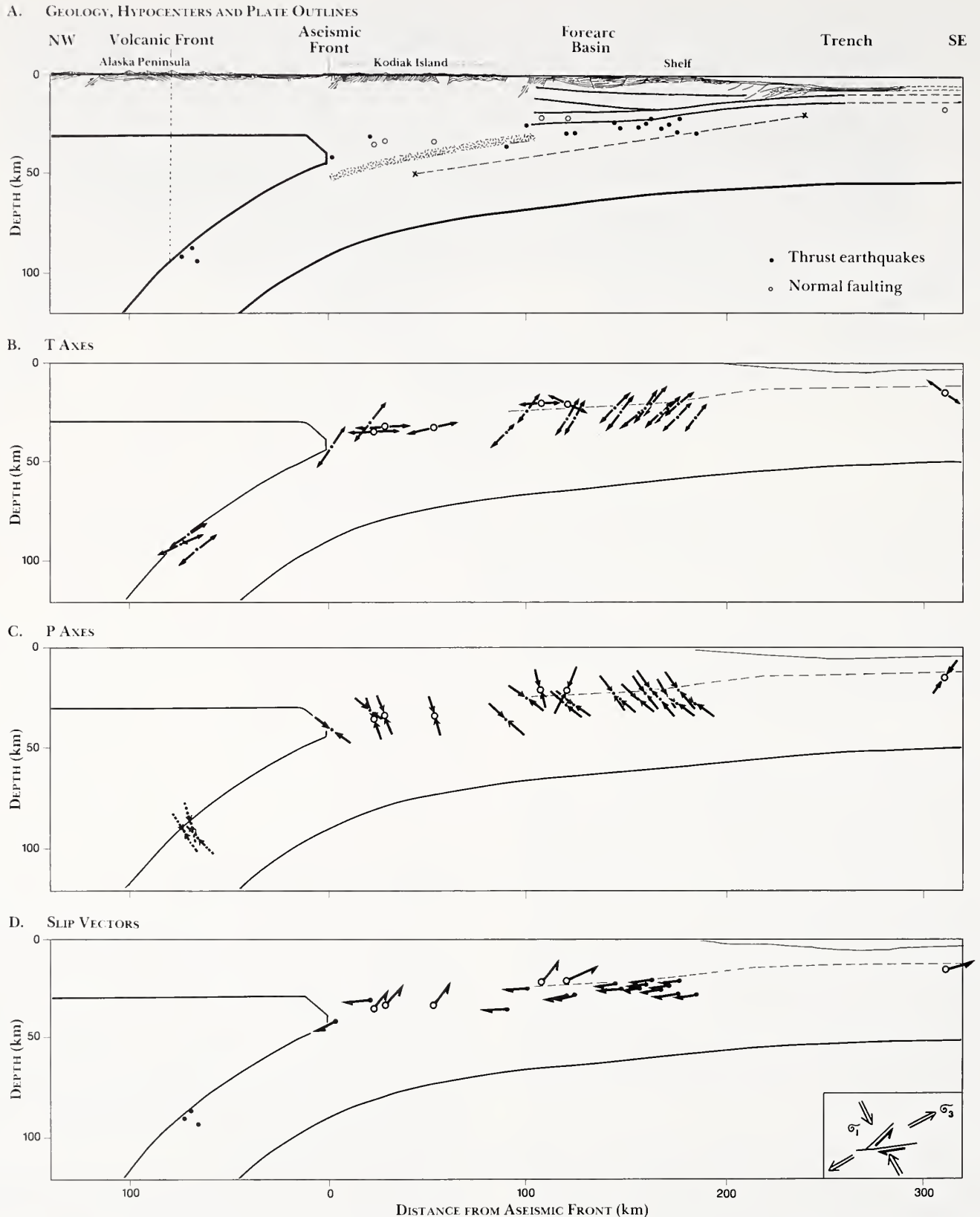


Figure 6-25. Seismic stress indicators in a cross section through the Kodiak region of the western Gulf of Alaska. (Modified from Jacob and Perez 1981.) A. Near-surface geology, hypocenters, and inferred plate outlines. The inclined dotted line represents the location of 1964 earthquake thrust fault inferred from geodetic data (Savage and Hastie 1966). B. Projected orientations of T axes. C. Projected orientations of P axes. D. Slip vectors. The insert in the lower right corner shows slip planes with an inferred stress system at the depth of the main thrust zone.

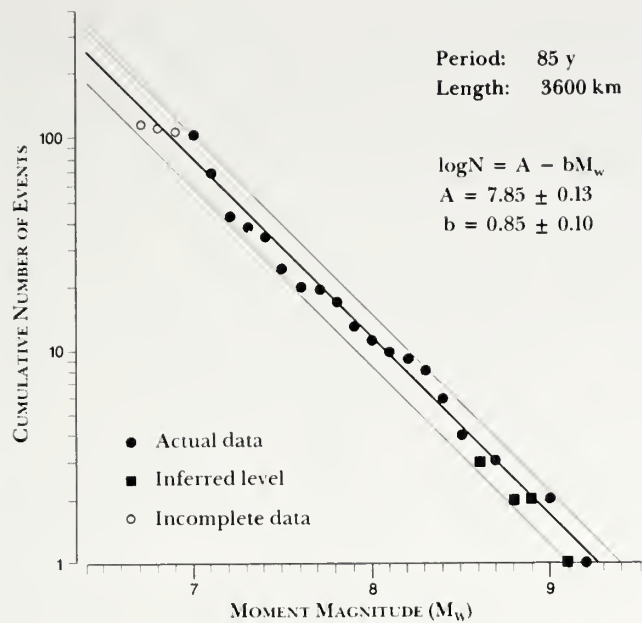


Figure 6-26. Cumulative number of large earthquakes as a function of magnitude M_w for an 85-y period (from 1897 to 1983) for the Alaska-Aleutian arc between Kamchatka and Yakutat—with inferred relationship $\log N = A - bM_w$. Straight lines fit slope b and intercept A , and delimit the maximum error for A . (Modified from Jacob and Hauksson 1983.)

range of conditional probabilities for a 10-y and a 20-y period (up to 1993 and 2003, respectively) and for two different statistical-model distributions of the recurrence times—for a log-normal (Fig. 6-11) and a normal distribution (see Jacob 1984; Jacob and Hauksson 1983). Note that the calculated probabilities apply for great earthquakes ($M_w > 7.8$) only. These are the primary results from Figure 6-27:

- 1) Seismic gaps in the Shumagin and Yakataga segments of the Gulf of Alaska have high probabilities (30% to 99%) of rupturing in great earthquakes during the next two decades.
- 2) The 1938, 1946, and 1964 rupture zones have much lower rupture probabilities, decreasing in this order.
- 3) The relative contrasts in probabilities between different regions are significant, but the absolute probability levels are poorly constrained and model dependent (Jacob 1984), and thus not too meaningful.

Two seismic-exposure studies by Woodward-Clyde Consultants (1978, 1982) are the most comprehensive attempts to quantify seismic hazards in offshore Alaska. They used extensive statistical methods, but the data base available for these studies was not complete enough to fully take advantage of the potential of the methods. The 1982 study assumed a 'semi-Markov process' for the temporal and magnitude relationships for great earthquakes (Patwardhan, Kulkarni, and Tocher 1980). However, the data base available for the historic earthquakes at that time was not as complete as it is now. Even an improved historic data base (Jacob and Hauksson 1983) may be too limited (going back only 200 y in one section of the eastern Aleutian arc,

and even less in most others) to warrant the more sophisticated approach.

However, from a methodological point, the study by Woodward-Clyde Consultants (1982) is important since it considered separate statistics for the great earthquakes for the first time, and used purely random Poisson statistics for the smaller-magnitude background activity. The latter was locally adjusted to reflect the different levels of background seismicity in the tectonically distinct subregions of trench, fore-arc, dipping slab, and volcanic arc. The contributions from these tectonic elements were then combined with those from the great plate-boundary earthquakes, allowing computation of the combined source characterization in each area. A result from this approach will be discussed in a later section (in conjunction with Fig. 6-31).

In summary, limited (but quantitative) statistical descriptions of seismic-source occurrences have recently become available for the Aleutian-plate boundary west of Yakutat Bay. These occurrences are expressed as a function of time, space, and magnitude. They include the concept of seismic gaps, or time-dependent probability for great earthquakes.

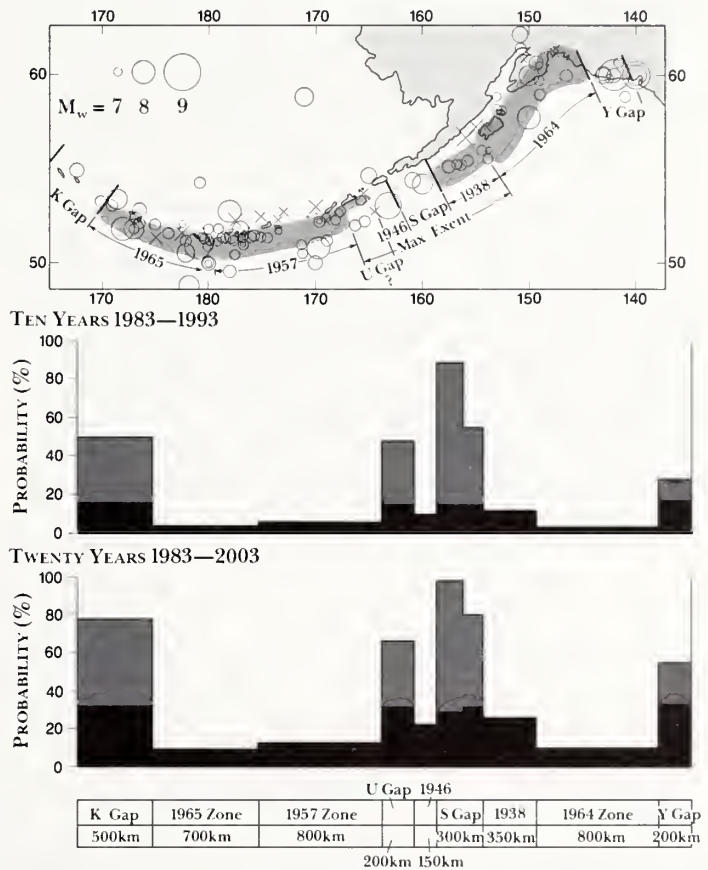


Figure 6-27. Conditional probability for great earthquakes ($M_w \geq 7.8$) along the Aleutian arc for a 10- and 20-y period. Map shows the geographical setting with seismicity ($M_w \geq 7$) since 1897. Solid shading on probability graphs represents log-normal distribution of recurrence times (see Figure 6-11); gray shading represents normal distribution. Note high probabilities in identified seismic gaps (from left to right) near Kamchatka (K), Unalaska (U), Shumagins (S), and Yakutat (Y). (Modified from Jacob 1984.)

For the Fairweather–Queen Charlotte transform boundary only qualitative assessments are presently available (Sykes 1971; McCann *et al.* 1979). They are practically non-existent either for the interior of Alaska or for areas outside the Gulf of Alaska region on which this survey focuses.

Even for the best-studied segments along the Alaska–Aleutian trench system, many details remain unresolved. These details include variations along the arc of average recurrence periods and the maximum possible magnitude of the largest earthquakes. It is unclear whether magnitudes are continuous between moderate- and maximum-magnitude earthquakes, or whether there is, in some sub-regions, a distinct lack of large earthquakes with magnitudes one or two units below the maximum-size earthquake (Davison and Scholz 1985). Recurrence periods for the largest (*i.e.*, giant) earthquakes ($M_w > 8.5$) are also not well known. Periods of a hundred years have been invoked on the basis of plate motions, the ratio of seismic to aseismic slip, and the average stress-drop estimates (Sykes and Quittmeyer 1981). However, many hundreds or perhaps even a thousand years have been suggested by Plafker and Rubin (1978). These longer recurrence periods are based both on inferences from uplifted marine terraces on Middleton Island and from the duration of interseismic submergence in the Prince William Sound and Copper River delta areas (Plafker 1969). Further geologic–paleoseismic studies are required to resolve these open questions.

Seismic Hazards (2): Strong Ground Motion Shaking

Although Alaska is by far the most seismogenic state in the United States, no systematic collection of digitally processed strong-motion data from Alaska was available until 1984. Attempting to do a seismic-hazards assessment for a region that does not have a strong-motion data base can introduce high uncertainties. The lack of strong-motion data stems from the fact that no strong-motion recording instruments were installed and operating in Alaska until after the great 1964 Prince William Sound earthquake.

About a dozen instruments were installed by the USGS immediately *after* this great earthquake. The instruments were placed along the Pacific Plate boundary, in Anchorage, and a few other municipalities, and at a few engineering structures. Today, about 75 accelerometer sites have instrumentation. Several stations were closed due to high maintenance costs in the late 1970s and early 1980s. A State of Alaska strong-motion program is only in the planning stage. In the early 1980s, a dozen new strong-motion recorders were installed in the Yakataga seismic gap (USGS) and in the Shumagin seismic gap (Lamont–Doherty Geological Observatory). The installation roughly coincided with the termination of the seismologic components of the OCSEAP-sponsored studies. A string of stations was originally installed along the Trans-Alaska Pipeline, but the data—if existent—are not in the public domain. For a summary of those strong-motion stations operating in Alaska, see Beavan and Jacob (1984).

Because the oil industry must assess offshore and onshore seismic hazards from strong ground motions, it sponsored the systematic compilation and digital processing of all significant Alaskan Pacific-coastal strong-motion data available up to 1983. This resulted both in the data report and the digital data sets by Beavan and Jacob (1984). Figure 6–28 shows the distribution both of earthquakes and of stations with processed records that resulted from this compilation. Table 6–1 lists earthquake-source characteristics for those earthquakes where strong-motion records were analyzed. Figure 6–29 gives an example of the digitally processed records. Note both the large horizontal ground displacements during the periods of between 2 and 4 s, and the zero-to-peak amplitudes in excess of ~30 cm (1 foot) at a distance 170 km from the source. The duration of the record is 80 seconds. Low-frequency ground motions can influence the response of both deep-water structures such as exploration and production platforms and of large bodies of fluids in storage tanks—both of which tend to have their natural periods of vibration in this frequency range.

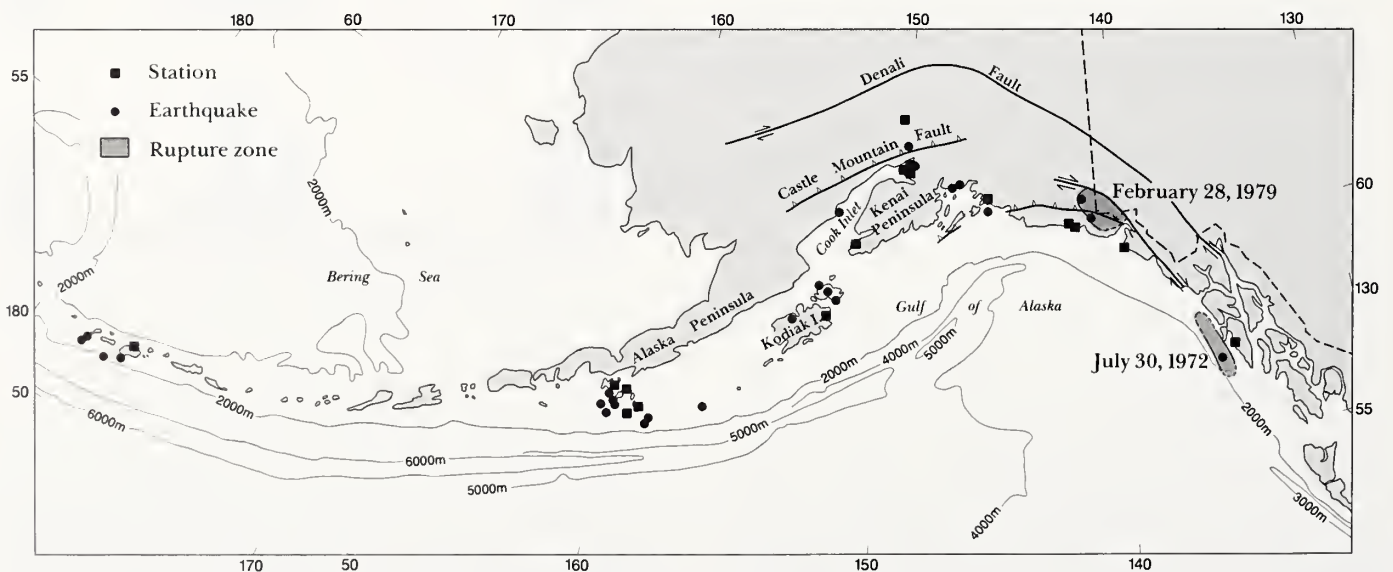


Figure 6–28. Distribution of stations and earthquakes for which digitized and processed seismic strong-motion records are available. Shaded areas show rupture zones of the two largest events with dates indicated. (Modified from Beavan and Jacob 1984.)

Table 6-1.
Alaska-Aleutian earthquakes for which processed strong-motion data exist.

y	ORIGIN TIME			LATITUDE °N	LONGITUDE °W	DEPTH km	MAGNITUDE M _w
	mo	d	h:min				
1964	06	05	09:50	60.350	145.870	16	5.2
1964	06	05	22:06	58.140	152.180	13	5.0
1965	09	04	14:32	58.290	152.500	32	6.8
1965	12	22	19:41	58.350	153.130	42	6.8
1968	12	17	12:02	60.150	152.820	82	6.3
1970	03	11	22:38	57.390	153.970	38	6.3
1971	05	02	06:08	51.420	177.210	38	6.8
1972	07	30	21:45	56.770	135.910	29	7.5
1974	04	06	01:53	54.870	160.290	37	5.6
1974	04	06	03:55	54.900	160.290	40	5.8
1974	08	13	03:46	51.490	178.110	47	6.1
1974	11	11	05:17	51.590	178.080	69	6.1
1975	01	01	03:55	61.920	149.720	58	6.0
1975	07	25	10:40	55.040	160.410	38	5.6
1976	02	22	07:21	51.570	176.810	61	4.7
1979	01	27	18:57	54.790	160.640	53	6.2
1979	02	13	05:34	55.170	156.940	47	6.5
1979	02	28	21:27	60.640	141.590	13	7.3
1981	12	28	10:28	54.669	160.407	33	3.8
1983	02	14	03:20	54.736	158.882	25	6.3
1983	02	14	08:10	54.854	158.843	25	6.0

Probably the most important findings from the strong-motion data collected by Bevan and Jacob (1984) for Alaska, and from a similar data set for Japan collected by Wildenstein-Mori and Crouse (1981), are illustrated in Figure 6-30. These critical findings show that the scatter of peak accelerations (as a function of distance from earthquakes) is much larger in Alaskan subduction zones than the scatter for Californian earthquakes. Hence, in Alaska, the highest peak accelerations can be significantly larger than the highest accelerations observed in California (Joyner and Boore 1981) for similarly sized earthquakes at the same distances.

A quantitative analysis of the causes for the difference between Californian (mostly shallow strike-slip) and Alaskan (mostly subcrustal subduction-zone thrust) earthquakes and their associated peak accelerations is still pending. Likely candidates for explaining the differences include: 1) higher stress drops for the Alaskan sources (perhaps facilitated by higher confining pressures at greater depths), 2) lower slab temperatures, and 3) a more compressive tectonic stress regime. Lesser absorption during wave propagation in the Alaskan crust may contribute to the difference, but is probably not a major controlling factor. Jacob and Mori (1984) compare the subduction-zone

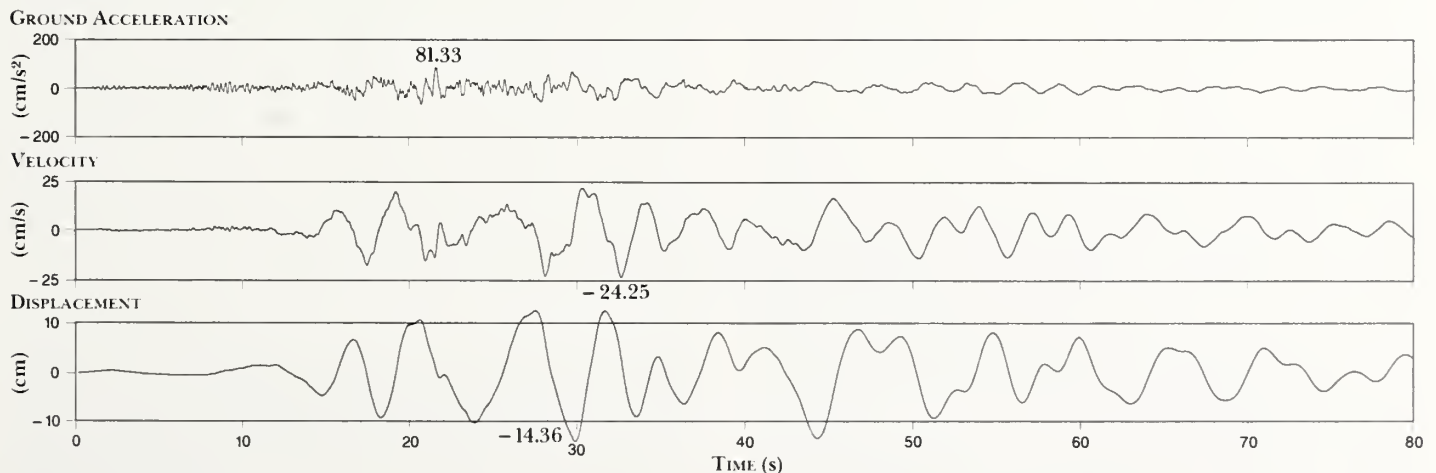


Figure 6-29. Processed strong-motion record for north-south horizontal component of ground acceleration, velocity, and displacement recorded at the Yakutat airport (~166 km from the epicenter of the St. Elias earthquake, M_w = 7.3) of February 28, 1979. (Modified from Bevan and Jacob 1984.) Note zero-to-peak amplitudes for displacements of 14 cm, velocities of 24 cm/s, and accelerations of 80 cm/s².

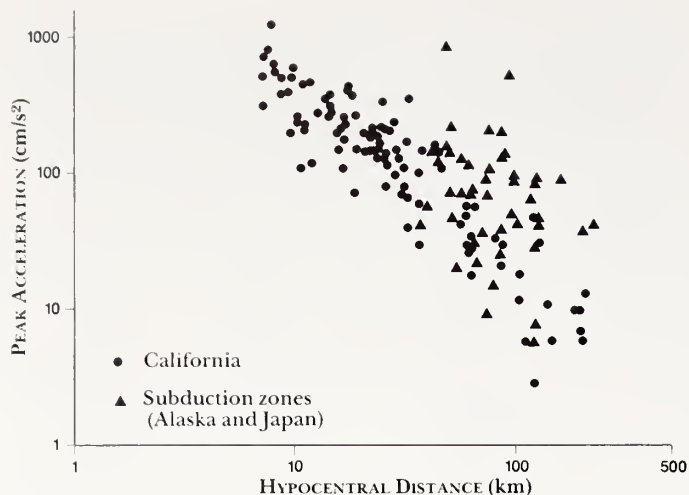


Figure 6-30. Comparison of peak ground acceleration to hypocentral distance for California earthquakes and Alaska and Japan subduction-zone earthquakes for events with magnitudes 6 to less than 7. Note higher peak values for many subduction events at any given distance (Jacob and Mori, unpubl. data).

attenuation laws (e.g., peak acceleration vs. distance at constant M_w , see Fig. 6-30) with the attenuation laws of Woodward-Clyde Consultants (1982) for their Alaskan OCS seismic exposure study. A quantitative statistical treatment of the new subduction zone attenuation data of Beavan and Jacob (1984) is still pending. The results of these studies have not been incorporated into any systematic seismic-exposure mapping, and strong-motion data for the most important Alaskan subduction-zone earthquakes with magnitudes (M_w) equal to or greater than 7.5 are not yet available.

Seismic Hazards (3): Seismic-Exposure Mapping

Seismic exposure mapping is a computational process that is used to generate maps of ground-motion levels expressed in probabilistic terms. For instance, one may want to map the contours of those peak accelerations that would not be expected to exceed a certain probability within a given period. For example, if the probability were 67% for a time period of 40 y, that would imply a 33% chance that the mapped values of acceleration will be exceeded.

Both empirical data and statistical criteria are needed for this type of mapping. For instance, the location, the recurrence, and the magnitude distribution for earthquakes must be known. The attenuation of ground-motion parameters and their functional dependence on factors such as magnitude, travel path, distance, and site conditions must be prescribed. Finally, the period of interest and the probability level of exceedence (or non-exceedence) for which the map is intended must be specified.

Once the input quantities are established, the seismic exposure is obtained by computing (for each grid point on the map) the cumulative distribution function for the chosen ground-motion parameter—based on contributions from all the sources in the region. The shape of this cumulative distribution function—when read at the chosen

percentage of non-exceedence—yields the expected ground-motion level at the grid point. Then the results for the system of grid points are contoured on the map for easy visual display.

Sometimes, only limited empirical input data are available, but many are needed to properly specify the source, the attenuation, and the statistics of the exposure model. This situation can lead to undesirable subjectivity that can contribute to significant differences in the outcome of the hazards-exposure computation. It is desirable, therefore, to obtain a quantitative understanding of the sensitivity of the output in regard to variations in the input and model parameters.

The need for sensitivity studies is illustrated in two exposure maps (Fig. 6-31 and 6-32). Both maps show peak accelerations at a 67% probability of non-exceedence within a 40-y period between 1982 and 2022. (Remember that exposure mapping becomes time-dependent as one goes beyond a random Poisson model for the occurrence of earthquakes!) The first of the two maps (Fig. 6-31, adopted from Woodward-Clyde Consultants 1982, Vol. II: Fig. 10) shows a rather smooth distribution of peak accelerations characterized by a broad ridge of high values (reaching a plateau at 300 cm/s^2), but with no values higher than that. The high is best developed on the margin between Kodiak and the Shumagins, but (for reasons not fully clear to this reporter) they drop off toward the Yakataga gap and Southeast Alaska transform margin.

The second map (Fig. 6-32, adopted with only minor modification from J. Hobgood, formerly with Woodward-Clyde Consultants, pers. comm., 1981) is from an early test run with the same exposure routines applied to obtain Figure 6-31. Figure 6-32 does use a slightly different source geometry as well as a different attenuation law for peak accelerations from subduction-zone sources at small depths and distances. (For a discussion of these attenuation laws, see Woodward-Clyde Consultants (1982) Volume II: Figure 7.) Otherwise, the same recurrence relation and statistical criteria as in Figure 6-31 were applied. Nearly twice as high peak-acceleration levels were assumed at short distances in the attenuation laws. Consequently, the exposure map in Figure 6-32 shows higher peak accelerations in the outer shelf of the Shumagin and Yakataga seismic gaps where the main thrust zones have not only high probabilities for large thrust earthquakes but also come very close to the surface. These previously unpublished test results (for sites with competent soils) show maxima of 540 cm/s^2 on the outer Shumagin shelf, and 680 cm/s^2 near the Pamplona Ridge off the coast in the Yakataga seismic gap.

It is interesting from an historical point of view, that at the time of this test computation some investigators felt the high maximum values were unrealistic. The current data base of strong-motion records for subduction zones near the source is still insufficient to resolve this question, but values higher than those shown in Figure 6-30 are quite likely. Even earlier studies, such as Woodward-Clyde Consultants (1978, Vol. III: Fig. 3-22), obtained maxima of about 420 cm/s^2 in the Shumagin segment, but were located farther inland where the Wadati-Benioff zone is about 60 km deep.

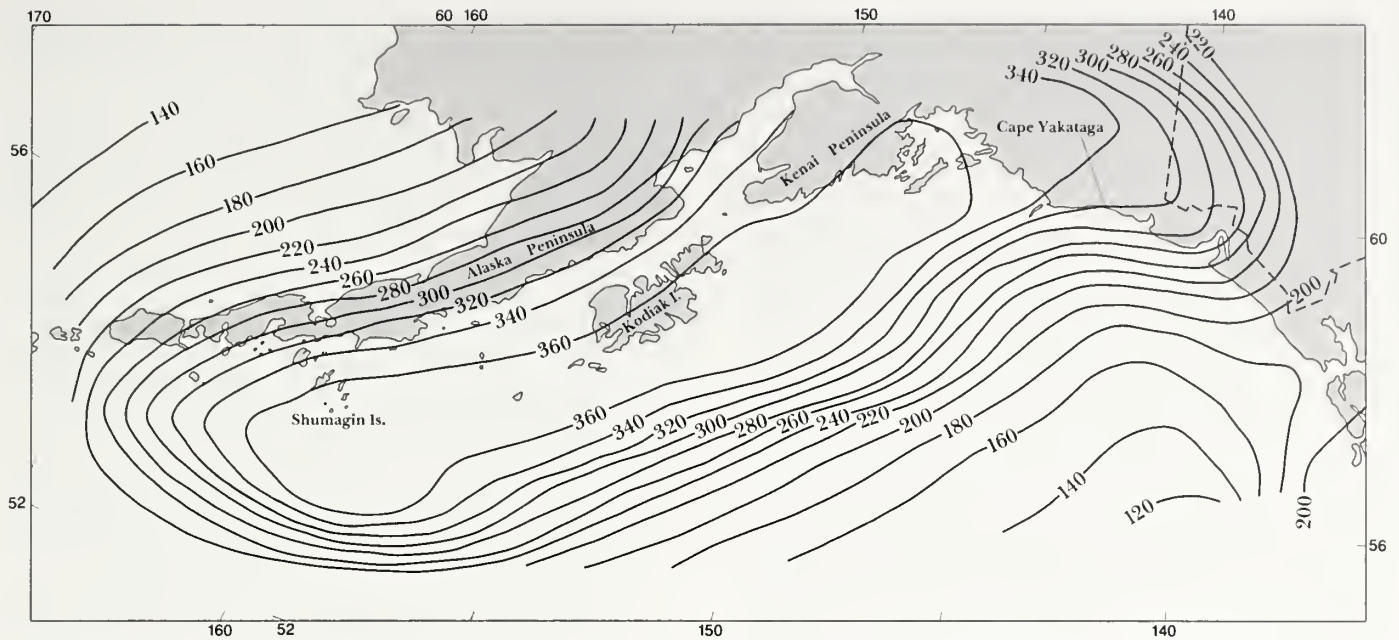


Figure 6-31. Contour map for peak ground accelerations (cm/s^2) that have a 67% probability not to be exceeded within a 40-y period from 1981 to 2021. (Modified from Woodward-Clyde 1982.)

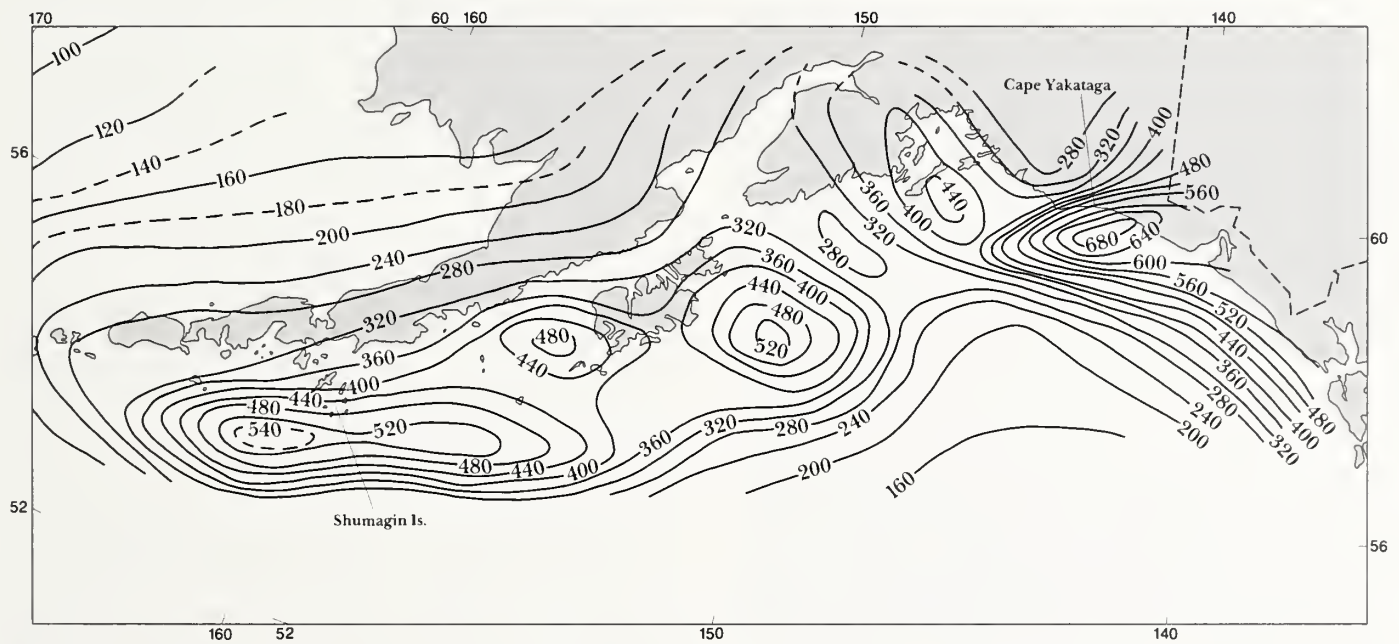


Figure 6-32. Contour map for peak ground accelerations (cm/s^2) as described in Figure 6-31, except that an attenuation law which uses higher acceleration levels at short distances from potential sources was applied (for details, see text). Note that contoured values in Yakataga and Shumagin seismic gap regions reach almost twice the levels shown in Figure 6-31 (J. Hobgood, unpubl. data).

A set of Alaskan hazard maps for peak horizontal accelerations (with a 90% probability not to be exceeded in 10, 50, and 250 y) was prepared by Thenhaus, Ziony, Diment, Hopper, Perkins, Hanson, and Algermissen (1985). The maps are based on:

1) marginally valid Poisson statistics for earthquakes regardless of magnitudes (*i.e.*, the same statistics are applied to small and great events)

2) seismicity data that may have a strong temporal bias since they cover a very limited time period

3) ground-motion attenuation laws based on data for the western continental United States rather than for Alaska.

Therefore, the 10- and 50-y exposure maps may be important only for demonstrating the sensitivity of results to method and data, rather than for representing a realistic

assessment of Alaskan ground-motion hazards. This is especially true for the next few decades in the seismic gaps. Since, however, for very long exposure times (> 100 y) most statistical seismicity models should converge toward a Poisson model, their map for the 250-y exposure time may provide a useful result representing long-term hazards—if it is corrected for attenuation laws applicable to Alaska. Without such corrections, the maps show peak accelerations for the shelf regions between Shumagin Islands and Yakutat that are between 600 and 700 cm/s^2 . These figures have a 90% probability of not being exceeded (or a 10% probability of being exceeded) within 250 years.

Inconsistencies in exposure mapping show that a systematic sensitivity study for the Gulf of Alaska is needed. This applies especially as long as the empirical attenuation laws are as poorly constrained by actual strong-motion data from the Gulf as they are now.

For the Gulf of Alaska, the Woodward-Clyde Consultants reports (1978, 1982) also give seismic exposure maps for other ground-motion parameters such as root-mean-square (RMS) acceleration, peak velocity, and others. Unlike for other regions of the United States with high seismic hazards potentials, there is not yet an authoritative hazards map available for all of Alaska.

Tsunamis and Local Waves

In coastal regions of Alaska, tsunamis (seismic sea waves) are often the cause of the most damage associated with great earthquakes. A catalog both of tsunami observations from Alaska and of the pertinent literature for the period prior to 1969 is given by Cox and Pararas-Carayannis (1976). Many refinements and additions of this information are contained in Sykes (1971), Davies *et al.* (1981), and House *et al.* (1981). A large amount of mostly observational data on the tsunami associated with the Great Alaskan Earthquake of March 27, 1964 is compiled in Volume III (Oceanography and Coastal Engineering) of the National Research Council Report (1972).

A more recent review of tsunami-related research has been given by Houston (1979). Steinbrugge (1982) gives a good general compilation of the tsunami effects, damage, losses, and of present tsunami zoning for the United States (including Alaska). In addition, Wiegand (1970) treats many of the engineering and physical aspects of tsunamis including speed, coastal-wave amplification, wave-forces, and run-up effects.

Tsunamis and other, localized wave surges are generated during earthquakes or volcanic eruptions by one of several types of displacement at the boundaries of a body of water:

- 1) The ocean bottom/water interface is directly deformed by faulting or by the primary displacement field of a major earthquake. It causes a tsunami with regional effects on open coastlines, and the tsunami may travel across an entire ocean.
- 2) An earthquake-induced submarine landslide can change the ocean bottom topography. If such a submarine slide occurs in a semi-enclosed bay, the tsunami can be highly localized and its run-up heights

may substantially exceed the general run-up heights from the regional tsunami of the same causative earthquake.

- 3) The third type of tsunami usually occurs as a localized and often highly directed surge generated not by changing the bottom topography, but by the high-speed impact between water and a subaerial landslide, volcanic debris flow, or an ice avalanche.

The three types of tsunamis or surges can be distinguished in many instances, but if two or more types are simultaneously triggered during a regional earthquake, or during a major volcanic eruption with earthquake, their relative importances may not always be readily separable. These complexities make it also difficult to predict local tsunami effects.

Examples of maximum run-up heights of tsunamis and local waves at coasts, bays, and inlets in Alaska as a result of the 1964 Earthquake are:

- 30 (from 10 to 60) m in Port Valdez Inlet
- 20 m at Chenega village in Prince William Sound
- 10 to 20 m at Kodiak
- less than 5 m in Shelikof Strait.

However, some of those run-up heights are dominated by local waves. Other tsunami effects include:

- 30 m at Scotch Cap lighthouse on Unimak Island from the nearby 1946 event of magnitude M_s equal to 7.4 that may have triggered a huge submarine slide
- 9 m at Port Graham (Kenai Peninsula) generated by a debris avalanche during the 1883 eruption of St. Augustine volcano in lower Cook Inlet
- 10 m in Yakutat Bay during the September 5, 1899 quake, probably from a splash wave.

Earthquake-triggered landslides or debris avalanches can set up water surges with astoundingly extreme run-up properties. Most notorious is Lituya Bay along the Fairweather Fault with reported maximum run-up heights of 120, 24, 60, 150, and 525(!) m in the years 1853–1854, 1874, 1899, 1936 (slide, no quake), and 1958, respectively (Miller 1960).

Tsunamis can travel far and still cause considerable damage—especially where bay or inlet morphology locally amplifies the effects by factors of two to four when compared to open-coast run-up heights. The maximum run-up heights in Hawaii for the 1946 eastern Aleutian (Unimak) event measured 18 m, and the Great Alaskan Earthquake of 1964 caused run-ups of greater than 9 m in Crescent City, California.

A U.S. Army tsunami hazards map (Steinbrugge 1982), which is not widely circulated, puts all of the open coasts of the Gulf of Alaska in Zone 3 (run-up of 5–10 m), except for inlets and fjords, which are categorized in Zone 4 (10–17 m) and possibly Zone 5 (excess of 17 m). These heights are supposed to give values not to be exceeded with a 90% probability in 50 years. This probability may be correctly assessed for the regional tsunami effects, but many of the locally induced 1964 run-up heights exceeded these values.

A quantitative physical description of the coastal run-up process (especially in near-source regions) as a function of

(a) static displacements of the ocean floor during the earthquake and (b) coastal morphology and bathymetry at the receiver site, is still in its early stages and probably will remain so for some time to come. Ward (1982) advanced a method for a computational prediction of tsunami amplitudes and their radiation patterns as a function of the seismic moment tensor, source geometry, and source depth for distances large compared with the source dimension, *i.e.*, mostly at teleseismic distances.

The speed with which a tsunami travels is approximately $c = \sqrt{gh}$, where g is 9.81 m/s^2 , and h is water depth in meters. This implies speeds of 800 km/h in the deep ocean, and 150 km/h or 40 m/s and less on the shelf. These speeds give (in many instances) sufficient lead times between the origin time of an earthquake and the arrival of the first tsunami wave at a coastal site so that tsunami warnings can be issued for distances of a few 100 km and more from the source—provided sufficient seismologic and communication facilities are regionally available and that they remain operative during a great earthquake. The Alaska Regional Tsunami Warning System in Palmer, Alaska (operated by NOAA) has this important alerting function for Alaska. It is tied into the international Pacific-wide Tsunami Warning System that has its operational center in Honolulu, Hawaii. Localized seiches or tsunamis during a regional event, *e.g.*, those triggered by local landslides during shaking, cannot be detected with sufficient lead time for the localities they affect and, thus, no suitable warning method exists for them.

The shallower the earthquake, *i.e.*, the closer the strain source to the ocean floor, the larger is the efficiency with which a tsunami is generated—given a certain moment (or magnitude) of the source. This relation is confirmed both from theoretical considerations (Ward 1982), and from observations (Nishenko and McCann 1979; Fukao 1979; and Abe 1979), which indicate that tsunamis are most efficiently generated by subduction-zone earthquakes during which secondary steep faults cut the ocean floor in the fore-arc region. This was certainly the case near Montague Island for the Great Alaskan Earthquake of 1964 (National Research Council 1972, Vol. 4). A recent SEABEAM (side-scanning sonar) survey of the Shumagin shelf (S. Lewis, Lamont-Doherty Geological Observatory, pers. comm., 1985) suggests that faulting and perhaps extensive slumping is prevalent offshore at Unimak Island, the site of one of the largest tsunamis ever recorded. It was generated by only a moderate-sized earthquake ($M_s = 7.4$) in 1946.

Modest progress has been made during the last decade to improve the quantitative assessment of tsunami hazards for Alaska. Maps have been issued by the State of Alaska's Division of Emergency Services, in cooperation with federal agencies. They are available for selected, generally more populated coastal segments, and show little more than zones of 'possible flood area' that cover the coastal strips between sea level and elevations to 100 feet (30 m) above sea level. The maps provide the public with fundamental tsunami safety rules and instructions on tsunami warning signals.

Since the coast in the Gulf of Alaska is one of the most important economic zones in Alaska, tsunami research, consideration of tsunamis in coastal engineering projects, and the implementation of an effective, reliable, and fast

tsunami warning system that can reach endangered communities within minutes of a large earthquake must rank high on the priority list for both State and Federal agencies. It is crucial to maintain a modern tsunami-mitigating system.

Other Seismic Hazards

Seismic hazards come in many fundamentally different forms: there are those related to direct natural effects like shaking, faulting, subsidence, flooding, tsunami, soil-failure, slides, flows, and avalanching. In addition, there are the secondary effects on man-made structures, and the effects from the failures of man-made structures that cause fires and the loss of water, power, and other essential services. Both geologic and secondary effects can cause fatalities and substantial economic loss. We discuss here only the geologic aspects, and these only to the extent that the reader is guided to the pertinent literature. We refer again to the National Research Council (1972) eight-volume report on the Great Alaska Earthquake of 1964, and to Grantz, Plafker, and Kochadoorian (1964), Wiegel (1970), and Steinbrugge (1982) for the geologic, engineering, and public-economic aspects of seismic hazards, respectively.

One of the most consequential phenomena of the 1964 Earthquake was the failure of unconsolidated weak sediments during the minute-long shaking and dynamic loading that occurred both onshore and offshore. The failure of sediments in the Bootlegger Cove Formation (Updike, Dearborn, Ulery, and Weir 1984; Updike 1984) caused widespread slides in the Anchorage down town area and at nearby sites such as 4th and L Street, Government Hill, and Turnagain Heights. These extensive failure zones and the graben, slide, and pressure-ridge formation areas were earlier attributed to dynamic soil-liquefaction, which occurred preferentially in the weak central layer of the Bootlegger Cove Formation. More recently, shear sensitivity and the collapse of the silty clays in that formation have been emphasized as causes (Updike 1984; Updike *et al.* 1984).

When nearshore submarine sediments in Valdez and Seward failed during the 1964 Earthquake, they caused slumps that took the dock facilities with them. Some of the post-1964 submarine slopes at both sites are much steeper when compared with their pre-1964 configurations. Onshore strips of land adjacent to the slides were weakened by extensive fracturing in 1964. Therefore, these areas are likely to fail again in future earthquakes and may not be feasible sites for reoccupation. Hampton, Carlson, Lee, and Feely (Ch. 5, this volume) review other offshore regions in the Gulf of Alaska that have either observed or potential submarine slope instabilities, as well as review their geotechnical properties.

In 1964, many coastal zones of Alaska experienced a coseismic tectonic subsidence or uplift that measured several meters, along with flooding or shoaling at extreme tides. These shore changes caused considerable economic damage and required the relocation or raising of facilities in areas where neither the earthquake shaking nor the tsunamis had done much damage. Two examples of severe subsidence effects were the Homer and the Seldovia areas on the Kenai Peninsula.

The 1964 Earthquake caused fissuring, cracking, sand boils, and ground flow (especially into narrow topographic depressions across stream channels where systematic shortening caused the buckling of railroad trestles that crossed them). Other effects included avalanching, rockslides, and other, lesser geologic and geotechnical events. Similar geologic hazards can be assumed for future great earthquakes in the Gulf of Alaska. Careful site-specific assessments of these hazards must be made in the future on a project-by-project basis.

Volcanic Hazards

Between Unimak Island in the west and Sitka in the east there are about 40 Quaternary and Holocene volcanoes unequally spread over this more than 2,000-km-long section of the PAC-NAM Plate boundary in the Gulf of Alaska. Most of the volcanoes are located between Unimak Island and Cook Inlet along the Aleutian Trench, although there is a small second group in the Wrangell Mountains, and the lone Edgecumbe volcano and its subsidiary edifices on Kruzof Island near Sitka (see Figure 6-6). The volcanic activity within the Aleutian group east of Aniakchak volcano (the Katmai-Cook Inlet trend) has been summarized by Kienle and Swanson (1983a). They show that 10 of the 22 Quaternary-Holocene volcanoes in this group have been active in historic time. Coats (1950) and Simkin *et al.* (1981) are, respectively, general source references on Aleutian and other Alaskan volcanic activity. For assessment of volcanic risks globally, and the effect of volcano hazards on insurance policies and the public, see publications by Munich Reinsurance Company (1984) and Steinbrugge (1982).

The largest of all witnessed volcanic eruptions in the Gulf of Alaska was the 1912 Plinian eruption of Novarupta in the Katmai group. A Plinian eruption constitutes explosive activity with large amounts of tephra and is often associated with caldera collapse. Novarupta was by far the world's most voluminous eruption in this century (Hildreth 1983). It produced ~20 km³ of ash-fall tephra and less than 15 km³ of ash-flow tuff within ~60 hours. By way of comparison, the volume of ejecta associated with the laterally directed, May 18, 1980, Mount St. Helens eruption was at least 10 times smaller, and the volume of *new* volcanic ash was at least a 1,000 times smaller than that of the Katmai eruption. Locally, ash deposits were up to 17 m thick. Deposits measure ~30 cm on Kodiak Island, and the 3-cm cumulative ash-fall contour stretches southeasterly for ~400 km from Katmai to beyond Kodiak and into the open Pacific Ocean (Fig. 6-33). This eruption created entirely new landforms, including the Valley of Ten Thousand Smokes and the collapse of the summit of Mount Katmai.

Based on radiocarbon dates, twice during the last 2,000 y the source of the White River ash in the Wrangell Mountains produced ejecta volumes on the order of 20 and 25 cubic kilometers. These are spread widely over eastern Alaska and parts of adjacent Canada (Lerbekmo and Campbell 1969). The Wrangell volcanoes have also been the source of the 80,000-year-old 'Old Crow' tephra (with a total volume of 50 km³) that is spread over most of central Alaska (Westgate 1982). Mount Spurr (1953), Mount Redoubt (1966-1968), and

Augustine volcano (1976, 1986) erupted and caused ash to fall in populated regions (Fig. 6-34). In the first case, ash damaged equipment in Anchorage.

How frequent, how wide-spread, and how severe are volcanic hazards in the Gulf of Alaska? Although there is no single comprehensive study or reference on volcanic hazards for the entire Gulf of Alaska, several descriptive and quantitative assessments of volcanic hazards in portions of Alaska's volcanic regions have been made.

For the Aleutian volcano group (74 volcanoes), McNutt (1983) tried to establish the average eruption frequency (per 100 y per volcano) as a function of volume. To do this, he used: 1) ash layers in young Pacific ocean-floor sediments that he probed by piston cores, 2) ash layers dated on land in the Shumagins and on the Alaska Peninsula, and 3) historic and recent records of eruptivity. He concluded that on average one eruption per volcano every 100 y with about 0.1 km³ of ejecta can be expected, but that an eruption with a volume of a few km³ may occur only once every 100,000 y for any one volcano. These are very crude occurrence-frequency estimates that take a form somewhat analogous to the $\log N = A - bM_w$ relationships between earthquake occurrences and their magnitudes.

McNutt (1983) also plotted maximum ash thickness versus distance from the source vent, with the log of the ejected material volume as a parameter (analogous to parameterization of peak ground-motions vs. distance for different M_w). While the data scatter widely, the maximum ash thickness on average falls off inversely proportional to distance for a range of between a few and several hundred kilometers. Thus, 15 m of deposits at 1 km would attenuate to 1.5 m at 10 km, and 15 cm at 100 km—values that are crudely compatible with maximum values for the Katmai event of 1912. Note that these values apply in the direction of the prevailing wind. In other directions, the fall-off is much more rapid. Thus the prevailing wind directions and speeds are most important for probabilistic estimates of ash-fall hazards.

McNutt (1983) mapped two regions (between Mount Veniaminof and Frosty Peak on the Alaska Peninsula, and between Akutan and Vsevidof on Umnak Island in the eastern Aleutian Islands), with regard to areas with 100-y ash accumulations of more than 10 cm and 4 cm, respectively. He also mapped zones with likely debris or lava flows, and mapped valleys with geologic ally young volcanic mud flows that extend for distances beyond 50 km from the source vents. Recent geologic mapping on the Alaska Peninsula by Dettnerman, Miller, Yount, and Wilson (1981a,b) provides locally detailed information on the extent of ash flows, as well as lava and caldera mud flows. The spectacular mobility of ash flows around Aniakchak on the Alaskan Peninsula and around Fisher caldera on Unimak Island have been pointed out by Miller and Smith (1977).

Probably the most serious volcanic threat for Alaska exists in the Anchorage/Cook Inlet/Kodiak/Kenai region where about half of Alaska's population is concentrated and exposed to potential volcanic hazards. Augustine, Iliamna, Redoubt, Spurr, and Hayes (Fig. 6-6) are the prominent volcanoes bordering Cook Inlet, but future, newly forming volcanic vents could also become sources of volcanic hazards.

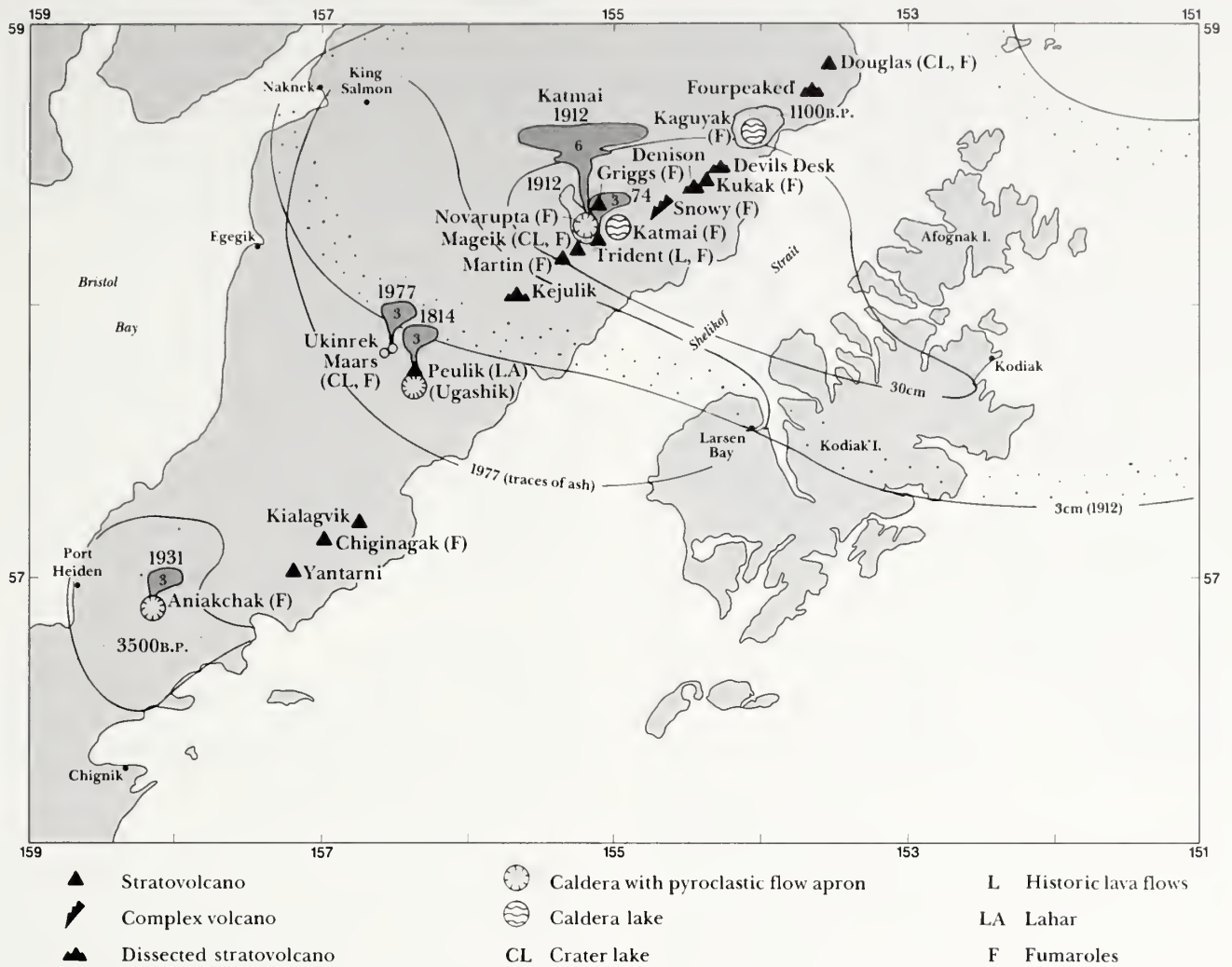


Figure 6-33. Map of major volcanic centers, historic eruptions, and generalized volcanic hazards in and near the Katmai area of the Alaska Peninsula. (Modified from Kienle and Swanson 1983a.) Numbers in plume symbols refer to the Volcanic Explosive Index (VEI) described by Simkin *et al.* (1981).

The volcanic hazards to the Cook Inlet region (primarily from Augustine volcano) have been specified in great detail by Kienle and Swanson (1983b, 1985) and by Kienle, Davies, Miller, and Yount (1986). Of particular interest is the potential of Augustine volcano to cause destructive tsunamis in Cook Inlet. Some of the tsunamis would apparently be generated by the rapid impact between massive avalanches composed of dry volcanic debris and the sea. For instance, on October 6, 1883, the western tip of the Kenai Peninsula at Port Graham was inundated by a 10-m-high tsunami that had been generated both by an eruption and the associated debris avalanche of the Augustine volcano. It took approximately 25 min for the tsunami to cross Cook Inlet (a distance of about 70 km) before it reached the Kenai Peninsula.

Ashfalls are also a major concern for the Cook Inlet region. Ashfalls can, for instance, severely impede power generation in combustion plants, or preclude vital air traffic. For example, air traffic in and out of Anchorage was temporarily closed in 1953 during an eruption of Mount Spurr.

Figures 6-33 and 6-34 (from Kienle and Swanson 1983a) schematically show historic ashfall distributions from volcanoes extending from Aniakchak (in the southwest) to Mount Spurr (in the northeast). A summary of Holocene tephra in the upper Cook Inlet (Riehle 1985) suggests one major tephra fall every 150 y, and one perceptible ashfall every 12 years.

Other known volcanic hazards in Cook Inlet are associated with lahars (volcanic mudflows) originating, for instance, at Redoubt volcano and descending into the Crescent and Drift River Valleys (Riehle, Kienle, and Emmel 1981). Coastal flash-flooding occurred, for example, on January 26, 1966, and posed a potentially serious risk to the Drift River tanker terminal.

A quantitative volcanic-hazards assessment for all volcanically active regions of Alaska is still pending. Except for those areas within close proximity of volcanic centers (<30 km), volcanic hazards generally pose a lesser degree of risk than the hazards caused by the seismic sources discussed

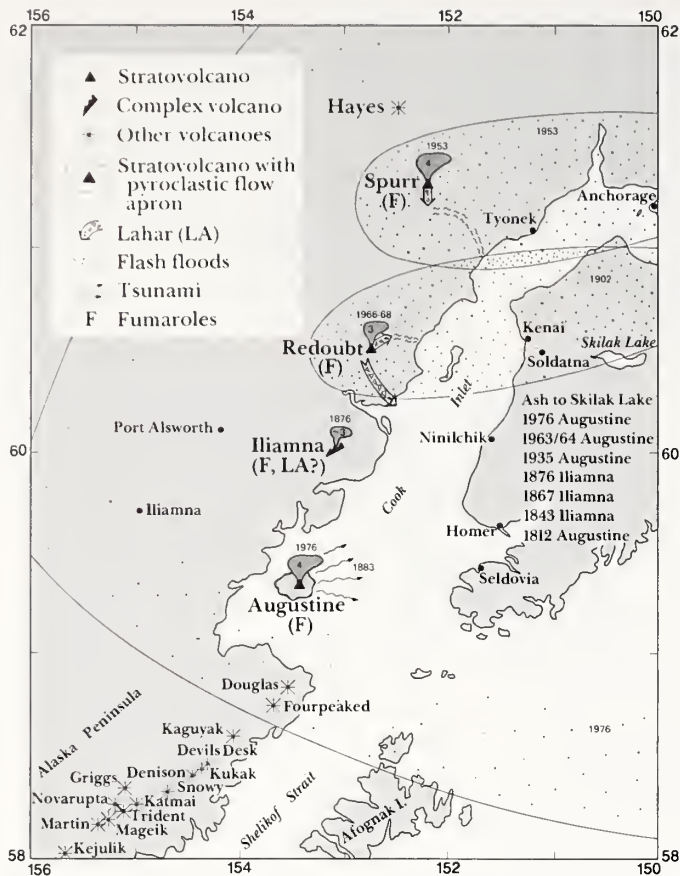


Figure 6-34. Map of major volcanic centers, historic eruptions, and generalized volcanic hazards for the Cook Inlet region. (Modified from Kienle and Swanson 1983a.) Numbers in plume symbols refer to the Volcanic Explosive Index (VEI) described by Simkin *et al.* (1981). Note listing of recent ashfall at Skilak Lake on the Kenai Peninsula.

earlier. Unfortunately, the two hazards are additive. Given the population density of the Anchorage metropolitan area and its proximity to Mounts Hayes, Spurr, Redoubt, Iliamna, and Augustine (the latter four of which were active within the last 200 y), the cumulative risk from these volcanic sources is both real and finite. Clearly it calls for a much better quantitative assessment of the risks involved.

Any assessment of past activity should also be combined with continuous seismic monitoring of at least these five volcanoes closest to Anchorage, in order to provide some advance warning prior to an impending eruption. Over and above those occasions discussed earlier, several smaller communities along the Alaska Peninsula and the Aleutian chain had volcano alerts during the last few decades. These alerts were in connection with the activities of:

- Okmok on Umnak Island
- Akutan on Akutan Island
- Westdahl and Shishaldin on Unimak Island
- Pavlof, Kupreanof, Veniaminof, Ukinrek, and Peulik on the Alaskan Peninsula.

Although Makushin volcano on Unalaska Island has not been recently active, during any eruption, the towns of

Unalaska and Dutch Harbor would be extremely vulnerable. The same applies to Sitka, with its close proximity to Mount Edgecumbe. Lava flows, debris avalanches or mud flows, ashfall, and glowing debris avalanches (which sometimes surge out onto open water) are all potential hazards in case of an eruption. Add to these hazards the volcanically induced tsunamis, earthquakes, toxic precipitations, and fumes that must be considered potential threats, and the danger is considerable, however rare these occurrences may be.

Challenges to Human Activity

The seismicity, volcanicity, tectonics, and related geohazards of the Gulf of Alaska, combined with increasing population and development, pose severe challenges for the future. Their very existence calls for (1) a solid scientific understanding of the nature of these hazards, and (2) the development of realistic policies based on this knowledge that, when implemented, carefully balance the short-term needs for development with the long-term needs for preservation and the avoidance of catastrophic losses.

Scientific Challenges

The highly dynamic tectonic environment of the Gulf of Alaska poses formidable scientific challenges. One such scientific challenge is to unravel both the geologic history and the nature of the terrane accretion that formed most of continental Alaska along with its resources.

Another pressing challenge lies in accumulating and using this scientific knowledge to mitigate the adverse effects of geological hazards. One stumbling block lies in the fact that the hazards must be expressed quantitatively before they can be translated into economically viable public decisions and regulations. To mitigate seismic, volcanic, and tsunami hazards effectively requires solid observational data, which implies that a basic measurement capability must be maintained. The specific scientific and societal challenges that Alaskans face in this respect have been concisely summarized in a brief document prepared by an expert panel (Davies 1983).

Outlined here are a few practical and readily achievable points for future research that appear crucial for effective hazards mitigation:

- 1) *Paleoseismic Record*—Large earthquakes are rare (recurrence about every 100 y), and the written Alaskan historic record is short (about 200 y). Since one needs a long record of great earthquakes in order to establish a statistically meaningful model for their recurrence, geologic studies of paleoseismicity are crucial.
- 2) *Strong-Motion Data*—The collection of strong-motion records in the Alaska tectonic environment must be pursued with patience and persistence, regardless of strong-motion recording efforts elsewhere in the United States. This is because strong-motion properties in Alaskan subduction zones are distinctly different from those of other tectonic environments in the United States. Although the data are most urgently

needed for the Anchorage metropolitan area and for those offshore regions targeted for development, they probably can be obtained soonest (for great earthquakes), in the postulated soon-to-break seismic gaps of Yakataga and the Shumagin Islands. The data set must include strong-motions from sites both offshore and onshore, as well as from both soft and competent soils or rocks.

- 3) *Geohazards Atlas*—A comprehensive up-to-date atlas with quantitative seismic and other geohazards maps for the Gulf of Alaska region needs to be produced. It should reflect existing hazards data as well as the incompleteness of these data, but most importantly, it must fulfill the very practical and realistic needs of public and private users, planners, and decision makers.
- 4) *Tsunami, Volcano, and Earthquake Warnings*—Modern seismic network and mareographic sensing technology is available, and it can make tsunami warnings faster and more effective, bring volcano warnings to reality, and may even make short-term earthquake alerts possible. This will require, however, that modern communication facilities be made available to transmit crucial data from remote monitoring sites to data centers. The centers must be staffed with experts who can exert decisive judgment. Their assessments could not only provide decision makers with options ahead of impending calamities, but could inform them quickly on the extent and severity of a disaster in progress.

Public Challenges

Sooner or later, there is a price to pay when population centers get a foothold in earthquake and volcano country. The challenges to the Alaskan public lie in the dilemma of whether to pay attention to mitigation and the associated costs ahead of time, or to pay the full price of an unmitigated disaster when ever and wherever it strikes.

Alaskans heat their houses—a calculated yet comforting fire hazard—but in doing so, adhere to standard technology and a building code. They use common-sense practices that reduce the risk of fires in homes and in working facilities, and equip themselves with fire extinguishers and hydrants. It has finally become acceptable to maintain standing fire departments, at least in the larger communities.

Why, then, only 20 years after the Great Alaskan Earthquake of 1964, are multi-story buildings in downtown Anchorage rising from those same sites which so recently failed and slid?

Conclusion

A century is a small fraction of a rock's geologic memory, while a dozen decades occupy a major segment of Man's mind. Alaskan geology works at an imperceptible pace, while Alaskan urban development continues at an increasingly rapid pace. Alaskans (with their short human

memory) bustle along, day by day, while the earth beneath them slowly accumulates massive stresses and strains.

Overnight—in geologic terms—a colony of log cabins has turned into a metropolis that is oblivious to its potential for disaster—disaster that is guaranteed when tectonic forces like those of 1964 are unleashed again. In advance of the event, only a few seem to take quiet notice. Insurance companies make it their business to heed the numbers and the obvious, documentable odds. They set their rates, and limit, distribute, or exclude coverage, all the time acutely aware of the latent risks. Will they be the only ones who are well prepared when the geologic odds catch up with the rest of Alaska?

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Interaction Between Silled Fjords and Coastal Regions

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ABSTRACT

This chapter reviews the oceanography of the silled fjords bordering the Gulf of Alaska—with emphasis on both the physical and the biogeochemical interactions between the estuaries and the contiguous coastal regions. Of necessity, specific examples are drawn predominantly from relatively few localities that have been the sites of multi-year, interdisciplinary studies. However, comparisons are made with more comprehensively studied fjord provinces elsewhere in the world. As in all high latitude fjord environments, freshwater and sediment input, primary production, and other biogeochemical processes are subject to intense seasonal fluctuations.

In most of the Alaskan fjords studied to date it appears that an entrainment-driven circulation is not well developed, even at the time of maximum freshwater discharge. Circulation in the near-surface region, at intermediate depths, and within the basins (on various time scales) is dominated by events occurring in the coastal zone and within the Gulf. This physical regime in turn generates distinctive annual cycles in the sub-euphotic chemistry.

Nutrients regenerated both within the basin column and within soft-bottom sediments are predominantly exported out of the fjords. The Gulf of Alaska fjord province is geologically young, and the mean sediment discharge rate is correspondingly large. Sedimentation rates within the fjords may be very high, especially in those glacial fjords where the stratified estuarine circulation is relatively weak.

Introduction

Although a number of investigators (see review by Darnell and Soniat 1979) have emphasized the interdependence of estuaries and their contiguous coastal regions, it has been common practice to treat these marine environments as oceanographically independent entities. Such has largely been the case along the Gulf of Alaska coast. This region has not been studied extensively when compared with neighboring, lower latitude environments. For example, few of the more detailed studies of fjord-estuaries along the Gulf coast have included synoptic biogeochemical data from adjacent shelf regions. Inevitably, detailed knowledge of the mutual oceanographic influence of the fjords and the shelf region in the Gulf is very sparse, and the situation is probably little better in fjord provinces elsewhere in the world (Syvitski, Burrell, and Skei, in press). Nevertheless, there is increasing appreciation of the fact that such interactions (Fig. 7-1) are of major importance (Svendsen 1977). The pri-

mary purpose of this chapter is to review some of the information presently available, and hopefully stimulate further interdisciplinary work specifically directed to fjord-ocean interaction problems. The chapter discusses certain inlets in

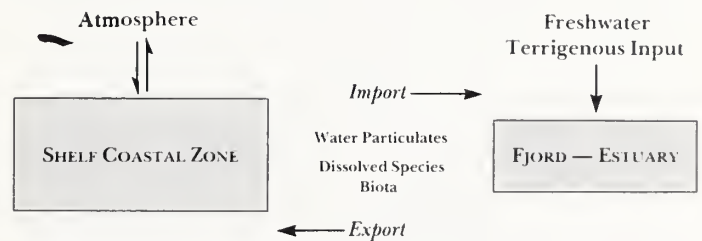


Figure 7-1. Schematic of fjord-coastal water interactions.

detail; these inlets are predominantly located along the Alaskan fjord coast from Ketchikan to the Kenai Peninsula—between 55° and 60°N (see Fig. 7-4; see also Hood, Figs. 1-1

through 1–4, Ch. 1, this volume). Conditions in fjords in the adjoining regions of British Columbia are also cited.

For various practical reasons, the sampling scales of oceanographic field programs can seldom be optimized for a range of multidisciplinary parameters and processes. Following the definition of Mann (1975) and others, it is clear that estuaries—including the near-surface zone of fjords—generally function as autonomous systems only with respect to processes that operate at frequencies of days or less. Thus, Winter, Banse, and Anderson (1975) used an approximately daily sampling scheme to document irregular bursts of phytoplankton production in Puget Sound, and linked those bursts to short-term mixing events. Most field programs operated in Alaskan fjords sampled at intervals of the order of months. At these frequencies, not only is there the danger of aliasing the data, but the danger that most in-fjord processes are likely to be affected by events occurring outside the fjord.

The time and space scales of oceanographic processes are intimately linked, and it is apparent that investigations specifically dedicated to unraveling shelf-estuary interactions would require observations that continued over a period of many years. Multi-year trends are evident from the comprehensive oceanographic data obtained for the northern Gulf shelf region (Xiong and Royer 1984). These trends can also be seen over four to five year periods in a southeast Alaska fjord system as is discussed later in this chapter. However, continuing investigations over many more years would be required before low-frequency (order of years) signals can be delineated with any degree of confidence.

Physical Interactions

Background

A two-way water exchange couples the Gulf of Alaska and the fjord-estuaries along the Alaska and British Columbia coast. Freshwater that is discharged via fjords and other estuaries is a major influence on shelf transport, and Gulf waters may episodically penetrate into the coastal inlets, replacing both intermediate and deep resident water.

The major driving force for geostrophic flow within the sub-surface Gulf mixed layer below 50 m (Royer 1979; Xiong and Royer 1984) is the Aleutian low-pressure system (Fig. 7-2) (Dodimead, Favorite, and Hirano 1963; Royer 1975). This system is dominant throughout the oceanographic winter season. Prevailing cyclonic winter winds (easterlies in the northern Gulf, becoming more southerly with decreasing latitude) generate on-shore Ekman transport along the coasts of Alaska and British Columbia. Computed upwelling-downwelling indices show that the maximum coastal convergence occurs in the northern Gulf during January and February (Bakun 1973), and begins progressively earlier (October through December) in the southern Gulf region (the data in Fig. 7-3 from Dodimead 1980 are for a 50°N locality). For greater detail on the meteorological conditions in this region, refer to Chapter 2 of this volume by Wilson and Overland.

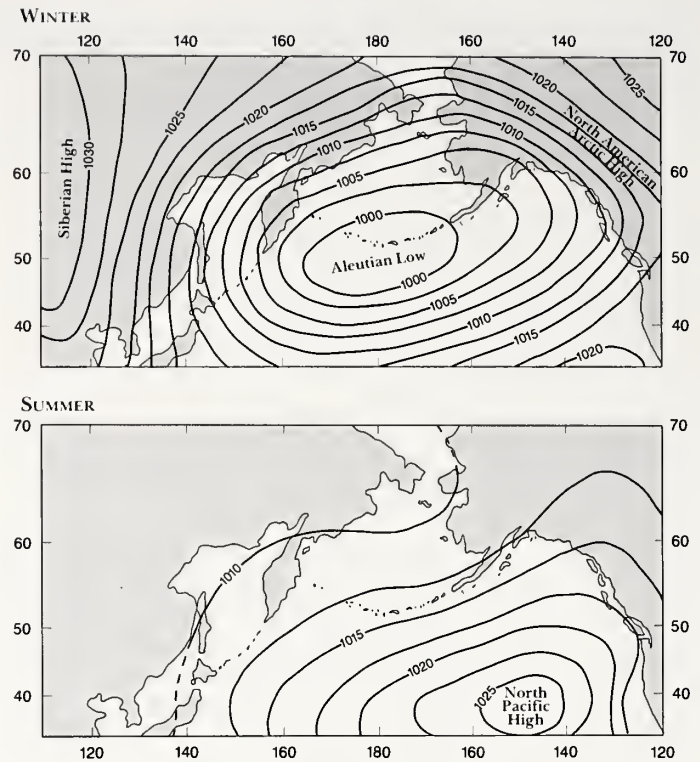


Figure 7-2. Mean seasonal sea-level atmospheric pressure patterns (millibars) for the north Pacific. (Modified from Dodimead *et al.* 1963; Royer 1975.)

The Gulf region is predominantly under the influence of weak high pressure centers throughout the summer (approximately May–September) (Fig. 7-2). A relaxation of the intense winter down-welling condition at the coast then permits the run-up of denser water onto the shelf and into the coastal waterways. Wind measurements obtained in the northern Gulf at this time of year (Livingstone and Royer 1980; Royer 1983) do not confirm off-shore, near-surface transport in this region as predicted by computed upwelling

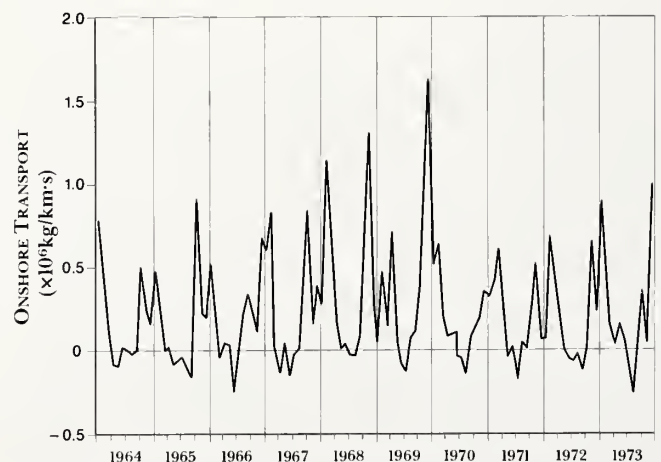


Figure 7-3. Mean monthly on-shore Ekman transport at 50°N, 130°W for the period 1964 to 1973 (data from Dodimead 1980).

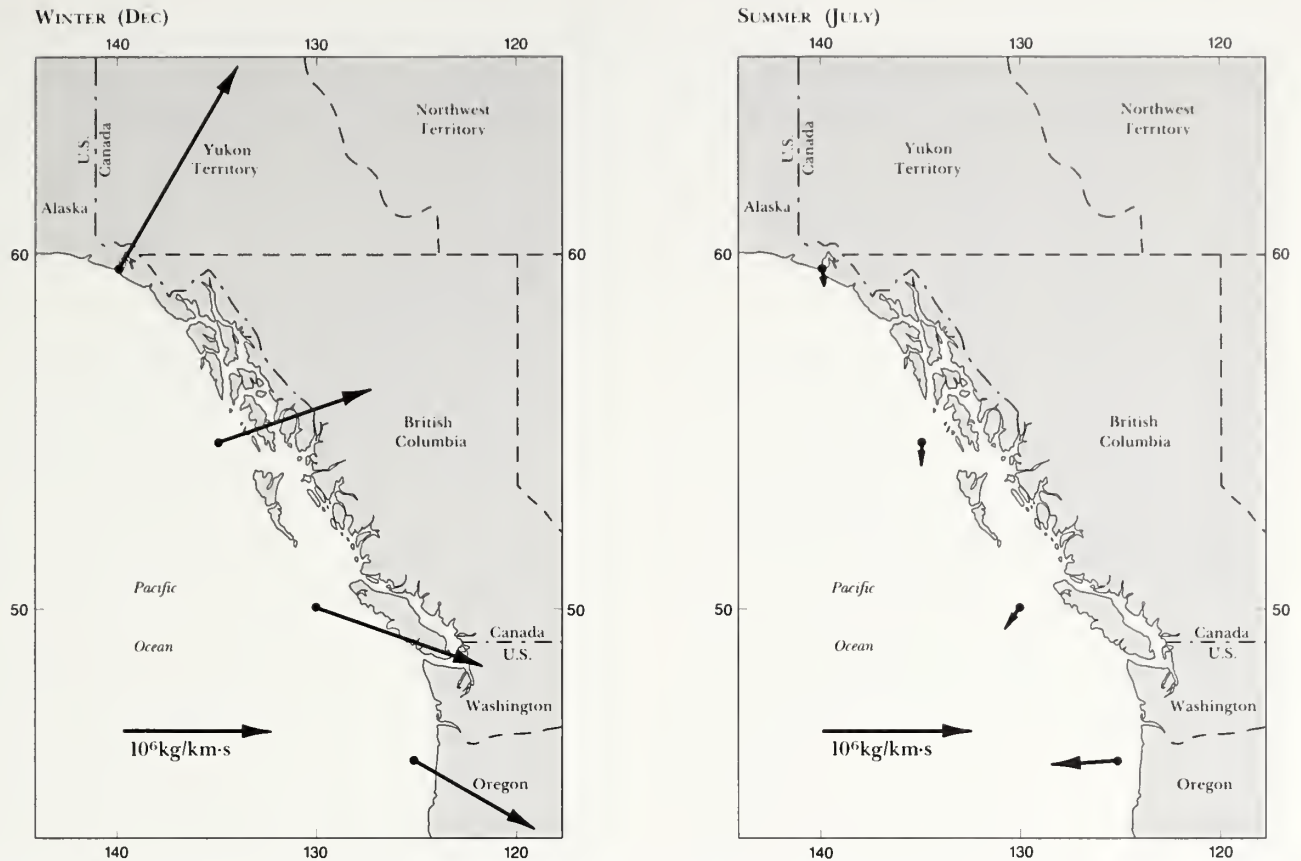


Figure 7-4. Mean monthly Ekman transport vectors, northeast Pacific coast, for December and July, for the period 1950 to 1959. (Modified from Crean 1967.)

indices (Bakun 1973, 1975; see below), although it is apparent from the data of Figure 7-4 (Crean 1967) that coastal divergence should increase in importance southwards in the summer.

Estuarine Circulation Within the Gulf Coast Fjords

The rate of both rainfall and freshwater discharge into the Gulf of Alaska is very high and becomes an important control on circulation (Tully and Barber 1960; Royer 1979). High mountain ranges run continuously along the eastern and northern Gulf coast, and the mean annual precipitation along the margins of both Alaska and northern British Columbia generally exceeds 240 cm (Crean 1967; Royer 1979). Much of this precipitation falls as snow which is stored for later discharge.

Local freshwater discharge patterns reflect the relative importance of both stored and direct precipitation and subsequent runoff. Because of the rugged terrain within the catchment areas, residence time for rainfall is typically very short. Consequently, peak freshwater influx from these fjords to the Gulf of Alaska occurs in the fall at the time of maximum direct precipitation. The precipitation stored as snow then generates a secondary discharge peak in the spring at lower latitudes (Fig. 7-5A), merging into the late summer-fall maximum in the northern Gulf region (Fig. 7-5B). The maximum freshwater influx from snow melt

occurs where large river systems that drain extensive hinterlands enter the Gulf. This influx normally occurs in spring through summer. This pattern appears to predominate along the coast of northern British Columbia (Pickard and Stanton 1980; Macdonald 1983).

In the northern Gulf there is a preponderance of glacial and snow-field run-off, and a paucity of large rivers. Glacial meltwater discharge reaches its peak in late summer to fall. While the single major river in this area—the Copper River—reaches maximum discharge levels in June and July (Roden 1967), the mean annual flow is only around 10% of the total regional discharge. This estimate was made by Royer (1979, 1982) from precipitation/run-off box models. Royer's line-source hydrology models predict maximum freshwater influx into the northern Gulf region in October, coincident with maximum sea-level.

Although the mean precipitation rate along the Gulf of Alaska coast is very high, discharge into the head of any particular fjord may be relatively low. This is a consequence of the characteristic watershed topography that surrounds each fjord. For example, the total catchment area for Boca de Quadra fjord (Southeast Alaska) is approximately ten times the marine surface area. Mean annual freshwater discharge via the Keta River at the head is $25 \text{ m}^3/\text{s}$, increasing to $\sim 40 \text{ m}^3/\text{s}$ through the period of maximum discharge in September and October (Fig. 7-5A). However, this is only about 15% of the total freshwater influx into this fjord. Discharge

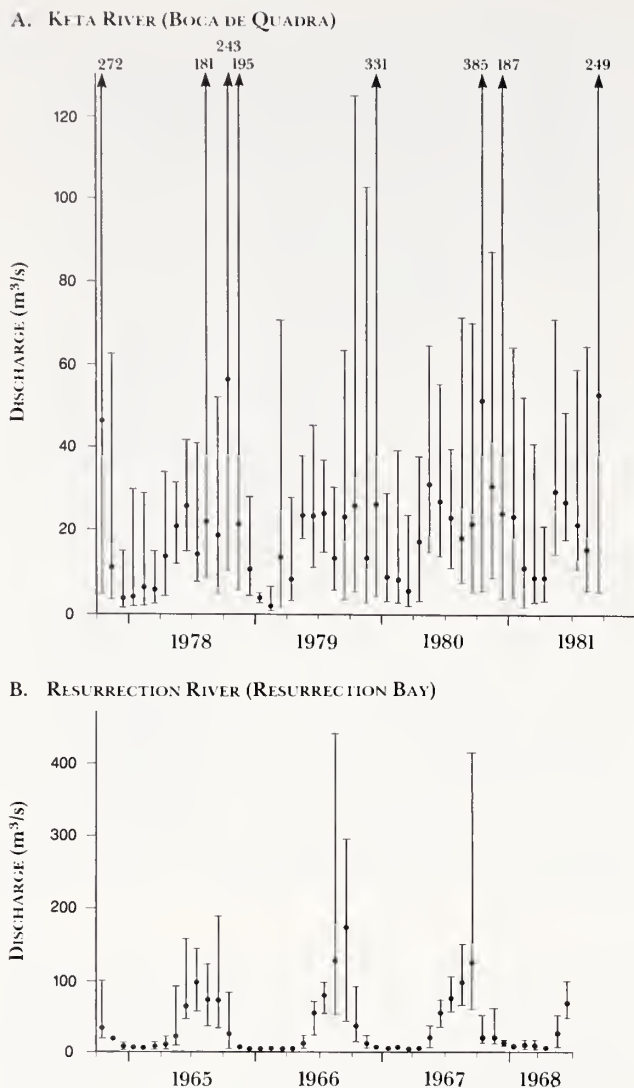


Figure 7-5. Patterns of seasonal freshwater discharge into the heads of two Gulf of Alaska fjords: monthly maxima, minima and means (U.S. Geological Survey Water Resources Data for Alaska, 1965–1981). (A) the Keta River into Boca de Quadra, for the period October 1977 through September 1981; (B) the Resurrection River into Resurrection Bay, for the period October 1964 to June 1968.

around the periphery of the fjord increases the stability of the upper water column, but does little to enhance classic, fjord-type estuarine circulation.

Royer (1982) computes a mean coastal freshwater input value for Southeast Alaska of $0.41 \text{ km}^3/\text{y}$ for each kilometer of coastline. This figure is of the same order as Pickard and Stanton's (1980) estimate of $0.44 \text{ km}^3/\text{y}$. This is nearly 100% greater than the annual mean discharge from the Boca de Quadra watershed. The discrepancy suggests a significant net supply of brackish water outside the mouth of this particular fjord, and Nebert (1982) has shown that a reverse estuarine circulation—inflow at the surface and outflow at depth—may be identified from hydrographic data in the lower reaches of the inlet throughout much of the year. Port Valdez provides another well-documented example of a

fjord where the expected two-layer circulation pattern is poorly developed. The mean salinity of the upper 100 m from the head to the mouth remains relatively constant year-round and may even *decrease* down-fjord in mid-summer (Muench and Nebert 1973). A poorly developed estuarine circulation, substantially confined to the surface 15 to 20 m zone, has been observed in October in this fjord.

In addition to the relatively low freshwater discharge at the heads of many Alaskan silled fjords, the large regional tidal ranges must favor a mixed over a layered near-surface circulation. An indication of the relative importance of either pattern is shown by the ratio of freshwater input to the tidal prism. The annual mean of this ratio for Boca de Quadra is 0.012, and corresponding values for some other well-studied Alaskan fjords are all less than 0.05 (Endicott Arm: Nebert 1972; Port Valdez: Muench and Heggie 1978; Resurrection Bay: Heggie and Burrell 1977). Bowden (1980) has noted that estuaries having ratio values less than 0.1 are likely to fall into the partially to well-mixed categories. Studies at Silver Bay, southeast Alaska (McAlister, Rattray, and Barnes 1959; Rattray 1977), have been cited by Dyer (1973) as illustrating entrainment-driven fjord circulation. While this mode of transport may occur in the summer when the ratio of freshwater discharge to tidal prism is around 0.08 (Fig. 7-6B), it rarely occurs through the winter when river inflow is low (Fig. 7-6A). Based on present evidence, it appears that near-surface circulation in Silver Bay is not typical of the circulation that develops in Alaskan fjords in general (see also discussion by Nebert 1985).

Fjord Intermediate Water Exchange

Shelf processes may cause a sporadic exchange of fjord intermediate water—that zone beneath the near-surface estuarine circulation, and above the sill. In relatively deep-silled fjords, estuarine circulation may be only weakly coupled to the intermediate water exchange (Stigebrandt 1981; Farmer and Freeland 1983). The best documented examples have been recorded from the west coast of Norway. Helle (1978) described the monsoonal reversal of the annual wind patterns along this fjord coastline from prevailing southerlies through the winter to periodic winds from the north in late spring and early summer. On-shore convergence in autumn and winter results in a sea surface set-up at the coast, as well as the barotropic and induced baroclinic flow of water up-inlet. This has been described for Josenfjord and adjacent inlets along the southwest Norwegian coast by Svendsen (1977, 1980) and modeled by Klinck, O'Brien, and Svendsen (1981). Summer-time wind reversals result in shallow upwelling of shelf waters at the coast (Svendsen 1981). Subsequent penetration into the fringing fjords is largely dependent on the depths of the barrier sills as described, for example, by Bakke and Sands (1977).

Computed transport ranges that are normal to the coast (as illustrated in Fig. 7-3) imply that off-shore Ekman transport should result in upwelling along the Gulf coast in the summer (Dodimead 1980), especially in the southern Gulf region (Fig. 7-4). However, Livingstone and Royer (1980) and Royer (1983) do not believe that summer winds reverse the northward-flowing coastal current in the northern Gulf.

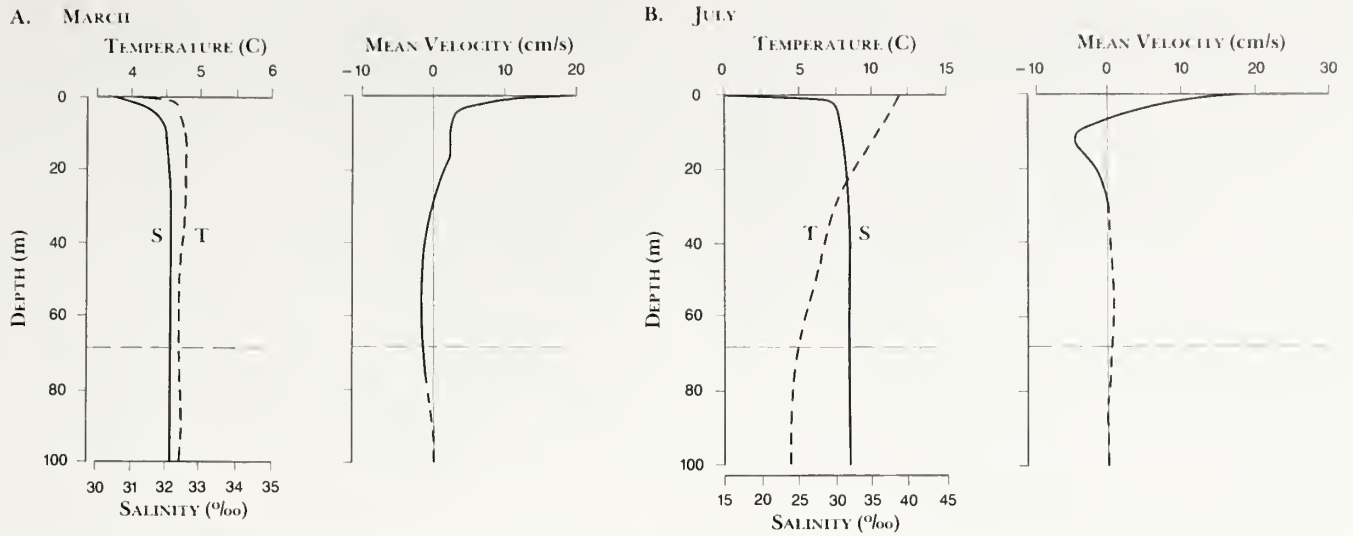


Figure 7-6. Vertical temperature, salinity, and velocity profiles (positive seaward), Silver Bay, Alaska, in March and July 1957. (Modified from Rattray 1977.)

Based on Norwegian experience, shallow coastal upwelling would be a significant and readily identifiable phenomenon in the summer because each water mass imported into the fjords has a distinct chemical signature and biota (see further discussion below). At present, there is no evidence that this occurs anywhere along the Gulf of Alaska coast. Relaxation of the intense winter downwelling condition in the summer does, however, result in an impingement along the coast of relatively deep and dense shelf water as described in the following section.

December through February is the period of maximum on-shore convergence in the northern and northeastern Gulf, and near-surface shelf waters are believed (Muench and Schmidt 1975) to be transported into Prince William Sound at this time of year (see also following discussion on zooplankton dynamics). However, to date, a large-scale exchange of intermediate zone water within Alaskan fjords has not been observed in late winter or spring. Figure 7-7 illustrates a temperature-characterized 'event' at around 50 m immediately outside the entrance of Boca de Quadra fjord in April (1983). This water was not present within the immediately adjacent fjord basin, and was no longer evident outside the fjord some six days later. Colonell (1980) has identified similar transient surges of external water into Port Valdez (Prince William Sound), and suggests they result from the passage of local weather systems.

Royer (1979) has observed that maximum set-up along the northern Gulf coast occurs in November. This set-up is out of phase with the winter peak in the computed downwelling index, but occurs immediately following the period of maximum annual freshwater influx into the near-shore zone. He believes that freshwater input is the dominant influence on the circulation of the upper mixed layer of the coastal Gulf in this region, and hence, that barotropic effects on the sea level are small. This pattern may similarly apply in Southeast Alaska and northern British Columbia. Dodimead (1980) shows that maximum sea levels at Prince Rupert (54°N) occur around December (Fig. 7-8), possibly slightly preceding the onset of on-shore Ekman transport

which, over the previous five years, has peaked abruptly in January and February. However, maxima recorded over a 20-y period occurred in a range that extends from November to January, and, as noted above, in this region, peak discharge from the major rivers occurs around June and July. Thus, Waldichuk (1964), in an earlier study of the sea level record at Prince Rupert, concluded that the baroclinic contribution to the pressure field in this region of the Gulf shelf was insignificant.



Figure 7-7. Vertical temperature profiles outside and inside the entrance sill of Boca de Quadra fjord, April 1983. (See Fig. 7-27 for longitudinal profile.)

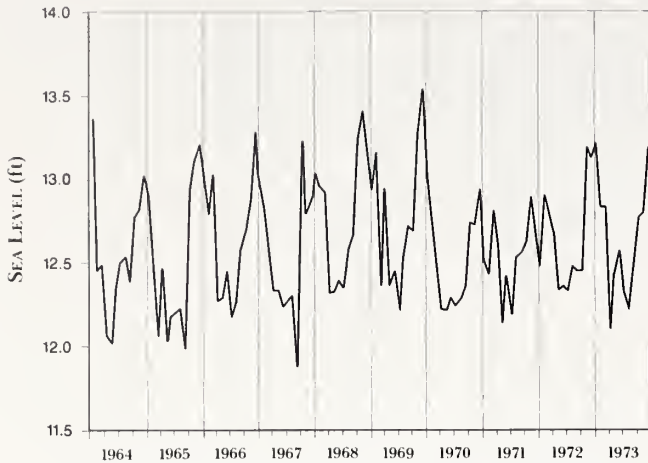


Figure 7-8. Mean monthly sea level values at Prince Rupert, British Columbia, 1964 to 1973 (data from Dodimead 1980).

Regardless of driving forces, it would be expected that shallow sub-surface shelf waters would be carried into the coastal waterways and fjords along the northern and eastern Gulf margin primarily in the fall—the period of maximum coastal set-up. It appears that, to date, the shelf-fjord intermediate-water exchange in this region has been specifically studied only within Boca de Quadra (a fjord located at 55°N , close to the Alaska-British Columbia border). Brackish surface water from the northern British Columbia rivers is transported northward along the coast (Crean 1967; Dodimead 1980), impacting the coastal waterways and penetrating into the outer reaches of Boca de Quadra (Nebert 1982, 1984). Figure 7-9A shows that through the winter (October through April 1983), the mean salinity of water between 30 and 50 m is lower outside the fjord than at the head. However, the transport of exterior water found at intermediate depths into the innermost basin at the head of Boca de Quadra has been identified only in the fall and early winter. Figure 7-10 illustrates a water mass that was characterized by higher temperatures, and centered at approximately 50 m both outside the mouth and toward the head of Boca de Quadra fjord in December 1980. Some chemical properties of this intrusion are noted below. Nebert (1984) has also described in detail the advection of warmer and less-saline shelf water at intermediate depths up to the head of this fjord system in October and November 1982. (Penetration over the latter period is marked by the net decrease in salt in the above-100-m region as shown later in Fig. 7-15.) Surface cooling through the winter isolates a warm core near the 50-m depth mark at the head of the fjord, and this core persists until the following spring.

In the southern Gulf region, maximum on-shore convergence occurs earlier (around December) (Figs. 7-3 and 7-4) than it does at higher latitudes. Winter on-shore convergence has been shown to generate energetic up-fjord movement of water at depths above 180 m within Alberni Inlet on the Pacific coast of Vancouver Island (Stucchi 1983). Cannon and Holbrook (1981) and Holbrook, Cannon, and Kachel (1983) have described in detail major inflows of coastal surface water into the fjord-like Strait of Juan de

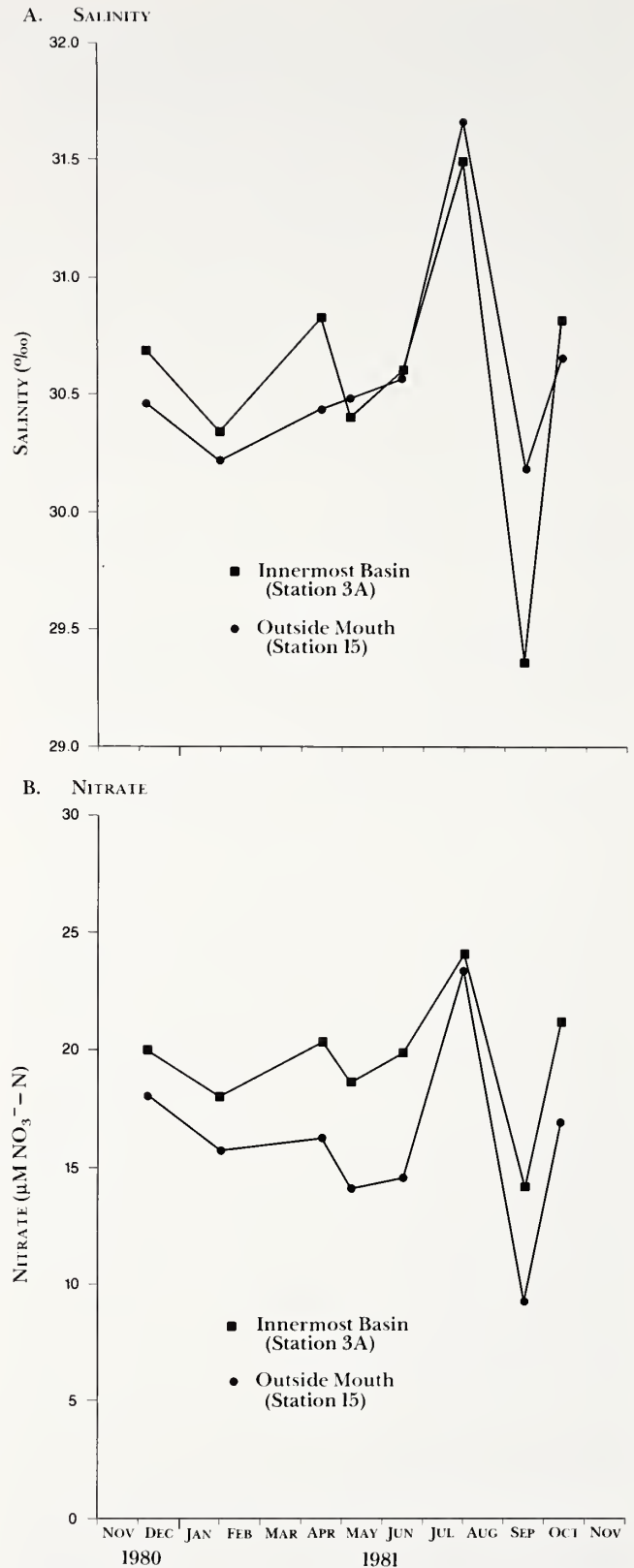


Figure 7-9. Mean values of salinity and nitrate concentrations within the 30- to 50-m intermediate water zone outside the fjord, and within the innermost basin, Boca de Quadra, November 1980 to October 1981. (See Fig. 7-27 for longitudinal profile.)

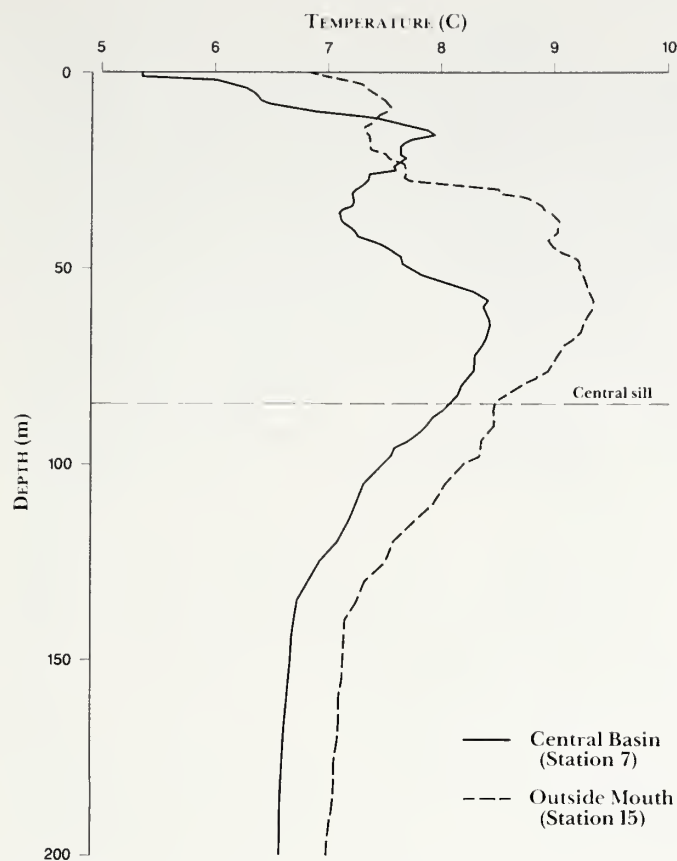


Figure 7-10. Vertical temperature profiles outside the mouth and within the central basin of Boca de Quadra fjord, December 1980. (See Fig. 7-27 for longitudinal profile.)

Fuca. Such intrusions also occur predominantly in the winter when more frequent and persistent southerly winds both promote coastal convergence and carry Columbia River water northward to provide an external source of less dense water. Flow into the west coast inlets of Vancouver Island and through the Strait of Juan de Fuca appears to be mainly baroclinic. This sequence thus appears to duplicate, on a larger scale, the intermediate-water exchange observed in Boca de Quadra fjord.

Intense down-fjord winds are a common occurrence along the Gulf of Alaska coast in winter, especially in glaciated regions. Such katabatic (Squamish or Taku) winds drive the surface layer seaward, promoting localized import and upwelling of intermediate water within the fjords. An example has been described from the Kitimat system of northern British Columbia by Macdonald, Cretney, Wong, and Erickson (1983). Episodic up-inlet winds may occur along this coast in the spring and summer. Farmer (1972) has described the reversal of the surface currents during such an event within Alberni Inlet.

Deep-Water Exchange

Sub-sill fjord basin water is replaced from seaward sources when higher density water is available for transportation in over the sill. Since at any time, this process is a func-

tion of the relative densities both at the sill height and within the basin, exchange depends both on the supply of denser external waters and on the mixing processes between the basin and the over-lying intermediate water, which progressively reduces the density of the resident basin water. The tidal range along the Gulf coast is larger (mean range of ~3.5–5.0 m, south to north) than along the fjord coast of Norway. Higher velocity tidal currents in the region of sill constrictions generate turbulent mixing, which in turn accelerates the rate at which the density decreases in the sub-sill water. This results in a more extensive deep-water exchange, and lessens the chance that anoxic water will be produced. Farmer and Smith (1980) have shown that super-critical tidal flow at the sill can lead to plunging waves that may descend to considerable depths within the basin. Figure 7-11 illustrates the temporal relationship between density at sill height (80 m), and at the bottom (~365 m) of the central basin of Boca de Quadra fjord. Complete water replacement may occur when these values coincide. In a stratified basin, the water will be replaced to some intermediate depth if the source-water density is less than the density of water at the bottom. The deep-water renewal processes in a wide variety of fjords have been reviewed in detail by Gade and Edwards (1980) and by Farmer and Freeland (1983).

As described above, water circulation in the Gulf of Alaska exhibits a regular seasonal pattern. The denser water runs up onto the shelf during the summer with the relaxation of the shoreward convergence that dominates in the winter. The shelf surface water, however, has a minimum density in the summer because of increased freshwater dilution and insolation, and a zone of minimum seasonal density variation centered at around 150 m on the northeastern Gulf shelf (Royer 1975) (Fig. 7-12). The density of source waters available to the fjord basins is therefore primarily a function of the sill depth (Muench and Heggie 1978).

Near-surface winter shelf water is the densest source water available to shallow-silled fjords. Basin water contained by a sill shallower than 150 m (in the northeast Gulf) has a lower density at comparable depths than water found in deep-silled fjords. Depending on the density differential across the sill (determined primarily by year-to-year variations in the source water density) replacement of sub-sill water should occur in the oceanographic winter (January to May). This is the time when the maximum shoreward Ekman transport occurs along much of the Gulf coast; however, mechanisms for transporting source water into shallow-silled fjord basins in this region have not been studied in detail. Nebert (1972) has shown that the tides may pump denser water that is present outside a shallow sill (Endicott Arm, Southeast Alaska) into the basin. Axially directed winds may also be an important local factor.

Yakutat Bay (60°N, 140°W) and its interior fjords are located between the northern Gulf region and southeast Alaska. The Bay consists of a number of basins enclosed by sills found at various depths. The seaward sill—which controls the entry of shelf source water—is the shallowest sill (around 25 m). Although the deepest penetration into interior basins occurs in the winter, as predicted, there appears

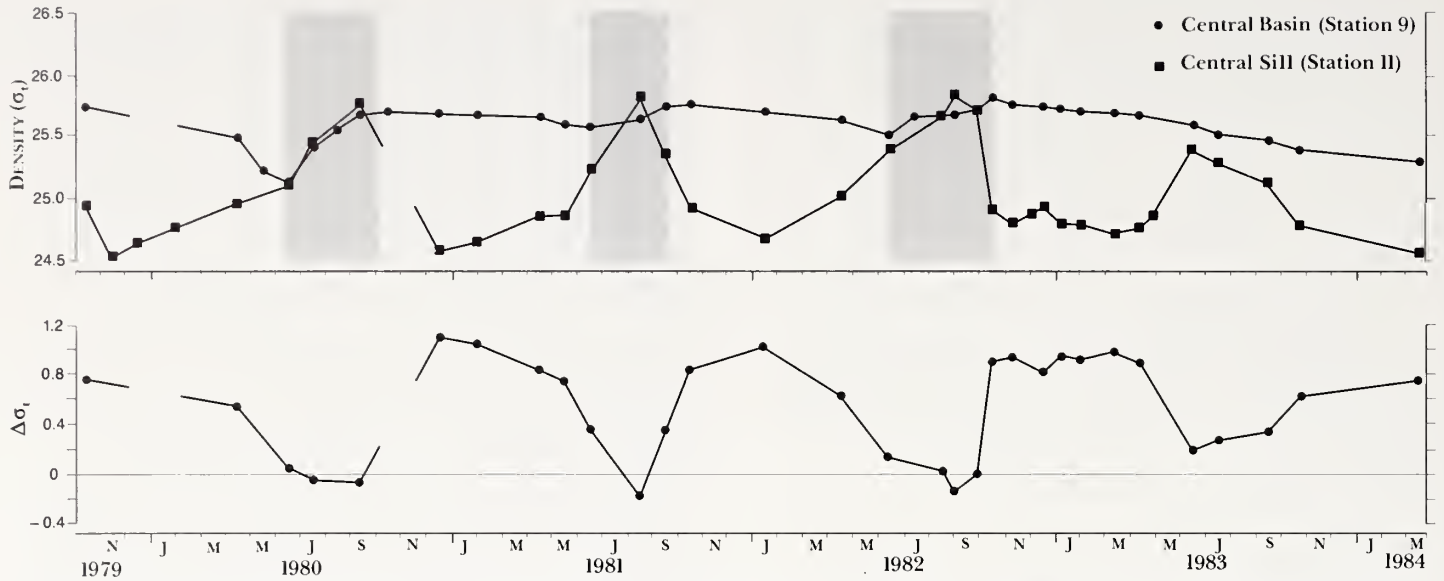


Figure 7-11. Time series distribution of density within Boca de Quadra fjord, October 1979 to March 1984. (Top) Densities at 100-m depth outside the central sill and near the bottom (350 m) of the deep central basin. The shaded zones mark periods of complete flushing of the central basin. (Bottom) Density difference between the source water and resident water at the bottom of the central basin. (See Fig. 7-27 profile for locations.)

to be considerable year-to-year variability. Reeburgh, Muench, and Cooney (1976) have shown that in April 1973 a deep but incomplete over-turn occurred in the fjord farthest removed from the coastal zone. Conditions in the Bay in 1977 are illustrated in Figure 7-13. In this year, replacement water had penetrated the outermost basin prior to sampling in early April, but by late July, the innermost basin had not been flushed and the density of the bottom water there was lower (<24.8) than it had been the previous September (>25.0).

Fjords separated from the Gulf by sills deeper than ~ 150 m are flushed through the summer season which is the period of minimum coastal downwelling. Figure 7-14 illustrates this flushing for Resurrection Bay (approximately $60^\circ\text{N}, 150^\circ\text{W}$), a fjord that opens directly onto the Gulf shelf and is guarded by a single sill at a depth of 185 m (Heggie and Burrell 1977, 1981). As the density of the external water at sill height increases in spring and early summer (*cf.* Fig. 7-11) and then starts to exceed the density of the resident basin water, the basin water is displaced to progressively

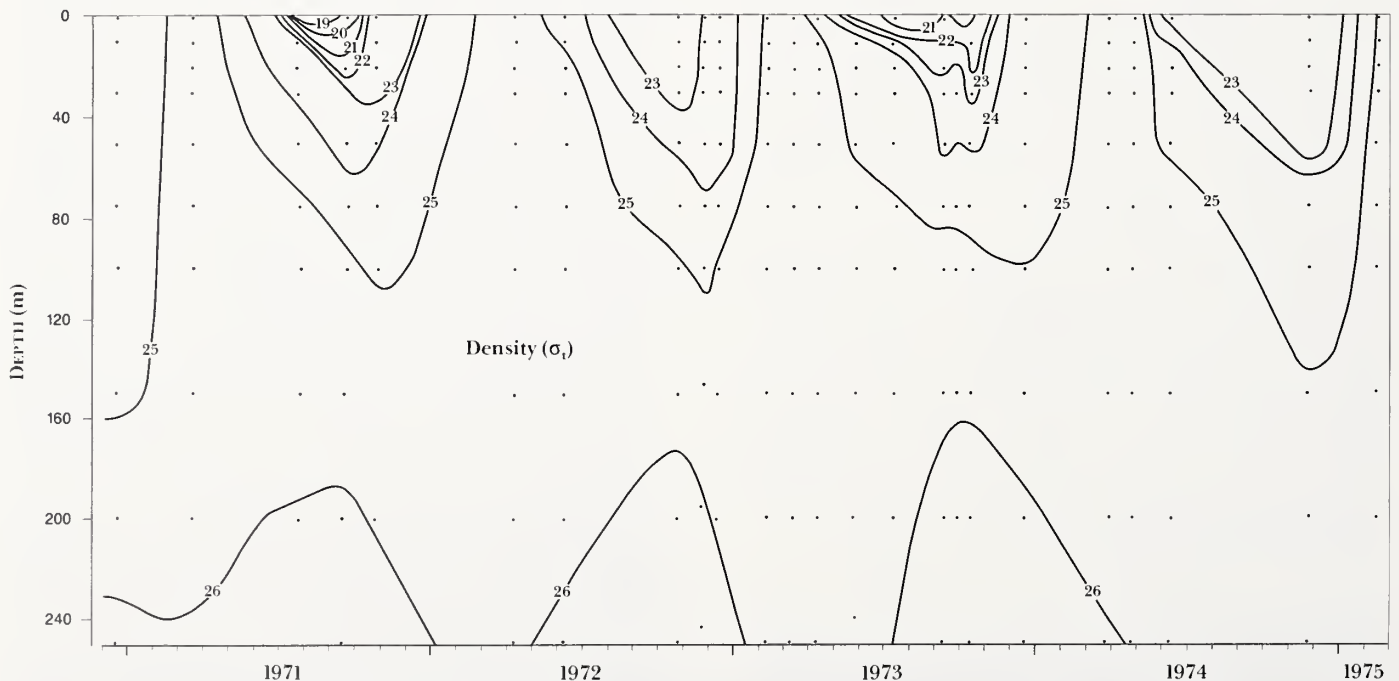


Figure 7-12. Time series vertical density distributions at a shelf station outside Resurrection Bay, December 1970 to February 1975. (Modified from Royer 1975.)

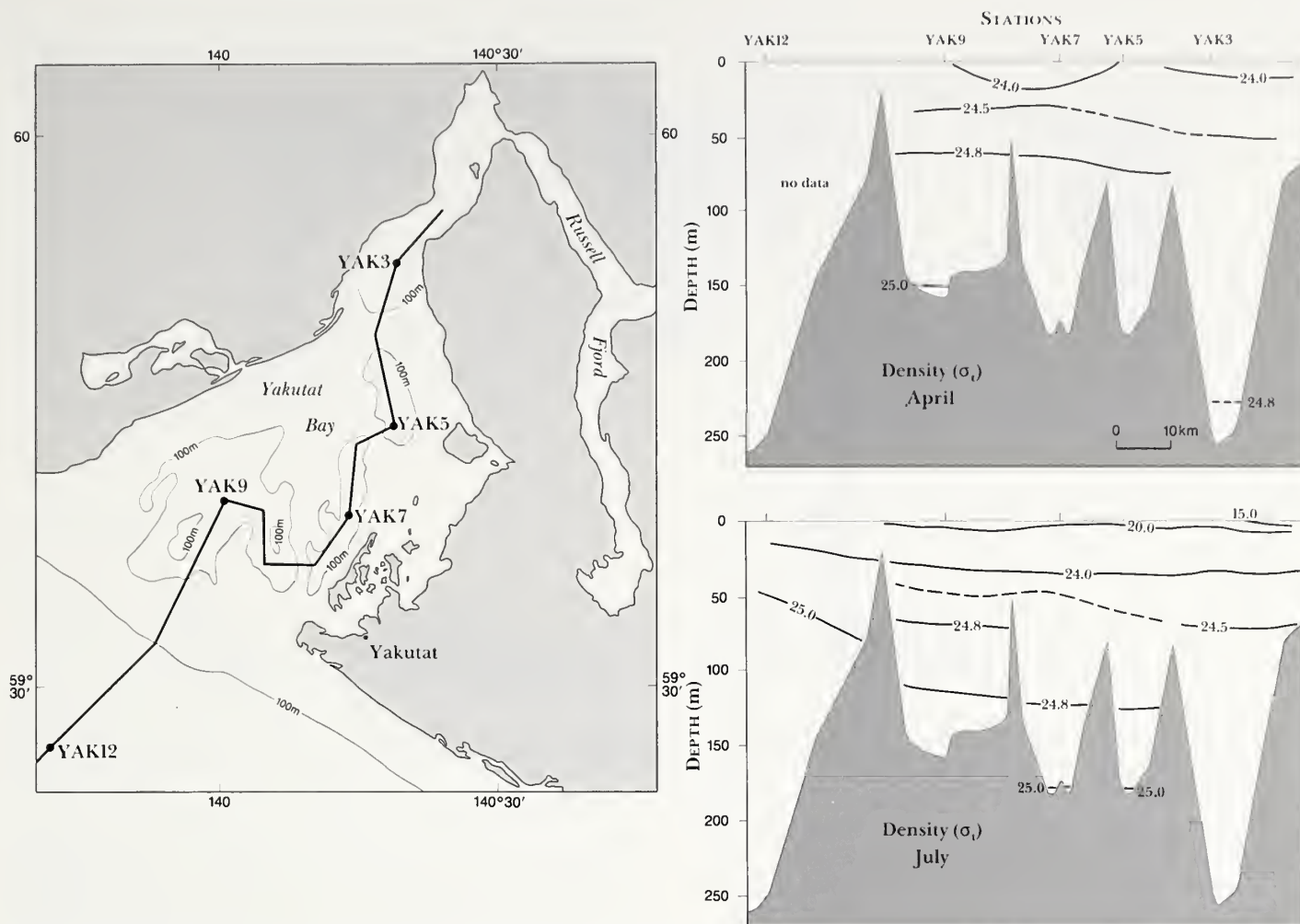


Figure 7-13. Yakutat Bay showing profile line through basins (100-m contour shown) and station locations (left), and longitudinal density profiles within Yakutat Bay basins, April and July 1977 (right).

deeper levels. This happens prior to the multiple flushing of the entire basin that occurs later in the season. The temporally changing chemical character of the source water, derived from progressively deeper horizons in the Gulf, is discussed later in this chapter. The flushing behavior of Resurrection Bay may be contrasted with that of the immediately adjacent shallow-silled (~ 15 m) Aialik Inlet where water replacement occurs in winter (D.L. Nebert, University of Alaska, pers. comm., 1984). Maximum sigma-t (density) values recorded at 200 m in the Aialik basin are less than 25.5, but are greater than 26.5 at the same depth within Resurrection Bay. Deep-water replacement in fjords on the Pacific coast of Vancouver Island also occurs in the summer (Stucchi and Farmer 1976; Stucchi 1983).

The basic winter-summer (shallow-deep silled) flushing patterns exhibited by the Gulf coast fjords are modified for basins separated from the open shelf by additional barriers (as is shown in Yakutat Bay: Fig. 7-13). The seaward terminus of the central basin of Boca de Quadra fjord in southeast Alaska is a sill located at ~ 85 meters. Water that lies at intermediate depths below the sill is renewed beginning in late spring, and in most years the basin appears to be completely flushed through the summer. Intervals for 1980 to 1982 when

the basin was flushed to the bottom are shown in Figure 7-11, and Figure 7-15 (data from Nebert 1984) illustrates the 1982 seasonal progression in terms of the mean net flux of salt into and out of the basin. This particular fjord basin is isolated from direct contact with external source water by an outermost basin (see longitudinal profile of Fig. 7-28 below) where sill-depth water entering the fjord is well mixed with over-lying water. Because of this feature, higher density water is required to flush the central basin than would be predicted based solely on the sill height and the density of the deep central basin water. In other words, the central basin exhibits an annual renewal sequence typical of the deep-sill fjord category defined by Muench and Heggie (1978).

Long-period events in the Gulf may have important impacts on water circulation within the fringing fjords. During 1982-1983, a major El Niño event affected water properties in the Gulf (Xiong and Royer 1984), and may have been a contributing cause of non-renewal within the deep central basin of Boca de Quadra in the summer of 1983 (Figs. 7-11 and 7-15). However, Nebert (1985) has shown no correlation between the long-term (38-year) upwelling-index record for the adjacent shelf region and known El Niño events.

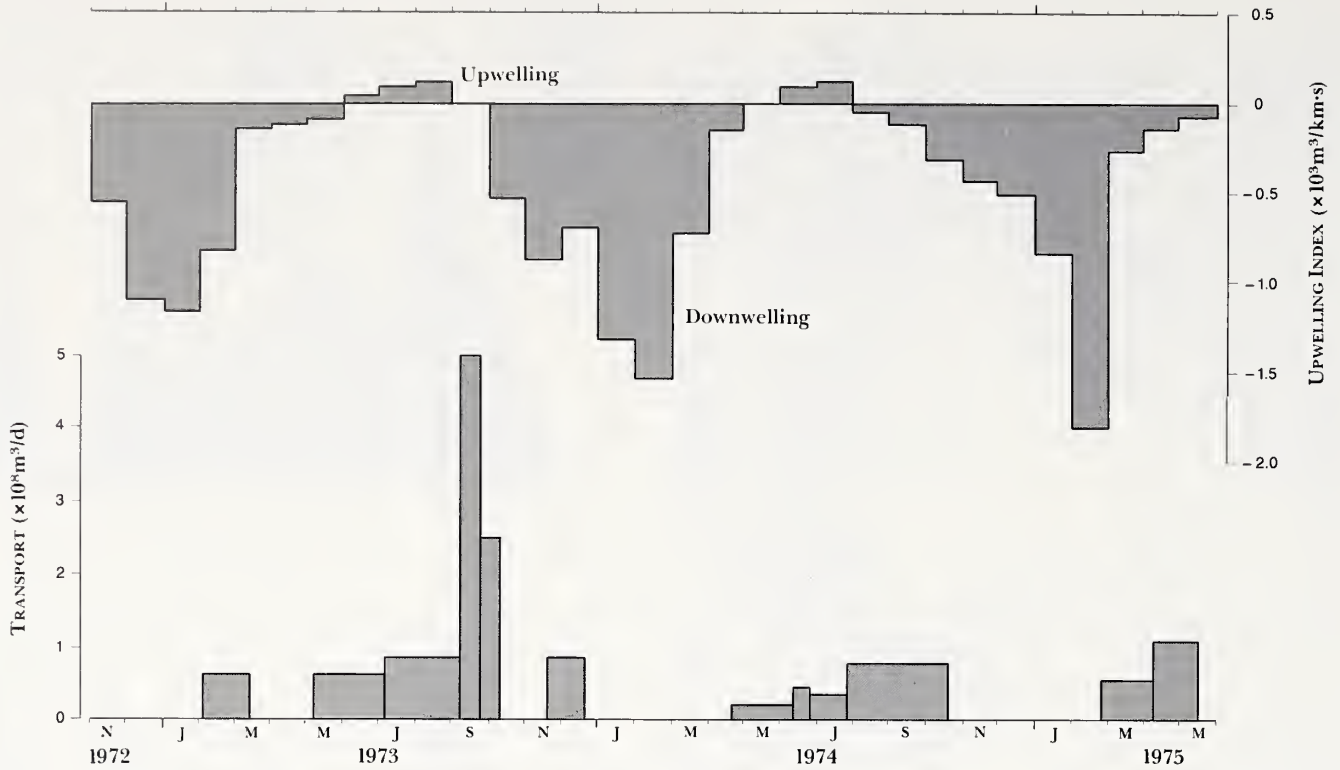


Figure 7-14. Computed seasonal advective transport into the Resurrection Bay basin, and mean monthly upwelling index values (Bakun 1973, 1975) at an adjacent Gulf shelf locality (approximately 60°N, 149°W), November 1972 to May 1975. (Modified from Heggie and Burrell 1981.)

The annual meteorological patterns in the Gulf are the primary influence on the renewal of sub-sill water within the fringing fjords, because the effect of mixing during storms provides source water of the required density. The annual renewal cycle typical of Alaskan fjords is believed to be expedited by relatively intense vertical mixing of the resident basin water between renewal periods. Tidal energy is the most likely source of subsurface vertical turbulence along this coast. High freshwater run-off has not been observed to block the supply of denser water to the basins—

a process that may occur in shallow-silled, poll-type fjords elsewhere (Edwards and Edelsten 1977). Although the renewal of shallow-silled basin waters (such as in Aialik Inlet) is inhibited in the summer when near-surface shelf water salinity is lowest, even the shallowest-silled Alaskan fjords appear to be flushed at least once each year. Nebert (1972) has shown that basin water in Endicott Arm (maximum sill depth ~30 m) is renewed almost continuously throughout the year. Tidal mixing and freshwater input generates a density gradient across the sill in the summer,

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100	92	187	28	270	81	153	504	116	190	183	50	107	25	248	86	77	106		
200	18	187	24	46	46	4	174	125	99	158	30	68	25	51	16	3	12		
300	50	112	17	31	35	37	81	32	8	49	5	20	17	16	19	5	5		
400	29	49	14	39	12	41	63	14	8	18	5	11	4	4	13	11	7		
500	11	11	7	23	6	17	29	5	0	0	5	6	0	2	8	5	7		
600	5	4	3	8	6	8	17	0	0	0	5	3	0	2	3	3	3		
	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
	1982							1983											

Figure 7-15. Seasonal net salt flux (kg/s) up-fjord from the ~85 m central sill within Boca de Quadra fjord, April 1982 to October 1983 (see Fig. 7-27 for longitudinal profile). Mean temporal changes for the depth segments and time intervals shown; positive values (net imports) shaded (data from Nebert 1984).

and during the winter, when freshwater discharge is low, the gradient is maintained because of a relative increase in the density of the source water (Nebert and Burrell 1981).

To date, very few individual fjords in Alaska and northern British Columbia have been examined in detail. A great deal remains to be learned about circulation patterns in these inlets. For example, since the mean tidal range tends to increase northward along the Gulf of Alaska coast, supercritical flow should be generated at the entrance to shallow-silled fjords. This flow should provide a sub-sill source of turbulent energy that will decrease the mean density of the resident basin water and promote more rapid turn-over. This phenomenon has been recorded in a number of fjords in British Columbia (Stucchi 1980; Farmer 1983), but has not yet been observed in Alaska.

Biological Interactions

Background

The biological coupling between estuaries and contiguous shelf areas has received increased attention in recent years. Considerably less is known about higher latitude fjord-shelf interactions when compared with the more commonly studied temperate zone environments. Pearson (1985) however, has noted that the impacts of migrating fish as well as of marine mammals and birds are likely to increase with increases in latitude. Fjords along the Gulf of Alaska coast are known to serve as nursery areas for a number of pelagic fish species such as pink salmon fry and herring. Estuarine nekton are characteristically bottom-dwelling species, but there must be free exchange between fjords and the adjacent coastal waters. Unfortunately, there have been no detailed studies of nektonic food webs in estuaries bordering the Gulf of Alaska that can compare with the work on salmon in the Strait of Georgia done by LeBrasseur, Barraclough, Kennedy, and Parsons (1969). In this section, therefore, only the interchange of planktonic components will be considered.

It has been noted previously that the interdependence of physical and biological processes both inside and outside fjords is a function of the relevant time scales. The near-surface, estuarine region of fjords is likely to be an autonomous ecological system (Mann 1975) only on time scales of less than days. A working relationship linking the residence time of estuarine zone water and phytoplankton turnover rates was initially developed by Ketchum (1954). Lewis and Platt (1982) have shown that the interaction of physical and biological scales may be quantified in terms of a scale length that is a function of both the longitudinal dispersion and the biological reaction rate. In upper Boca de Quadra fjord, for example, where the computed turnover rate of phytoplankton carbon is of the order of days (Burrell 1983b), the corresponding scale length appears to be between 1 and 10 kilometers. This is somewhat greater than, but comparable to, the scale for a Nova Scotia embayment that was determined by Theriault and Platt (1978).

Phytoplankton

Advection of phytoplankton over long distances within fjords (Braarud, Føyn, and Hasle 1958) and other estuaries (Tyler and Seliger 1978) has been reported. From detailed transport measurements taken at the sill region of Bedford Basin (Nova Scotia) over a 25-hour period, Platt and Conover (1971) determined that nearly 60% of one day's phytoplankton production was flushed into the adjacent coastal zone. Such direct determinations, even over such a short and possibly unrepresentative time period, are logistically very difficult. No equivalent work on potential export (or import) of phylogenous material has been attempted in any west coast fjord. However, knowledge of the periods and sites of enhanced primary production along the Gulf of Alaska coast both provides useful clues, and points to desirable future work.

In high latitude estuaries, a spring-summer diatom bloom keyed to an irradiation threshold (Stockner, Cliff, and Shortreed 1979; Hegseth 1982; and Erga and Heimdal 1984) is the most distinctive feature of phytoplankton growth. In southeastern Alaska, this event spans a few weeks (or less) between late March and early May (Fig. 7-16), and generally occurs progressively later in the year northward along the Alaskan fjord coastline. The peak bloom in Port Valdez in 1972 was in late April (Goering, Shiels, and Patton 1973) (Fig. 7-17) and in Resurrection Bay in 1974 in June (Heggie and Burrell 1977). For the localities illustrated in Figure 7-16, Burrell (1983b) computed that some 40% of the annual depth-integrated primary production (135 g C/m^2 in 1980) occurred over a 28-day period in March and April.

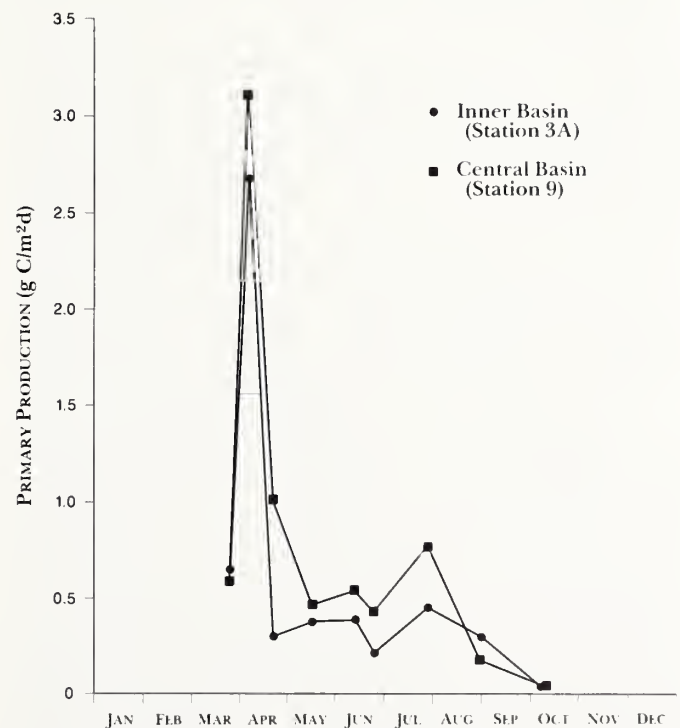


Figure 7-16. Depth-integrated ^{14}C uptake rates through the euphotic zone within Boca de Quadra fjord in 1982 (data from Burrell 1983b and VTN 1983).

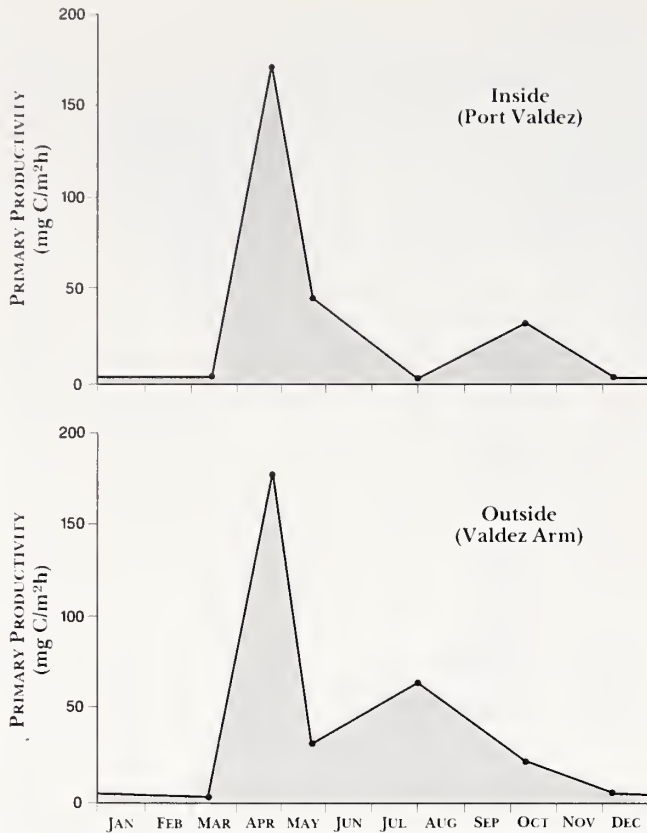


Figure 7-17. Annual depth-integrated ^{14}C uptake rates through the euphotic zone within Port Valdez fjord. Composite of data obtained in 1971–1972. (Modified from Goering, Shiels, and Patton 1973.)

In the absence of intense grazing and high turbidity, blooms may develop in those nutrient-rich waters that become stabilized to the point that turbulence does not persistently transport the cells below a critical depth. Because of increased freshwater discharge in the spring, this condition usually occurs earlier inside northern estuaries than it does in contiguous shelf regions. Blooms within fjords on the west coasts of Scotland and Norway commence several weeks earlier than they do on the adjacent shelves (Braarud 1974; Tett and Wallis 1978). Goering, Shiels, and Patton (1973) monitored seasonal carbon uptake both within Port Valdez and outside the sill in Valdez Arm, and found contemporaneous bloom periods (Fig. 7-17). However, in this case, a major portion of the freshwater influx occurs in the vicinity of the sill, and Muench and Nebert (1973) demonstrated that near-surface stratification at the time of the spring bloom did not differ significantly at these two localities. To date, there have been no synoptic ^{14}C uptake measurements taken both within and outside any other Alaskan fjord. Within glacial fjords in particular, it has been observed (*e.g.*, in Port Valdez: V. Alexander, University of Alaska, pers. comm., 1985) that a turbid fresh water influx occurring in spring may suppress or limit the intensity of the diatom blooms. In both shelf and coastal waters, contemporaneous grazing may prevent a bloom from developing even though increasing insolation tends to stabilize the surface zone.

From late spring into summer, freshwater influx into the fjords increases and the characteristic entrainment-driven circulation should generally assume greater importance. Increased or maintained phytoplankton population levels then require a suitable balance between turn-over rates and the residence time of the near-surface water within the fjord (Ketchum 1954). Computed phytoplankton carbon turn-over rates in upper Boca de Quadra and Smeaton Bay are around 1.0/d both at the time of the spring bloom and in early summer. Phytoplankton residence times are therefore probably much shorter than the mean residence time of the near-surface waters at the heads of these inlets. The flushing time of water within Port Valdez has been variously estimated at between 20 and 40 days (Muench and Nebert 1973; Colonell 1980). These values are predicated on complete mixing of the water column, and the residence time of the near-surface water is probably considerably smaller. If variable turbidity levels and other localized factors are ignored, conditions in Port Valdez should theoretically permit development of an autochthonous bloom which could extend throughout the inlet. Simultaneous sampling both inside Port Valdez and within the narrows region external to the sill (Goering, Shiels, and Patton 1973) showed that, although the bloom is near contemporaneous, the diatom species composition and dominance is different. This suggests that communion is not maintained both inside and outside the fjord proper, and may be due to increased turbulence in the vicinity of the sill.

In both Port Valdez (Horner, Dick, and Shiels 1973) and Boca de Quadra fjord (VTN 1983), it has been shown that, following the termination of the spring diatom bloom, there is a major change in the phytoplankton community structure. Smaller flagellate species assume dominance along with algae which generally have higher carbon uptake efficiencies, lower nutrient half-saturation constants, and a greater tolerance to reduced salinities. Phytoplankton production is characteristically nutrient limited in the post-bloom, summer-fall period in high-latitude, stratified estuaries. This certainly appears to be the case in Port Valdez and Boca de Quadra (the only Alaskan fjords that have been studied in detail to date) where, for example, ^{15}N -uptake experiments show that regenerated ammonia constitutes the primary source of nitrogen through the summer (Goering, Patton, and Shiels 1973; S. Whalen, University of Alaska, unpubl. data, 1984). Under these conditions, the enhancement of phytoplankton production (and potential export) requires the local injection of additional nutrients into the euphotic zone.

The two primary potential sources of 'new' nutrients (*sensu* Dugdale and Goering 1967) are the rivers, and the sub-euphotic marine waters. In most parts of the world, high nutrient concentrations are carried seaward by mature river systems that drain large watersheds—especially in areas that are subject to agricultural drainage and urban discharges. Parsons, Albright, and Parslow (1980) and Harrison, Fulton, Taylor, and Parsons (1983) estimate that up to 30% of the nitrogen utilized in the Strait of Georgia may be supplied by the Fraser River (with sewage contributing less than 10%). There are examples in this region (Parsons, Stephens, and LeBrasseur 1969), and in fjord provinces elsewhere

(Therriault, de Ladurantaye, and Ingram 1984), where productivity in coastal waters that are affected by the plumes of major rivers exceeds the productivity in adjacent fjords. Phytoplankton productivity in such cases is enhanced both because of the influx of riverine nutrients, and because of vertical entrainment of nutrient-rich marine waters from below. This may lead to imports of particulate organic material into the bordering fjords. As discussed previously, a number of large rivers inject water into the northward-flowing Alaska Coastal Current System, and conditions similar to those described in southern British Columbia may occur locally.

In the southern-most part of Alaska it appears that, although brackish water from the large rivers of northern British Columbia is transported into the coastal waterways in the spring, there may be only slight penetration into the fjords (only two have been studied in detail). However, over a four-year period, the dominant diatom species of the spring blooms changed from year to year, but was the same in any one year in two adjacent fjords. This may argue for external seeding.

In south central Alaska, where fjords open directly onto the Gulf shelf, there is a slight indication that an up-fjord drift of near-surface water occurs in the summer. It has been suggested (Heggie 1983), for example, that Copper River water impacts the mixed zone of Resurrection Bay at this time of year. Nutrients supplied by bay-head rivers are frequently cited as the primary cause of elevated phytoplankton production, or of secondary blooms, during the summer in Norwegian fjords (Sakshaug and Mykkestad 1973). This is especially true in polls (Wassmann and Aadnesen 1984). However, this appears not to be the case for the majority of fjords along the Gulf of Alaska coast. Naiman and Sibert (1978) have noted that heavy precipitation along the west coast of Canada has resulted in highly leached soils and a low nutrient content in the rivers. It is generally believed that the nutrient levels of the freshwater that is discharged into Alaskan fjords are significantly lower than levels in the non-depleted marine water. This is certainly the case both for precipitation that is initially stored as snow and for non-glacial rivers where the residence time of rainfall in the relatively small catchment areas is very short (Sugai and Burrell 1984). The chemistry of glacial meltwater in Alaska has not been systematically studied, but Goering, Patton, and Shiels (1973) stated that freshwater discharge into Port Valdez is rich in both silicic acid and nitrate. Other examples may also be cited where riverine influx of nutrients is locally important. For example, Brickell and Goering (1970) and Sugai and Burrell (1984) have demonstrated enhanced production in southeast Alaskan fjords at the time when decaying salmon resulted in higher ammonia concentrations in the rivers. However, because the freshwater influx into fjords in summer is relatively insignificant when compared with the tidal exchange, it is believed that, in general, riverine nutrients are a very minor contribution to phytoplankton growth in this fjord province.

Sub-surface marine water is the primary reservoir of the 'new' nutrients necessary to enhance phytoplankton production. River-plume entrainment is one method of injecting this water into the euphotic zone. Other mechanisms

that may be operating within fjords include wind mixing, estuarine circulation, and periodic destabilization of the surface waters by higher-than-average tides (Webb and D'Elia 1980). Short-term (order of days) fluctuations in productivity levels recorded in several fjords (Winter *et al.* 1975; Takahashi, Seibert, and Thomas 1977) may be attributable to such sporadic mixing of the near-surface zone. Under such conditions, a net export of autochthonous biogenic material from the fjord into the coastal zone might be expected.

Primary production may be enhanced in coastal frontal zones (Pingree, Holligan, and Mardell 1978; Parsons, Stronach, Borstad, Louttit, and Perry 1981). These zones are typically shallow regions of increased flow where vertical turbulence promotes upward transport of nutrients into the depleted surface zone. Parsons, Perry, Nutbrown, Hsieh, and Lalli (1983) and Parsons, Dovey, Cochlan, Perry, and Crean (1984) have demonstrated that sustained increases in phytoplankton production may occur in shoal areas adjacent to the mouths of certain fjords in southern British Columbia. Because of the high tidal range, similar enhancements in the northern Gulf region would be expected at the mouths of shallow-silled fjords. There is some preliminary evidence for this inside the 15-m sill of Aialik Inlet (D.C. Burrell, University of Alaska, unpubl. data, 1984), but there have been no direct studies of this phenomenon in any Alaskan fjord.

Parsons (Ch. 18, this volume) suggests that for various reasons (including the summer-time upwelling activity described above) mean primary production along the Gulf of Alaska shelf break is higher than it is within the fjords. However, no unequivocal shallow coastal upwelling events—such as are responsible for episodically advecting coastal waters into the fjords of Nova Scotia (Therriault, Lawrence, and Platt 1978) and western Norway—have been recorded within the fjords along the Alaskan coastline in the summer. In western Norway, Braarud (1975), Kattner, Hammer, Eberlein, Brockmann, Jahnke, and Krause (1983), Erga and Heimdal (1984), and others have demonstrated that influxes of coastal water may terminate existing fjord blooms, transport in remnant shelf communities, or re-seed with species better adapted to the new physical environment. For example, Kattner *et al.* (1983) note that *Thalassiosira nordenskiöldii* is better adapted to cold water conditions. No comparable abrupt changes in phytoplankton species composition have been recorded to date in coastal fjords along the Gulf.

In late summer and fall, differences in mean levels of primary production both inside and outside the fjord may be further accentuated as river-generated turbidity progressively limits the euphotic zone up-fjord. This prevents or suppresses secondary blooms which commonly occur at this time of year. The phenomenon has been extensively documented for a mainland British Columbian fjord (Stockner, Cliff, and Buchanan 1977), and is a general characteristic of Alaskan glacial fjords. Thus, the absence of the secondary October bloom within Port Valdez, which is evident outside the sill entrance in Valdez Arm (Fig. 7-17), has been attributed to high glacial silt loading towards the head of the fjord (Goering, Shiels, and Patton 1973). In Boca de Quadra (a non-glacial fjord), Sugai and Burrell (1984) have shown

that the peak river discharge of riverine-soluble humic material may also locally attenuate the euphotic zone at this time of year.

In shallow water estuaries, unit-area primary production by the fringing macrophytic algae and vascular plant communities may be at least an order of magnitude greater than phytoplankton production (Mann 1982; Seki 1982). Since a large proportion of detritus from these sources is relatively refractory, seaward transport may be a significant source of energy to the shelf benthos. However, because of their rugged topography, fjords characteristically have very reduced littoral zones. Pickard and Stanton (1980) catalogued a wide range of Pacific coast fjords and determined the intertidal to subtidal area ratios to be in the range 1:13 to 1:40. The intertidal regions of Smeaton Bay fjord amount to only 2.1% of the marine surface area inside the entrance sill (Burrell 1983b). It is estimated that littoral primary production within the adjacent Boca de Quadra fjord cannot exceed, and is probably far less than, 15% of the marine phytoplankton production. Although floating wracks—especially of *Fucus*—are commonly observed within the latter fjord, export into the contiguous waterways is believed to be insignificant.

Zooplankton

Both the seasonal distribution and the community structure of herbivores are major factors controlling fjord ecology. At a relatively basic level, fjords can be considered in terms of the two generalized trophic pathways discussed by Greve and Parsons (1977) and by Landry (1977). These pathways lead from small phytoplankton and zooplankton to jellyfish and similar predators, and from net phytoplankton, primarily diatoms, to the larger copepods and finfish. The frequently cited review by Matthews and Heimdal (1980) related these two patterns to poll- and fjord-estuaries, respectively—polls being both shallower and shallower-silled types of fjords. Wassmann (1983) noted that the basin depth within Lindåspollene in western Norway—perhaps the archetypical and most commonly referenced poll system—is too shallow to permit over-wintering of larger copepods. However, the most important feature of polls—stressed by Matthews and Heimdal (1980)—is that the shallow sill intercepts the pycnocline. Along the western Norwegian coast in particular, where tides are moderate and freshwater inflow is frequently high, this physical configuration acts as an effective barrier to recruitment of the larger calanoid copepod species from outside. Such characteristic differences in zooplankton ecology within two adjacent Norwegian fjords have been summarized by Fosshagen (1980). Factors other than the residence time of the water are usually important. In more open, turbulent fjords, primary production sustained by renewal of nutrients into the euphotic zone (and in some cases, advection of external phytoplankton stocks) are factors required to support populations of the large copepods. However, import of zooplankton into fjords from adjacent coastal regions appears to be a common—if not a characteristic—feature of regular fjords (Matthews, Hestad, and Bakke 1978; Falk-Petersen and Hopkins 1981). No comparable spatially and temporally

detailed studies of zooplankton community structure have been carried out in Alaskan fjords, although there have been a number of survey investigations.

The epipelagic zooplankton ecology of Boca de Quadra and Smeaton Bay (Southeast Alaska) over a three-year period has been summarized by VTN (1983), who have shown that summer holoplankton in the surface 25-m zone consists predominantly of small copepod species. For example, in Boca de Quadra in 1980, calanoid copepods such as *Pseudocalanus* and *Acartia* made up over 70% of the population, and in Smeaton Bay in 1981 *P. minutus*, *A. longiremis*, and *Paracalanus parvus* made up approximately 65% of the total. This mixture represents a classic poll-type community structure. Densities are relatively low in the spring and generally appear to increase through July and August. There is no firm evidence that the spring phytoplankton bloom in these fjords, which appears, based on phaeopigment distributions, to peak in late summer, is terminated by grazing. However, Burrell (1983b) has shown that the preliminary seasonal carbon-flux balance in the upper column only allows for a 10 to 15% sedimentation rate for phylogenous material falling out of the euphotic zone at the time of the spring bloom. This suggests that much more intensive grazing is possibly occurring below the euphotic zone. Figure 7-18 shows chlorophyll *a* and phaeopigment concentrations within Boca de Quadra in April 1983. At the time it was sampled (believed to be during the termination stage of the bloom) the phytoplankton biomass was essentially confined to the central and innermost basin regions, but phaeopigment to chlorophyll ratios were elevated in the near-surface water of the outermost basin. Such distributions suggest either that there is intensive grazing by the copepods that are advected into the outer reaches of the fjord where the intervening (~85 m) sill acts as a barrier to external recruitment, or that there is transportation of detritus into the fjord from the outside. The latter event has been documented for several fjords on the west coast of Scotland by Solórzano and Grantham (1975).

Damkaer (1976) recorded over-wintering populations of *Neocalanus* spp. within Prince William Sound, and it might be expected that larger copepod species would remain within the fjord systems—like Boca de Quadra—that incorporate deep basins. However, it is apparent that, since spring blooms are an annual feature of all Gulf coast fjords examined to date, phytoplankton production and grazing are uncoupled early in the season, and such fjords cannot be regarded as simple mesocosms of the adjacent shelf environment. A number of investigators (Parsons 1965; Frost, Landry, and Hassett 1983; see also recent review by Miller, Frost, Batchelder, Clemons, and Conway 1984) have shown that the plant-herbivore system within the Gulf of Alaska is in balance in the spring, and that the biomass increase at this time results from an increase of grazers, not of phytoplankton.

Populations of large oceanic copepods would be expected in the near-surface zone of many Alaskan fjords in spring (R.T. Cooney, University of Alaska, pers. comm., 1985) as a consequence of the prevailing patterns of on-shore transport of shelf waters as described in a previous section. The pattern may be envisaged with reference

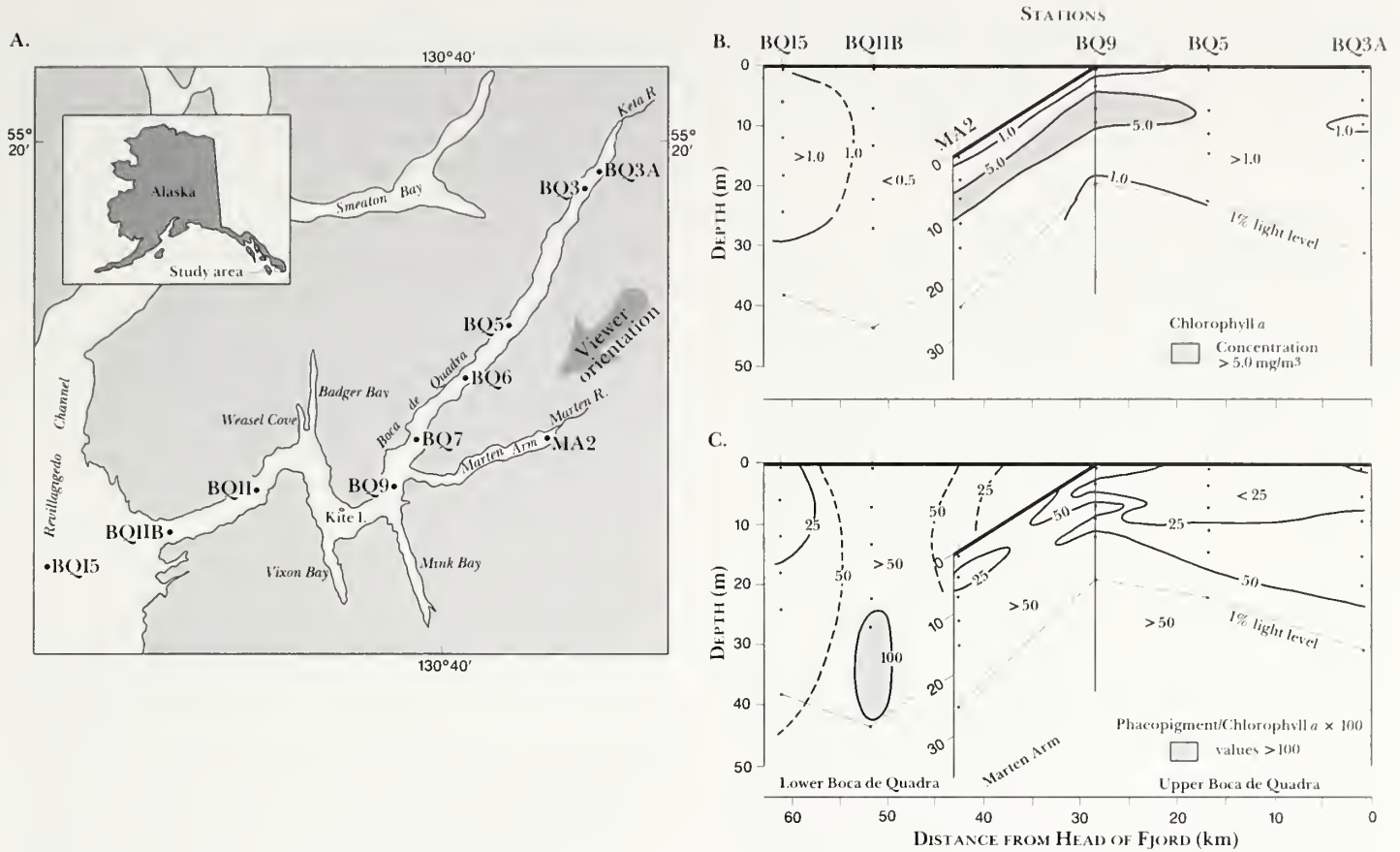


Figure 7-18. Longitudinal sections for surface to 50-m depth zone within Boca de Quadra fjord and subsidiary Marten Arm, April 1983. (A) Location map showing station positions. The primary sill is located at Kite Island (see Fig. 7-27 for longitudinal profile). (B) Isoleths of chlorophyll *a*. (C) Ratio of phaeopigment to chlorophyll *a* × 100.

to *Neocalanus plumchrus*, a large, ubiquitous copepod found along the fjord coast of Alaska and British Columbia. The life-cycle seasonal migrations of this organism (Fulton 1973) are shown in Figure 7-19. Adults over-winter in deep water (and hence resident populations should exist in a number of the deep fjord basins along the Gulf coast), but later migrate and feed as late copepodite stages near the surface around the time of maximum plant production. This ontogenetic sequence and the coupling with the vernal diatom bloom has been best documented for the Strait of Georgia (Parsons, LeBrasseur, Fulton, and Kennedy 1969; Parsons, LeBrasseur, and Barraclough 1970; and Harrison *et al.* 1983). The migration of *N. plumchrus* and allied oceanic species into the upper regions of the shelf column occurs at the time of coastal convergence. This migration provides a means of recruitment into contiguous fjord environments. Krause and Lewis (1979) described in detail the seasonal advection of *Eucalanus bungii* into Knight Inlet, British Columbia. Cooney (University of Alaska, unpubl. data, 1984) has shown that large copepods are advected from the Gulf shelf into Prince William Sound, and *N. plumchrus* is present in Port Valdez in the spring (Cooney, Redburn, and Shiels 1973). However, detailed work on the potential coupling between the Gulf and specific Alaskan fjords has not yet been attempted. It might be expected that the greatest potential impact would be in those shallow-silled fjords where basin

water exchange occurs predominantly in late winter and spring. However, as noted previously, from the limited observations available, it appears that the penetration of near-surface water into southeast Alaska fjords is much weaker in late winter than in early winter. Waters outside these fjords at this time of year are derived primarily from Inside Passage regions farther to the south in British Colum-

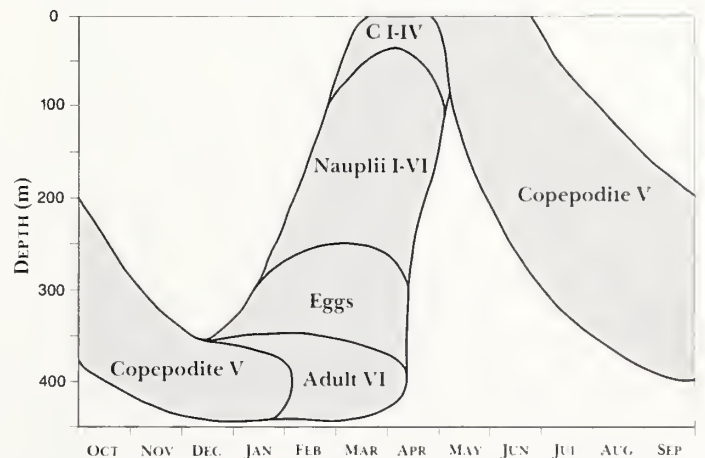


Figure 7-19. Schematic of life cycle of *Neocalanus plumchrus* in the Strait of Georgia: depth zones of nauplii, copepodites, and adults through the year. (Modified from Fulton 1973.)

bia, rather than being derived directly from the Gulf. Such observations may partially explain why large oceanic zooplankters such as *N. plumchrus* have not been observed in the euphotic zone up-fjord within either Boca de Quadra or Smeaton Bay at the time of the spring bloom.

Meroplankton

Time-series abundances of macro-infauna at two deep (~160 and 385 m) fjord basin stations in southeast Alaska are illustrated in Figure 7-20. There is an annual cycle of spring/summer recruitment followed by winter die-back, as well as a multi-year density fluctuation. Although pelagic larval development generally decreases in importance at high latitudes, this is the primary means of reproduction employed by invertebrates along the Gulf coast (H.M. Feder, University of Alaska, pers. comm., 1984). Pearson (1980) has noted that factors controlling the recruitment to fjord benthic communities are not well understood, but he believes that curtailment of free exchange between silled fjords and the adjacent coastal waters must be important. Both Pearson (1971) and Gage (1972a) suggest that the observed blurring of classic benthic community boundaries in fjords may be the result of larval confinement within the basins. However, Gage (1972b) has also concluded that there is a reduced benthic infaunal diversity in the shallow-silled Loch Etive when compared with neighboring fjords because of the physical barrier to larval import. Carpenter (1983) suggests that pandalid shrimp—either as larvae or adults—are transported into Aialik Inlet (northern Gulf) on flood tides and are then trapped behind the shallow (~15 m) sill.

Migrations of invertebrate larvae depend both on water circulation patterns and on the the distribution of the adults

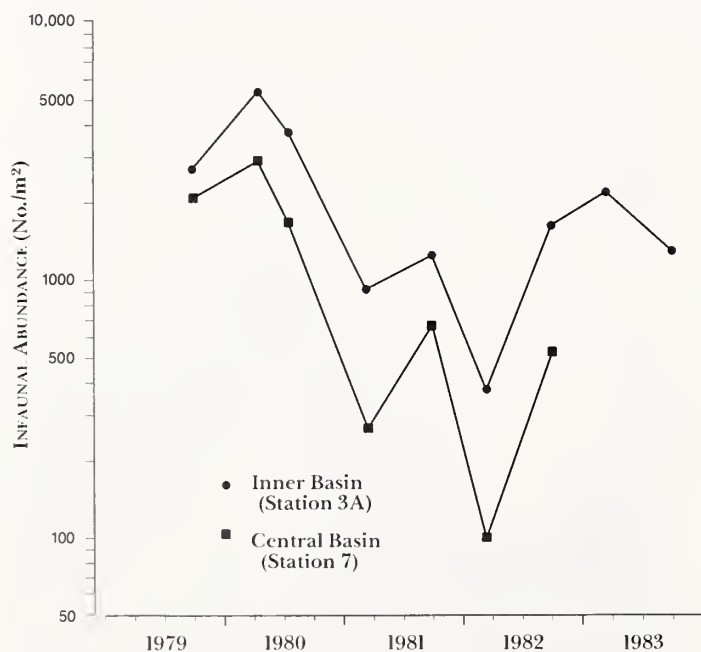


Figure 7-20. Seasonal densities of macro-infauna (>1 mm) at two basin localities (270 m depth in central basin, and 140 m in inner basin) within Boca de Quadra fjord, 1979 to 1983 (data from VTN 1983). (Fig. 7-27 shows longitudinal profile.)

(Harding, Vass, and Drinkwater 1982). Unfortunately, the dispersion dynamics for most larval groups are less well known in west coast fjord environments (Levings, Foreman, and Tunncliffe 1983) compared with many better-studied temperate estuaries (Kennedy 1982). It has been generally supposed that there is a wide broadcasting of larvae in the coastal zone, and Scheltema (1975) stated that most larvae produced within well-flushed estuaries are unlikely to be retained to maturity. In recent years however, in-estuarine larval retention has been increasingly emphasized (Sulkin and Van Henkelen 1982). Strathmann (1982) noted that dispersion is especially unlikely to be a favorable survival strategy in those estuaries that have strong physical and chemical gradients. However, in general, these strictures should be less applicable to fjords than to most other types of estuaries.

Chemical Interactions

Background

Attempts have been made to determine the oxygen and nutrient budgets (incorporating import-export terms) for a number of temperate estuaries. These estuaries have been both mixed and partially mixed, and determinations were made by applying relatively simple one- and two-layer box models (e.g., Bowman 1977; Taft, Elliot, and Taylor 1978). This approach may not be easily applied to silled fjords *in toto* because the circulations above and below the sill barrier are generally poorly coupled. However, for using these procedures, the above-sill region of the fjords should be a very suitable environment for quantifying the reactions and the transport of chemical constituents—especially in summer when stratification is at its greatest (Hamilton, Gunn, and Cannon 1985). Based on mean oxygen distributions, Gilmar-tin (1964) estimated that about 25% of the phytoplankton production was lost from a British Columbian fjord. As emphasized previously, the stratified estuarine flow that has been studied in the Alaskan fjords was found to be poorly developed, and for those fjords, tidal mixing and exchange is correspondingly more important than in many other fjord provinces. Therefore, determining the import-export exchange at the sill boundaries is a difficult exercise, and no attempt has been made to model the above-sill distribution of a non-conservative constituent within any Gulf coast fjord. Seasonal oxygen and nutrient budgets within the basins are a more tractable problem, and this is the primary topic considered here. (It should be noted, therefore, that both the oxygen and the nutrient distribution patterns described in this section do not *directly* relate to the autochthonous primary production discussed previously.)

Nutrients

Surface and Intermediate Waters

Nutrients are renewed in the surface zone each winter when water column stability is at a minimum. During the summer, uptake by the phytoplankton results in nutrient minima in the well-stratified near-surface zone. Increased

primary production at this time necessitates the import of exogenous nutrient supplies. In some fjord regions, the rivers may be a primary source (Wassmann and Aadnesen 1984), leading to an export into the coastal zone. However, since it appears that the influx of freshwater nutrients into many (most?) fjords along the Gulf of Alaska coast is relatively insignificant, 'new' nutrients must be supplied from marine sources. Upward infusion from the sub-euphotic region may occur via the mechanisms outlined in the previous section. The flux rates for nutrients moving between the Alaskan fjords and the external coastal regions are unknown since no detailed synoptic observations have been attempted. As noted above, in two fjords located near the Alaska-British Columbia border, water found between the estuarine circulation zone and the sill (Fig. 7-9 illustrates mean conditions between 30 and 50 m in Boca de Quadra) may be more brackish outside than inside the estuary. The coastal transport of freshwater in this area results in characteristic seasonal nutrient patterns within this transitional depth zone. For example, Figure 7-9B shows that nitrate is at higher concentrations year-round within the inner region of Boca de Quadra than it is outside the mouth.

In fjord provinces elsewhere in the world, on-shore convergence during the summer may result in periodic wholesale changes in the integrated nutrient contents of the near-surface waters (with concomitant changes in the plankton community structure, as discussed above). This phenomenon has been well described for inlets along the Nova Scotia coast by Platt, Prakash, and Irwin (1972). Wassmann (1984) has demonstrated how an influx of shelf water into Fanafjord (west coast of Norway) at relatively shallow depths may effectively eliminate the reservoir of sub-euphotic nutrients at the time when euphotic zone concentrations are at their lowest. Similar abrupt changes have not been observed in Alaskan fjords during the major phytoplankton production season. However, an influx of low-salinity water into the intermediate zone of a southeast Alaskan fjord at the onset of coastal downwelling has been described (Fig. 7-10). This water, which has a long residence time at the head of the fjord, has lower nutrient concentrations than the resident, penetrated water. Figure 7-21 illustrates contemporaneous silicic acid profiles both outside and inside the estuary in November.

It has been frequently observed that primary production is stimulated in the vicinity of large river plumes (see phytoplankton section), and Skreslet (1981) suggests that entrained nutrients associated with freshwater discharge along the west coast of Norway are a major factor influencing biological productivity in the adjacent coastal waters. The integrated flux of fresh water that feeds the Alaska coastal current is very large, but any effect on the indigenous biota is presently unknown.

Deep Waters

Nutrient species are regenerated within the basin water column, and especially within the soft-bottom sediments. It is believed that the major supply of labile organic material to depth occurs during the summer and hence that the maximum rate of remineralization occurs in summer as well. In

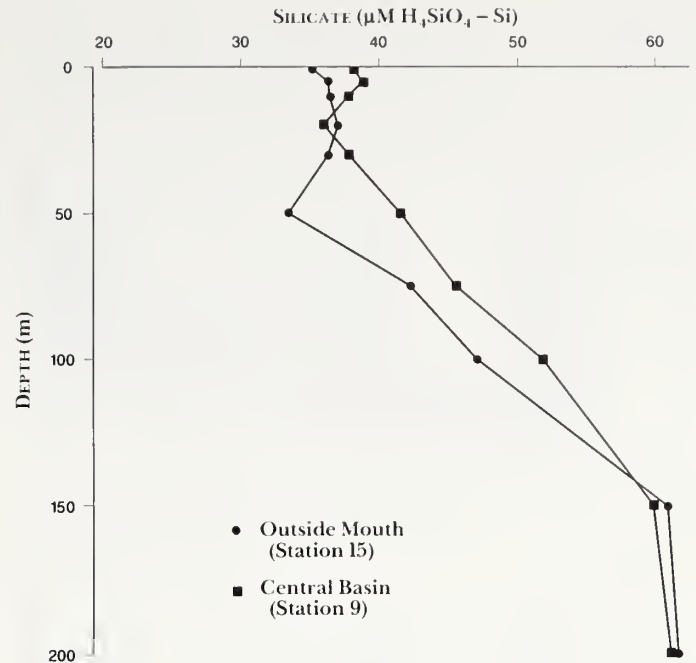


Figure 7-21. Vertical profiles of silicic acid concentrations within the upper water column outside the mouth and within the central basin of Boca de Quadra fjord, December 1980.

those Alaskan fjords where the sill is deeper than the zone of minimum annual density variation on the adjacent shelf, this is the season of deep-water renewal within the basins. No evidence of the benthic flux is retained within the basin column. However, during the oceanographic winter season when the relatively deep-silled basins along the Gulf coast tend to be advectively isolated, nutrient species effluxed from the sediments may accumulate if the regeneration supply exceeds the rate of upward loss out of the basin. Figure 7-22 illustrates elevated concentrations of nitrate and silicic acid in the bottom waters of the central basin of Boca de Quadra in April, prior to deep-water renewal.

From early spring through autumn (in deep-silled basins), a complex intermittent exchange sequence occurs. Shelf water of increasing density penetrates to deeper levels within the basin and flushes out the nutrient pool which has accumulated during the winter (Fig. 7-23). This expulsion of nutrient-rich water represents a subsidy to the exterior coastal regions at a time when phytoplankton production may be at a seasonal maximum. However, Føyn and Rey (1981) found a negligible impact on the primary production in coastal waters as nutrients were flushed from the fjords along the west coast of Norway.

Water that initially penetrates and flushes the basins has a relatively low nutrient content (Fig. 7-23). The resident basin water is displaced upwards into the intermediate zone at this time, and patches of displaced, high-nutrient water may persist up-fjord for extended periods. Macdonald (1983) has identified such uplifted remnants within the Kitimat fjord system of northern British Columbia, and an example from the head of Boca de Quadra is shown in Figure 7-24. Basin water that is injected into the long-residence-time, intermediate (above-sill) zone at the head of

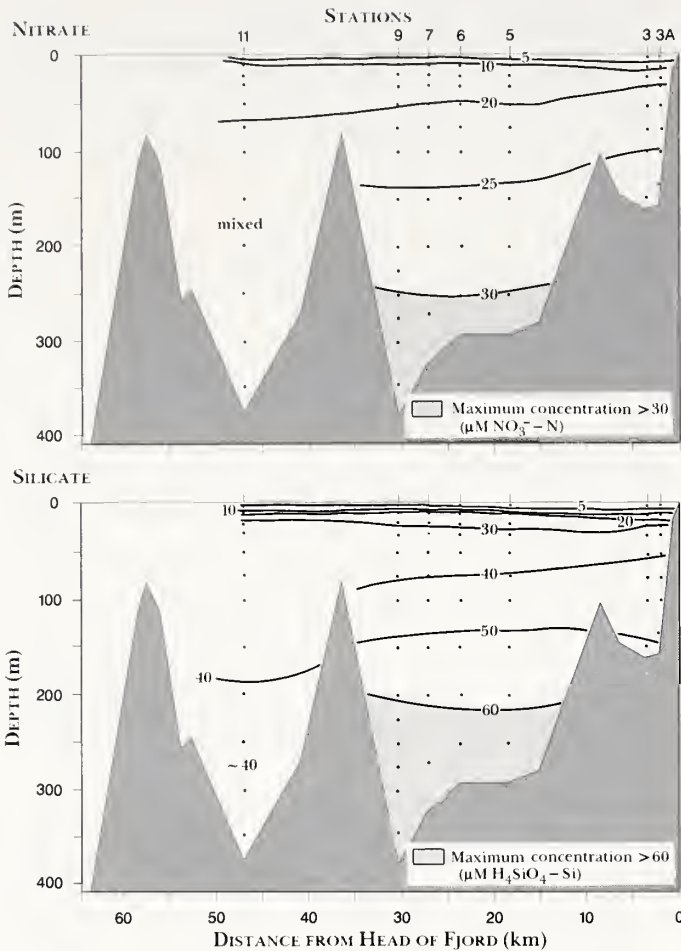


Figure 7-22. Longitudinal profiles of soluble nitrate and silicic acid concentrations within Boca de Quadra fjord, April 1980. Samples taken at localities and depths shown; shaded areas show regions of maximum concentrations.

the fjord, while brackish water dominates outside the fjord mouth, may be a primary explanation for the longitudinal nitrate gradient demonstrated in Figure 7-9B. Progressively throughout the summer, denser water masses with their higher nutrient concentrations are emplaced in the basins. By September and October (immediately prior to the winter isolation period), Boca de Quadra reaches its highest annual mean nutrient content within the basin. A similar pattern occurs in Resurrection Bay in the central Gulf (Fig. 7-25), and is likely to be a characteristic feature of deep-silled fjords all along this coast.

In Resurrection Bay, Boca de Quadra, and other deep-silled Alaskan fjords, nutrients regenerated at and within the sediments accumulate within the basins throughout the winter and are then flushed from the fjord during the summer. However, elevated concentrations may be restored during the latter part of the deep water renewal sequence in late summer and fall. Although there are no detailed mass-balance computations, it is estimated that in Boca de Quadra in 1981, the autochthonous production of silicic acid, and its import into the basin from outside, were nearly balanced. Both the annual benthic flux (which is periodically flushed either directly out of the basins or up into

the intermediate zone), and the net advective import between mid-September and mid-October (at the end of the summer renewal period) are estimated to be in the range of 20- to 25 $\times 10^6$ moles.

Within this same fjord, it is interesting to compare the preliminary transport-rate estimates for remineralized nutrients across the soft-bottom basin interface with the phytoplankton requirements in the overlying near-surface zone (Burrell 1983b). The rate of carbon degradation within the deep central basin region appears to be around 10% of the mean annual primary uptake value (Burrell 1983a). From a knowledge of the diatom fraction present through the primary summer production period, phytoplankton silicon requirements are estimated to be $\sim 1.5 \text{ M/m}^2\text{y}$, and, via a number of independent procedures (Burrell 1983b; Hong and Burrell, University of Alaska, unpubl. data, 1985), the benthic flux is estimated to be in the range of 9 to 36% of the euphotic uptake. Both computations are sensitive to the ratio between the fjord surface area and the soft-bottom substrate surface area—a ratio that can only be approximated.

These data suggest that any phytoplankton production that is over and above the production that is stimulated by nutrients regenerated *in situ* is not primarily or directly

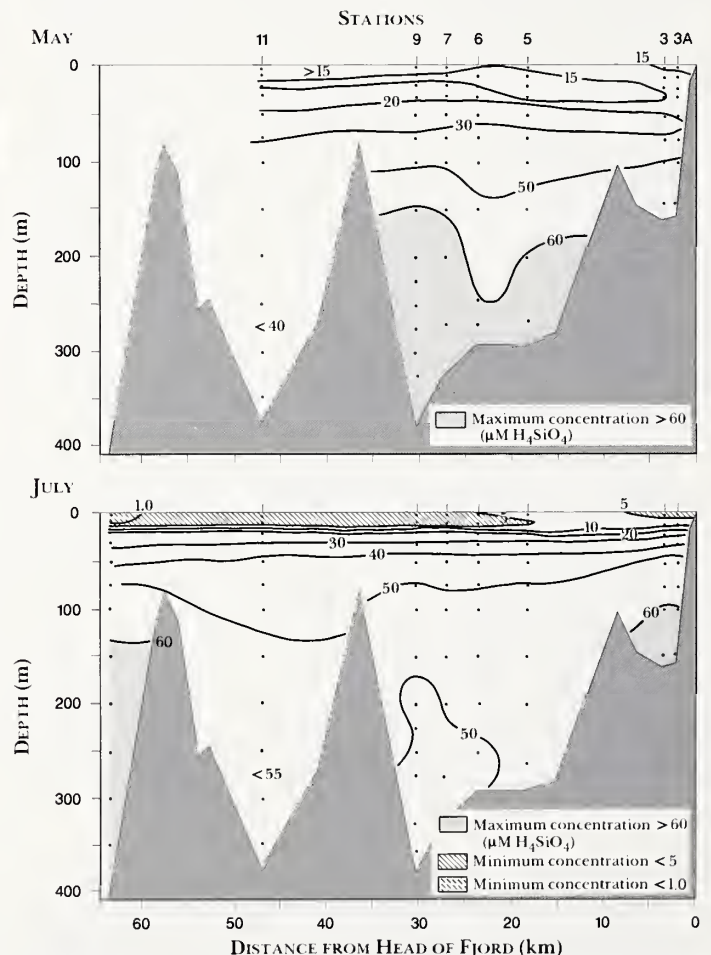


Figure 7-23. Longitudinal profiles of silicic acid concentrations in Boca de Quadra fjord, May and July 1980. Shaded areas show regions of maximum and minimum concentrations.

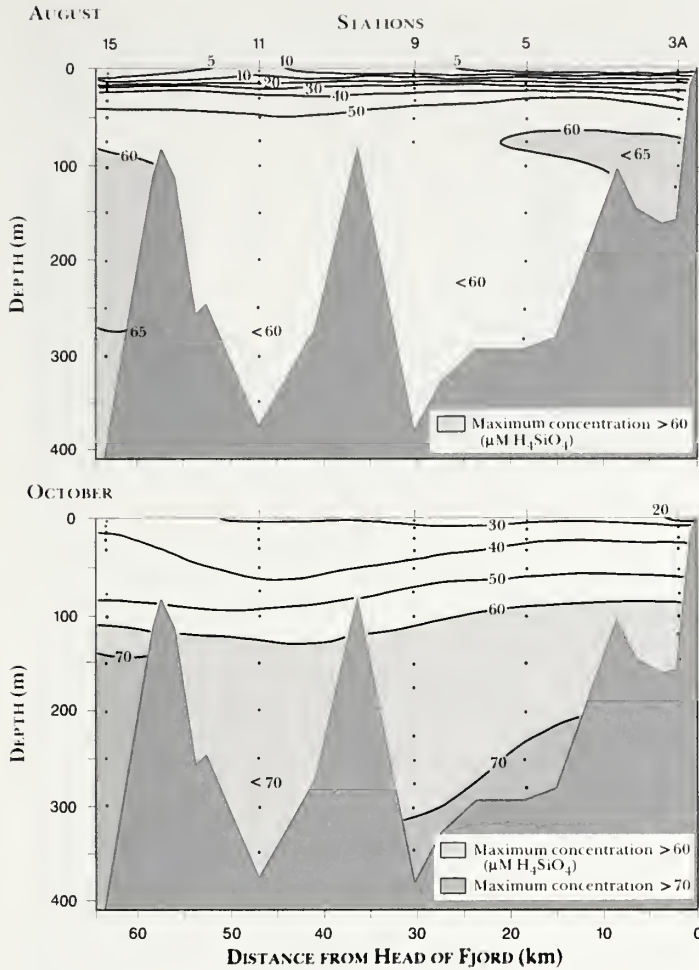


Figure 7-24. Longitudinal profiles of silicic acid concentrations, in Boca de Quadra fjord, August and October 1981. Shaded areas show regions of maximum concentrations.

fueled by the nutrients that are derived from the immediately underlying basin sediments. Throughout the summer growth season, the near-surface zone is well stratified. This means that nutrient resupply will most likely be from external sources both via estuarine circulation and via various localized shallow mixing processes. One potential method for estimating the nutrient subsidy required from outside the fjord is to measure the net downward sedimentation of phytoenous detritus out of the euphotic zone. This method is currently being attempted in Boca de Quadra using sediment-trap measurements.

Dissolved Oxygen

Theoxic-anoxic character of basin waters is controlled to a large extent by the transport patterns of dissolved oxygen progressing from shelf regions into the fjords. The fjord basins examined to date along the northern and central Gulf coast (except in the case of the deep basin of Boca de Quadra in 1983) have been flushed at least annually, and sub-sill waters within Alaskan fjords have not been observed to go anoxic at any time. It would appear, therefore, that in these higher latitude estuaries, the labile organic detritus supply and degradation rates rarely out-

strip the oxygen resupply rate during the period. Saanich Inlet, on the southeast coast of Vancouver Island, is a commonly cited seasonally anoxic fjord (Anderson and Devol 1973) which is also flushed annually. However, dissolved oxygen within the fjord basin is naturally depleted within a few months. There is also some input of anthropogenic carbon into this fjord.

Burrell (1983b) has estimated a mean winter time oxygen use rate of 68 μM/l/y within the deep central basin of Boca de Quadra. This estimate is based on net rates of decrease and computed resupply rates from the above-sill 'reservoir' over the same time intervals. Benthic oxygen-consumption rates were determined from incubated core samples that were retrieved from the deepest region of the same basin. The rates were some three times greater in the summer than in the winter (433 and 156 μM/m²h, respectively) (G. Hong, University of Alaska, unpubl. data, 1984). This indicates that the mean annual basin consumption rate is about double the winter value. Even so, this is a much smaller utilization rate than the values given by Barnes and Collias (1958) and by Christensen and Packard (1976) for areas within the temperate zone system of Puget Sound (195 and 238 μM/l/y, respectively). It should be noted that the latter authors believed that less than 10% of their observed oxygen increase was attributable to vertical diffusional resupply, whereas in Boca de Quadra it appears that about half of the oxygen consumed in the basin and sediments is contemporaneously transported in across the free basin boundary. Heggie and Burrell (1981), using an advection-diffusion model structured for fjord basin conditions, have computed year-round (*i.e.*, for both the winter advectively isolated and summer flushing periods) oxygen utilization rates of 170 μM/l/y within the basin of Resurrection Bay on the north central Gulf coast.

Seasonal dissolved oxygen concentration patterns in the fjord basins are, predictably, approximately the reverse of the nutrient distributions discussed above. During the

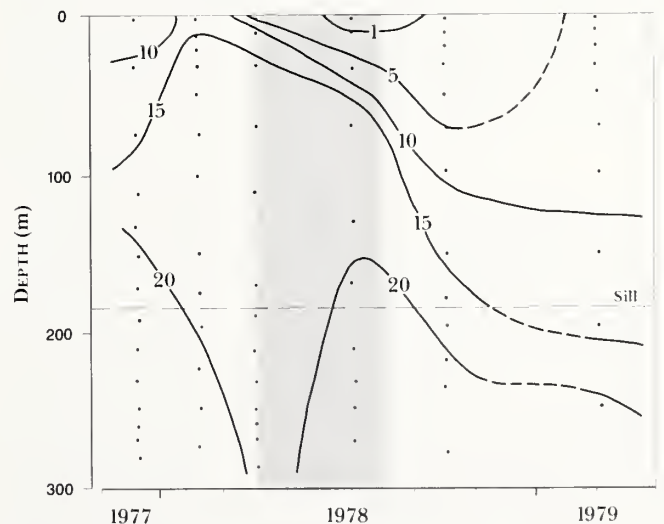


Figure 7-25. Time-series vertical distribution of nitrate (μM NO₃⁻ - N) within Resurrection Bay, November 1977 to March 1979. The shaded zone marks period of complete flushing of the basin.

winter in deep-silled basins, dissolved oxygen levels decrease as consumption exceeds replacement. (Consumption rates are believed to be generally at a minimum at this time of year, however.) The initial spring-summer flushing event emplaces water having a relatively high dissolved oxygen content and having relatively low nutrient concentrations. However, denser replacement waters that enter at the end of the summer flushing period typically have reduced oxygen concentrations and an elevated nutrient content. This pattern generally reflects the depth at which the source water originated as the density of the intrusions increases. This is well illustrated by the summer time sequence observed in Boca de Quadra in 1980 (Fig. 7-26). Helle (1978) has noted that upwelled water along the Norwegian fjord coast has a relatively low dissolved oxygen content because the source water is originally shelf water which has been advected into the coastal trough. However, replacement water entering Alaskan deep-silled fjords in late summer and fall is believed to be relatively deep water from the Gulf. Freeland (1983) recorded upwelling of low oxygen-concentration water along the west coast of Vancouver Island. In a fashion that is analogous to that described for soluble nutrient species, intrusions of denser water sinking to depth within the basins displace resident low-oxygen water towards the surface. This transport occurs on a time scale of days to weeks and may severely impact the sessile benthic fauna, as has been demonstrated in Saanich Inlet by Tunnicliffe (1981). Figure 7-27 illustrates both the uplift and the isolation of remnants of winter water at the head of Boca de Quadra fjord in July.

Water within the basins is replaced by progressively denser water throughout the summer. However, both the oxygen and the nutrient content of the source water varies non-linearly throughout the summer, and hence these parameters may serve as useful, quasi-conservative tracers of successive infusions. The computed conservative 'NO' index has been used to map advective intrusions into Russell Fjord (Yakutat) (Reeburgh *et al.* 1976; Reeburgh and Kip-

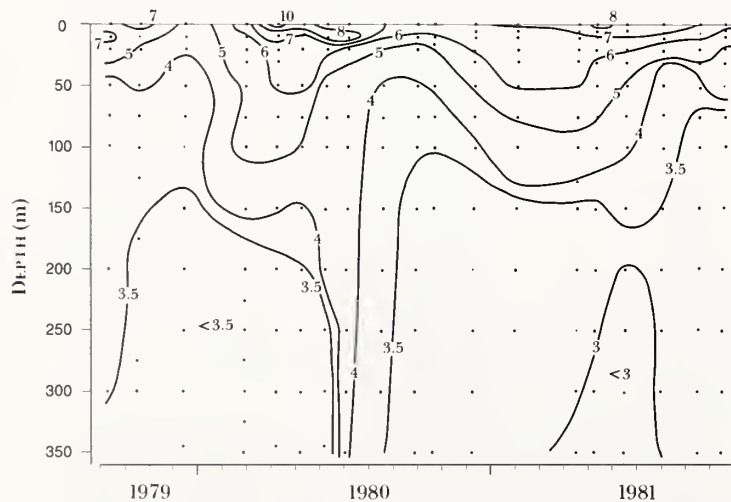


Figure 7-26. Time-series vertical distribution of dissolved oxygen (ml/l) within the central basin (Station 9) of Boca de Quadra fjord, September 1979 to October 1981 (see Fig. 7-27 for location).

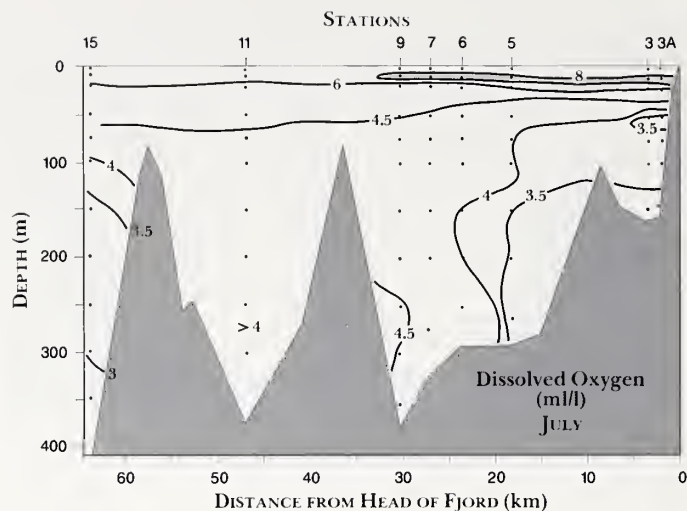


Figure 7-27. Longitudinal profile of dissolved oxygen concentrations (ml/l) within Boca de Quadra fjord, July 1980. Shaded area shows region of maximum concentrations (> 8 ml/l, $357 \mu\text{M/l}$).

phut, Ch. 4, this volume). However, since deep water replacement is generally independent of the mixed-layer circulation, in the few other Gulf coast fjords studied in any detail, individual nutrient and oxygen tracers appear to function equally well.

Time-series dissolved oxygen concentrations at the bottom (~ 365 m) of the central Boca de Quadra basin are shown in Figure 7-28. It is apparent that over this three-year observation period there has been a progressive decline in the mean oxygen content of the bottom water in each successive winter. Assuming a nearly constant mean annual flux of labile carbon, this pattern probably reflects changes in the shelf source waters that enter the fjord in the summer. This parallels the multi-year decrease in density referred to previously.

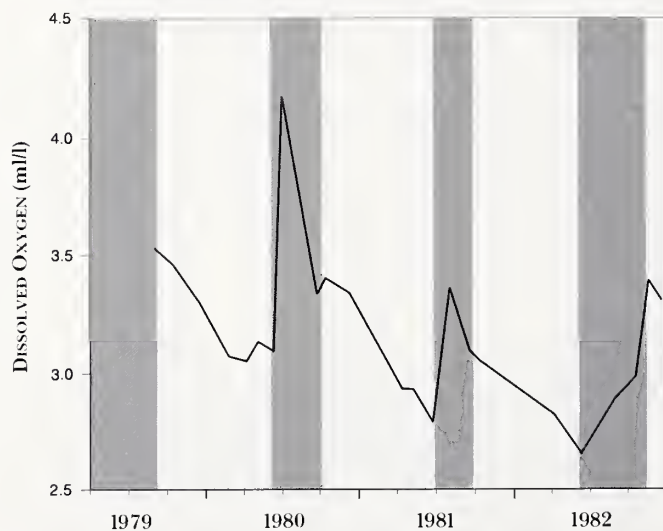


Figure 7-28. Time-series dissolved oxygen concentrations near the bottom (350 m) of the central basin of Boca de Quadra fjord, September 1979 to December 1982. The shaded zones mark periods of complete flushing of the basin.

Dissolved Organic Carbon and Heavy Metals

Sugai and Burrell (1984) give a mean figure of 10.6 g C/m²y (carbon per unit area of watershed) as the amount of dissolved organic carbon (DOC) that is exported into Smeaton Bay, a fjord adjacent to the British Columbia boundary in Southeast Alaska. While this value is high when compared with values from temperate zone rivers (Schlesinger and Melack 1981), it is comparable to values recorded for the Nanaimo River of southeast Vancouver Island (Naiman and Sibert 1978). Comparatively high discharge rates of terrestrial DOC may therefore be characteristic of Gulf coast fjords. The mean annual concentration of DOC found in major rivers that feed into Smeaton Bay is about twenty times greater than the particulate organic carbon (POC) concentration. The DOC concentration reaches a peak both in late spring to early summer and in the fall. Since these are periods of maximum freshwater discharge, the major DOC input flux (80% of the annual total of $\sim 4.5 \times 10^8$ moles) also occurs at these times.

The highly polymerized humic compounds of dissolved organic material (DOM) that are found in the rivers flocculate upon mixing with seawater (Sholkovitz 1978; Morris, Mantoura, Bate, and Howland 1978), so this fraction is generally believed to constitute a relatively small proportion of the total freshwater humate pool (Hunter 1983). Mantoura and Woodward (1983) have shown that the bulk of the DOM discharged by the rivers consists of the more soluble fulvic acids which are not immediately sedimented under estuarine conditions. This means that during the summer, terrigenous DOC may be exported into coastal regions of the Gulf.

Significant quantities of certain soluble heavy metal species may also be exported seaward out of the fjords. The stability of humic-metal compounds generally appears to parallel the Irving-Williams series (Schnitzer and Khan 1972). Copper and iron, in particular, are believed to form high-stability soluble complexes in natural waters. Abundant evidence shows that both these elements may be substantially complexed by humic material in anoxic sediment pore waters (Krom and Sholkovitz 1978; Mantoura, Dickson, and Riley 1978), and Lieberman (1979) believes that 20 to 50% of the soluble copper in Lake Nitinat, a permanently anoxic fjord on the Pacific coast of Vancouver Island, is organically complexed. While much less is known about organo-metallic bonding in aerobic marine environments, this may be the primary explanation for the conservative behavior of the copper that was observed (Holliday and Liss 1976; Hunter 1983) in estuaries that received high influxes of humic material. A conservative distribution of copper through the fresh-marine mixing zone of Boca de Quadra is illustrated in Figure 7-29 (data from Erikson and Stukas 1983). Similarly, Sugai and Burrell (1984) showed that acid-soluble iron decreases only slightly with increasing salinity in the adjacent Smeaton Bay fjord, in contrast to the substantial removal of acid-soluble iron that was recorded both in more temperate estuaries (Boyle, Edmond, and Sholkovitz 1977; Sholkovitz, Boyle, and Price 1978), and in laboratory mixing experiments (Bale and Morris 1981). In Smeaton Bay (and presumably also in other Gulf of Alaska fjords) there appears to be a mechanism that allows soluble

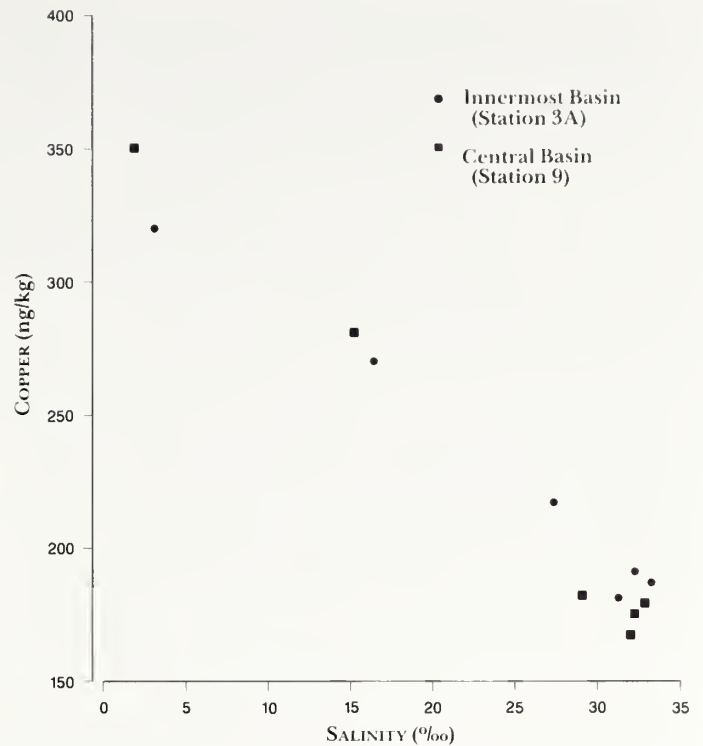


Figure 7-29. Soluble ($<0.4 \mu\text{M}$) copper concentrations versus salinity in the central and innermost basins of Boca de Quadra fjord, in September 1983 (data from Erickson and Stukas 1983).

iron to be maintained and transported in marine water, and hence possibly out into contiguous shelf areas.

From mass balance computations applied to Resurrection Bay, Heggie (1983) suggests that copper may be transported in from exterior coastal regions. Because of the large volume of freshwater that is discharged into the Alaska Coastal Current System, it has been noted that the near-surface transport of brackish water into the fringing fjords may be a common occurrence at certain times of the year. The imported copper found in Resurrection Bay could, therefore, originate from suitable freshwater sources such as the Copper River further south along the Gulf coast.

Geological Interactions

Input of terrigenous sediment into the Gulf coast fjords occurs primarily throughout the summer. Since a river's ability to transport particulate material is an exponential function of its flow rate, the sediment-mass flux is the highest during enhanced-volume discharge. This occurs during the spring-summer thaw, and especially in late summer-fall, which is the period of maximum direct precipitation. Over 90% of the sediment deposited by the Keta River into upper Boca de Quadra fjord is carried in during a few weeks in September-October. This happens primarily during major storms, since the residence time of rainfall in the catchment area is very short. VTN (1984) showed that both suspended load and precipitation maxima, some 3 to 4 km upstream from the mouth of the river, coincide without notable hysteresis.

Fjords are generally well stratified throughout the summer. Particulate sediment that is added at the surface of well-stratified estuaries tends to be transported shelfward along with the brackish surface layer. It may be generalized that less sediment is deposited within this kind of estuary than in more thoroughly mixed estuaries. Turbid sediment plumes that extend long distances seaward are characteristic features of many glacial fjords (Burrell 1972). How much of this material is carried beyond the confines of the fjord to the open shelf regions depends largely upon the supply rate, upon local hydrographic conditions, and upon the physiography of the inlet. In this respect it is instructive to compare conditions within Alaskan fjords with more thoroughly documented examples from along the mainland coast of British Columbia. For example, mean freshwater discharge from the Homathko River into the head of Bute Inlet is around $250 \text{ m}^3/\text{s}$, and the mean annual influx of particulate sediment may approach 10^7 mt (Syvitski and Farrow 1983). In this fjord, Syvitski, Asprey, Clattenburg, and Hodge (1985) have described the behavior of the largely inorganic particulate sediment within defined upper and lower prodelta environments. In this case, the upper prodelta environment is the river-dominated near-field. Seaward from this region, particulate sediment concentrations were found to be related to the distance from the riverine source by a constant empirical power function. (Sedimentation rates are a function of the square of the mean particle radius.) Finer particles are carried progressively further seaward and, in Bute Inlet, particulate sediment-load concentrations may exceed 1 mg/l some 50 km down-fjord from the head. In contrast, the mean freshwater influx into the head of Boca de Quadra fjord ($25 \text{ m}^3/\text{s}$; Fig. 7-5A) is around an order of magnitude less than the influx into Bute Inlet. Particulate loads in the surface zone do not generally exceed 1 mg/l except within a few kilometers of river outfalls in late summer (and locally at the time of the spring bloom).

As discussed previously, because of both the relatively low freshwater discharge into the heads of many Alaskan fjords and the strong tidal signal along the Gulf coast, stratified estuarine circulation flow patterns may not be well developed. In these cases, particulate sediment tends to be deposited closer to the source. Sills physically retain sediment within the fjord basins, which invariably are sites of net sediment accumulation. All fjord-estuaries are geologically recent features and, as a generalization, mean rates of sediment discharge are a function of their relative age. Sedimentation rates of the order of 0.01 cm/y have been recorded for mature European fjords (Aarseth, Bjerkli, Björklund, Bøe, Holm, Lorentzen-Styr, Myhre, Ugland, and Thiede 1975; Calvert and Price 1970). However, the Gulf coast province is very young, and in glacial inlets, annual depositions as high as 1 to 10 m have been measured (Hoskin and Burrell 1972; Mackiewicz, Powell, Carlson, and Molnia 1984). Sedimentation regimes within fjords along the British Columbia-Alaska coast—contrasted with fjord domains elsewhere in the world—have been discussed in detail by Syvitski *et al.* (in press) and will not be reiterated here.

It is possible that sediment—especially biogenic material—that originates from seaward of the fjord may be transported in and trapped within the basins of some fjords

(Syvitski *et al.*, in press). This could occur, for example, if more productive surface water was advected in over the sill, as has been described for the Saguenay Fjord, Quebec—a fjord that borders the relatively productive estuary of the St. Lawrence River (Therriault, de Ladurantaye, and Ingram 1980, 1984). Comparable examples have not been described for the Gulf of Alaska region, however.

Most shelf sediment has probably been transported by the relatively few major rivers which drain into the Gulf. This has been best documented to date for the northeast Gulf region as discussed by Hampton, Carson, Lee, and Feely (Ch. 5, this volume). Gatto (1976) has estimated that the mean sediment discharge from rivers entering Cook Inlet approaches $3 \times 10^7 \text{ mt/y}$, and most of this material is carried through the Inlet and deposited in the Shelikof Strait to the west of Kodiak Island (Feely and Massoth 1982). This region also receives large quantities of sediment from the Copper River. Hein, Bouma, Hampton, and Ross (1979) have shown that material derived from these two major river systems may be distinguished on the basis of characteristic suites of clay minerals.

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Section 3

Biological Resources

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ABSTRACT

Microbial population levels in the Gulf of Alaska appear comparable to those in other regions of the Pacific Ocean. However, these levels are lower in surface waters in the Gulf of Alaska than they are in the Bering and Beaufort Seas. There are regional differences in species distribution within the Gulf as well as differences in the dominant species as compared with other marine ecosystems; pseudomonads do not dominate. Bacterial communities in the Gulf are taxonomically and physiologically diverse. Bacteria capable of growth at low nutrient concentrations are particularly versatile with respect to their tolerance of variations in environmental parameters and their use of diverse substrates as sources of nutrition.

Pathogens have not been extensively studied; some microbial diseases of fish and shellfish have been reported, and some human pathogens are associated with crabs collected near areas of human habitation. The distribution of hydrocarbon utilizers correlates positively with areas of hydrocarbon accumulation. Exposure to hydrocarbons affects microbial activities, with potential long-term impacts on ecological productivity.

Detrital microorganisms are very important in food webs and contribute to overall productivity. Microbial populations, particularly important in carbon and nitrogen cycling in marine ecosystems, are similar to those reported for more temperate climates. The highest rates of microbial productivity in the Gulf occur in areas directly influenced by river inputs and the transport of fine-grained sediments. Bacterial activities are closely tied to phytoplankton production.

Distribution of Microbial Populations

Traditionally, the distribution of bacteria in marine ecosystems has been determined by enumeration using viable plate count procedures with high nutrient media (ZoBell 1946). Such enumeration procedures were thought to give the highest counts and, therefore, to be representative of the microbial biomass in a given sample. However, marine microbiological studies in the last few decades have shown that the viable plate count is selective (Jannasch and Jones 1959) and only accounts for a fraction of the total microbial biomass that is revealed by the acridine orange direct count

procedure or by a variety of biochemical methods (Atlas 1983). Thus, microbial ecologists now question the value of viable plate counts and rely more upon nonselective enumeration procedures such as the biochemical quantification of microbial constituents and direct microscopic observations.

These modern enumeration procedures, however, often leave unresolved questions, such as: 1) are the microorganisms enumerated by such procedures living or dead, 2) are the microorganisms active or dormant, and 3) are they representative of a particular species? Different investigators have used a variety of both traditional and modern enu-

meration methods in marine studies. This practice has severely limited the ability to make accurate comparisons between different regions of the oceans.

Nevertheless, we can make some generalizations about the distribution of microorganisms in marine ecosystems. For example, microbial numbers are relatively high in nearshore, upwelling, and estuarine waters, but fall off to between 1 and 100/ml in pelagic waters (ZoBell 1946; Wood 1965, 1967; and Atlas and Bartha 1981). Kriss (1963) estimated that seawater overlying continental shelf regions contains between 10^3 and 10^4 bacteria per milliliter. Relatively high numbers of microorganisms occur in the top few centimeters of most marine sediments (10^7 to 10^8 /g), but the numbers taper off in deeper sediment layers (Wood 1965, 1967; Atlas and Bartha 1981). In nearshore regions of the marine ecosystem there is a mixture of autochthonous (indigenous) and allochthonous (non-indigenous) microorganisms.

Most bacteria in marine ecosystems are Gram-negative and motile; often greater than 95% of the bacteria isolated from seawater samples are Gram-negative motile rods (Wood 1965, 1967). There is a relatively high proportion of proteolytic bacteria in marine habitats compared with water or soil habitats (Atlas and Bartha 1981). While *Pseudomonas* or *Vibrio* species are often found to be the dominant genera in marine environments (ZoBell 1946; Colwell and Liston 1961; and Wood 1965, 1967), *Flavobacterium* species are also found in relatively high numbers (ZoBell 1946; Colwell and Morita 1972). For example, in Chesapeake Bay, Lovelace, Tubiash, and Colwell (1967) found 56% *Vibrio* species, 18% *Pseudomonas* species, and 6% *Flavobacterium* species, along with *Spirillum*, *Achromobacter*, *Hyphymicrobium*, *Cytophaga*, *Microcylus*, and actinomycetes. Some Gram-positive bacteria such as *Bacillus* are normally found in marine sediments (ZoBell 1946; Wood 1967).

Enumeration of Microorganisms in the Gulf of Alaska

Bacterial populations in the Gulf of Alaska have been enumerated through a variety of procedures (Atlas 1982), including:

- using the direct count procedure with acridine orange staining (Daley and Hobbie 1975) for total counts
- using several media and incubation conditions for enumeration of viable bacteria (such as marine agar 2216 at 5C for viable counts of heterotrophic bacteria) (ZoBell 1946)
- using hydrocarbon-mineral salts media for determining numbers of hydrocarbon-degrading microorganisms (Atlas 1979).

Population levels in the Gulf of Alaska (Atlas 1977, 1982; Kaneko, Hauxhurst, Krichevsky, and Atlas 1978) appear to be comparable to other regions of the Pacific Ocean (ZoBell 1946; Wood 1967). Numbers of viable heterotrophic bacteria are lower in the Gulf of Alaska surface waters than in the Bering and Beaufort Seas; total direct bacteria counts, however, are not significantly different between these regions (Table 8-1) (Kaneko *et al.* 1978; Atlas 1982). This observation presents a paradox because the waters of more northern

seas are subject to more severe environmental conditions and thus it might be expected that they would have lower bacterial numbers. The suggestion has been made that the presence of sea ice in circumpolar seas enables certain bacteria to reach higher numbers or to survive longer than they would in more temperate waters (Atlas and Griffiths 1984). No such differences would be expected for sediments because they are subjected to relatively uniform environmental conditions. Indeed, both viable and total bacteria counts in Arctic and subarctic sediments are not significantly different (Table 8-1).

No significant seasonal differences in either viable or direct bacteria counts have been found in water and sediment samples from the Gulf of Alaska despite seasonal differences in surface water temperatures or microbial metabolic activity (Table 8-1) (Griffiths, Caldwell, and Morita 1982; Kaneko *et al.* 1978; Atlas 1982). Counts of hydrocarbon-degrading microorganisms show that these bacteria constitute only a small proportion of the total bacterial communities that occur in the water and sediment of the Gulf of Alaska (Roubal and Atlas 1978).

Total numbers of microorganisms are about an order of magnitude lower in the northern and central portions of lower Cook Inlet than elsewhere in the lower Cook Inlet region (Atlas, Venkatesan, Kaplan, Feely, Griffiths, and Morita 1983). In both lower Cook Inlet and Shelikof Strait, the range of total numbers of microorganisms is similar, generally with only one order of magnitude variation. Atlas *et al.* (1983) reported an association between the microbial population distribution and the sedimentation patterns for fine-grained particles in Cook Inlet and adjacent waters.

Taxonomy of Microbial Populations in the Gulf of Alaska

Investigators have performed taxonomic studies on Gulf of Alaska isolates that were randomly selected both from marine agar enumeration plates (copiotrophs) and from low-nutrient isolation media (oligotrophs) (Hauxhurst, Krichevsky, and Atlas 1980; Horowitz, Krichevsky, and Atlas 1983). The isolates have been extensively characterized using a large number of morphological, physiological, and nutritional tests; ~300 phenotypic characteristics were determined for each strain (Kaneko, Krichevsky, and Atlas 1979; Hauxhurst *et al.* 1980). The data have been analyzed using numerical taxonomic procedures that included cluster analyses (Sneath and Sokal 1973). Clusters of strains with similarities greater than 75% were designated as taxonomic groupings (Liston, Wiebe, and Colwell 1963). Hauxhurst *et al.* (1980) described the Gulf of Alaska's major taxonomic groups for both water and sediment samples (Table 8-2).

The distribution of bacterial species appears to be quite different between the northeast and the northwest Gulf of Alaska. Distribution differences also occur between these Gulf of Alaska regions and elsewhere in the Pacific Ocean, and in other Alaskan continental shelf regions (Hauxhurst *et al.* 1980). Many new 'species' or genera probably exist both within the Gulf of Alaska and within other northern marine ecosystems.

There appears to be a spatial discontinuity in the distribution of *Microcylus* species in Alaskan coastal waters.

Table 8-1.

Comparison of numbers of microorganisms found in Arctic and subarctic marine waters (numbers/ml) and sediments (numbers/g).

LOCATION	TIME	DIRECT COUNT	VIALE COUNT	HYDROCARBON UTILIZERS
SEDIMENT				
Beaufort Sea	Summer 1975	$6.2 \pm 1.1 \times 10^8$	$2.0 \pm 1.1 \times 10^6$	-
Beaufort Sea	Winter 1976	$3.7 \pm 1.0 \times 10^8$	$2.5 \pm 1.9 \times 10^5$	-
Beaufort Sea	Summer 1976	$2.1 \pm 0.9 \times 10^9$	$8.3 \pm 6.7 \times 10^6$	-
Beaufort Sea	Summer 1978	$1.6 \pm 0.8 \times 10^9$	$5.3 \pm 3.2 \times 10^6$	$2.5 \pm 2.2 \times 10^4$
Norton Sound	Summer 1979	$2.1 \pm 1.9 \times 10^8$	-	$9.2 \pm 9.6 \times 10^3$
North Bering Sea	Spring 1979	$1.7 \pm 1.4 \times 10^9$	-	$2.6 \pm 3.3 \times 10^3$
Mid-Bering Sea	Spring 1980	$2.3 \pm 1.4 \times 10^9$	-	$3.0 \pm 1.8 \times 10^2$
South Bering Sea	Summer 1980	$1.9 \pm 2.5 \times 10^9$	-	$3.0 \pm 1.0 \times 10^3$
South Bering Sea	Winter 1981	$3.0 \pm 2.3 \times 10^9$	-	$2.5 \pm 1.7 \times 10^3$
NW Gulf of Alaska	Fall 1975	-	$6.3 \pm 6.2 \times 10^5$	$8.9 \pm 3.1 \times 10^2$
NE Gulf of Alaska	Spring 1976	$3.0 \pm 1.6 \times 10^9$	$1.0 \pm 2.3 \times 10^6$	$3.6 \pm 3.5 \times 10^2$
Cook Inlet	Fall 1976	$1.5 \pm 1.9 \times 10^9$	$2.2 \pm 2.1 \times 10^6$	$2.9 \pm 7.1 \times 10^3$
Cook Inlet	Spring 1977	$7.7 \pm 3.8 \times 10^8$	$4.2 \pm 5.7 \times 10^6$	$6.7 \pm 9.1 \times 10^3$
Cook Inlet	Fall 1977	$5.9 \pm 2.2 \times 10^8$	$4.4 \pm 5.6 \times 10^6$	$8.4 \pm 8.3 \times 10^3$
Cook Inlet	Spring 1978	$4.9 \pm 1.5 \times 10^8$	$2.4 \pm 2.7 \times 10^6$	$5.6 \pm 4.9 \times 10^3$
Cook Inlet	Spring 1979	$2.6 \pm 1.6 \times 10^9$	$3.3 \pm 2.3 \times 10^6$	$6.3 \pm 5.8 \times 10^3$
WATER				
Beaufort Sea	Summer 1975	$8.2 \pm 7.2 \times 10^5$	$9.6 \pm 4.8 \times 10^3$	-
Beaufort Sea	Winter 1976	$1.8 \pm 1.3 \times 10^5$	$6.1 \pm 7.0 \times 10^2$	-
Beaufort Sea	Summer 1976	$5.2 \pm 3.9 \times 10^5$	$5.0 \pm 3.2 \times 10^4$	-
Beaufort Sea	Summer 1978	$6.7 \pm 4.9 \times 10^5$	$3.5 \pm 2.9 \times 10^4$	$2.6 \pm 1.3 \times 10^1$
Norton Sound	Summer 1979	$2.8 \pm 1.5 \times 10^5$	-	-
North Bering Sea	Spring 1979	$1.4 \pm 0.9 \times 10^5$	-	$1.1 \pm 1.2 \times 10^1$
Mid-Bering Sea	Spring 1980	$2.0 \pm 1.7 \times 10^5$	-	$1.1 \pm 5.7 \times 10^0$
South Bering Sea	Summer 1980	$2.6 \pm 1.5 \times 10^5$	-	$1.5 \pm 1.0 \times 10^0$
South Bering Sea	Winter 1981	$9.3 \pm 7.2 \times 10^5$	-	$2.2 \pm 6.2 \times 10^0$
NW Gulf of Alaska	Fall 1975	$3.0 \pm 1.0 \times 10^5$	$1.0 \pm 0.7 \times 10^2$	$1.8 \pm 4.7 \times 10^0$
NE Gulf of Alaska	Spring 1976	$1.4 \pm 0.9 \times 10^5$	$1.1 \pm 0.8 \times 10^2$	$1.3 \pm 1.7 \times 10^0$
Cook Inlet	Fall 1976	$3.2 \pm 2.9 \times 10^5$	$1.6 \pm 1.5 \times 10^2$	$6.4 \pm 1.5 \times 10^1$
Cook Inlet	Spring 1977	$2.5 \pm 0.9 \times 10^4$	$3.9 \pm 4.9 \times 10^2$	$3.7 \pm 1.5 \times 10^1$
Cook Inlet	Fall 1977	$5.8 \pm 2.4 \times 10^4$	$1.7 \pm 1.8 \times 10^2$	$3.7 \pm 4.5 \times 10^1$
Cook Inlet	Spring 1978	$8.1 \pm 3.1 \times 10^4$	$1.0 \pm 1.6 \times 10^2$	$4.8 \pm 5.4 \times 10^1$
Cook Inlet	Spring 1979	$4.2 \pm 2.2 \times 10^5$	$3.7 \pm 3.0 \times 10^2$	$2.6 \pm 3.4 \times 10^1$

Although common to the contiguous regions of the northwest Gulf of Alaska, Bering Sea, and Arctic Ocean, this genus is not common to the northeast Gulf of Alaska. *Microcyclops* species were identified near the Aleutian Islands (Hauxhurst *et al.* 1980) and have also been found in the Beaufort Sea (Kaneko *et al.* 1979) and the Bering Sea (Atlas 1982).

In the northeast Gulf of Alaska, *Moraxella* and *Acinetobacter* were the most frequently detected bacterial genera. However, the dominant *Moraxella* and *Acinetobacter* populations found in the northeast Gulf of Alaska were not found in samples from the northwest Gulf of Alaska (Hauxhurst *et al.* 1980). Although *Acinetobacter* and *Moraxella* strains are readily isolated from marine habitats, they had not been found as dominant marine bacterial populations (Wood 1967).

Vibrio and *Beneckea* are commonly found in marine ecosystems (Kaneko and Colwell 1973, 1974), and these genera were found in the Gulf as well as in the Beaufort Sea (Kaneko *et al.* 1979). The repeated failure to find dominant populations of *Pseudomonas* in the Gulf (Hauxhurst *et al.* 1980) is

not likely to be an artifact of isolation procedures because, using the same basic medium marine agar 2216, ZoBell and colleagues (ZoBell and Upham 1944; ZoBell 1946) isolated numerous *Pseudomonas* species in the Pacific between Hawaii and California. Simidu, Kaneko, and Taga (1977) also isolated *Pseudomonas* species from the Pacific Ocean.

Characteristics of Gulf of Alaska Bacterial Populations

Gram-negative rods were predominant in all the water samples collected in the Gulf of Alaska (Hauxhurst *et al.* 1980; Hauxhurst, Kaneko, and Atlas 1981; and Horowitz *et al.* 1983). Approximately one-half of the bacterial populations were pigmented (predominantly with yellow, orange, and brown pigments) although the incidence of pigmented bacteria in the northwest Gulf of Alaska was somewhat lower than in the northeast Gulf (Hauxhurst *et al.* 1980; 1981). The high incidence of pigmented bacteria is similar to that

Table 8-2.
Descriptions of taxonomic groups of bacteria isolated from the Gulf of Alaska.

NORTHEAST GULF OF ALASKA ISOLATES
1. Gram-negative, non-motile rods-coccobacilli often occurring as pairs. The morphological and metabolic features of the organisms closely resembled those of the <i>Acinetobacter-Moraxella</i> group.
2. Gram-negative, motile, oxidase-positive, fermentative, curved or straight rods. Members of these clusters resembled strains classified in the genera <i>Aeromonas</i> , <i>Beneckea</i> , and <i>Vibrio</i> .
3. Gram-negative, non-motile rods producing yellow, orange, or brown pigments. Bacteria with these characteristics are included in the genus <i>Flavobacterium</i> .
4. Gram-negative, non-motile, non-fermentative, oxidase-positive, catalase-negative rods which are not actively proteolytic in gelatin media. These strains resembled non-motile strains of <i>Alcaligenes</i> .
5. Gram-positive, motile rods producing pink colonies and spherical bodies in older cultures. The morphogenesis of these strains is representative of coryneform bacteria (e.g., <i>Arthrobacter</i>).
6. Gram-positive-Gram-variable, motile, large rods forming endospores and growing aerobically. The strains in this cluster clearly belong in the genus <i>Bacillus</i> .
7. In addition to the organisms that formed defined major clusters, several minor clusters showed characteristics of the genera <i>Flavobacterium</i> (Gram-negative, motile rods producing yellow pigments), <i>Pseudomonas</i> (Gram-negative, motile rods growing only oxidatively), and <i>Vibrio</i> (Gram-negative rods generally with a curved axis).
NORTHWEST GULF OF ALASKA ISOLATES
1. Gram-negative, oxidase-positive, non-pigmented, fermentative, motile rods. These organisms were similar to <i>Beneckea</i> species.
2. Gram-negative, oxidase-positive, non-pigmented, variably fermentative, motile, curved or straight rods. The characteristics of these organisms closely resembled those of <i>Vibrio</i> or <i>Beneckea</i> species.
3. Gram-negative, facultatively anaerobic, straight rods producing non-diffusible yellow pigments, presumably classified in the genus <i>Flavobacterium</i> .
4. Gram-negative, yellow-pigmented, non-motile rods forming partial rings. These organisms were morphologically similar to members of the genus <i>Micrococcus</i> .
5. Gram-negative, oxidase-positive rods producing violet pigments characteristic of the genus <i>Chromobacterium</i> .
6. Gram-negative, straight or curved rods that are catalase-negative. These strains have not been identified.
7. Gram-negative, non-pigmented, pleomorphic rods exhibiting bipolar inclusions. These bacteria have not been identified.
8. In addition to the organisms that were recovered in defined clusters, several individual organisms showed characteristics of coryneform bacteria (large rods forming spherical bodies in older cultures) and several others were Gram-positive cocci which exhibited characteristics of the genus <i>Micrococcus</i> (Gram-positive cocci producing pigments and occurring singly or in pairs).

found in other Alaskan continental shelf regions (Kaneko *et al.* 1979), but is even higher than that reported for some temperate marine waters (Lovelace *et al.* 1967).

Slightly less than half of the Gulf of Alaska bacterial isolates were motile; higher percentages of motile bacteria were found in water samples (49%) than in sediment samples (38%). The majority of the bacterial populations grew at temperatures of 5 to 20C, but true psychrophiles, incapable of growth at 20C, were found in only two-thirds of the samples. The majority of isolates at most stations required NaCl for growth.

A higher incidence of pleomorphism was found among isolates from low-nutrient media (33%) than for strains isolated from high-nutrient media (8%) (Horowitz *et al.* 1983).

Pleomorphism has been associated with oligotrophic bacteria; the increased surface area appears to be important because it permits bacteria to use nutrients at very low concentrations (Moaledi 1978; Poindexter 1979, 1981a, 1981b).

Physiological Tolerances

Investigators have developed physiological tolerance indices so they could describe how isolates from microbial communities grow under environmental conditions that differ from the conditions that existed at the time of isolation. These indices indicate the abilities of bacterial populations to tolerate both natural ecological variability and ecological disturbances (Hauxhurst *et al.* 1981). Different physiological tolerance indices are used to describe the abilities to grow over ranges of temperature (P_T), pH (P_H), and salinity (P_S) (Table 8-3) (Hauxhurst *et al.* 1981). There was a significant difference in P_S values for communities in sur-

Table 8-3.
Summary of physiological tolerance indices, nutrient utilization indices, and taxonomic diversities showing mean values.

	INTERTIDAL GULF OF ALASKA	OFFSHORE GULF OF ALASKA	WEST OF KODIAK ISLAND	COOK INLET	EAST OF KODIAK ISLAND	BEAUFORT SEA
WATER						
P_T	0.82	0.78	0.72	0.78	0.80	0.60
P_H	0.58	0.55	0.35	0.57	0.62	0.62
P_S	0.58	0.41	0.11	0.57	0.61	0.26
N_c	0.85	0.76	0.63	0.76	0.82	0.55
N_a	0.41	0.32	0.49	0.28	0.27	0.29
N_{ca}	0.61	0.51	0.45	0.46	0.59	0.37
N_{aa}	0.61	0.62	0.70	0.69	0.50	0.32
N_h	0.06	0.04	0.14	0.00	0.05	0.00
N_T	0.58	0.51	0.53	0.50	0.52	0.31
H'	3.0	3.0	2.9	2.9	3.0	2.6
J'	0.64	0.70	0.75	0.67	0.71	0.68
SEDIMENT						
P_T	0.79	0.69	0.59	0.71	0.72	0.55
P_H	0.50	0.55	0.52	0.51	0.59	0.72
P_S	0.55	0.28	0.17	0.18	0.41	0.35
N_c	0.97	0.87	0.79	0.86	0.90	0.67
N_a	0.54	0.46	0.43	0.35	0.55	0.56
N_{ca}	0.64	0.57	0.55	0.44	0.68	0.69
N_{aa}	0.70	0.74	0.67	0.78	0.74	0.40
N_h	0.00	0.13	0.10	0.12	0.14	0.00
N_T	0.65	0.61	0.57	0.55	0.67	0.46
H'	3.4	3.8	3.6	3.6	4.0	4.0
J'	0.74	0.84	0.84	0.84	0.85	0.86

P_T = physiological tolerance index for temperature.

P_H = physiological tolerance index for pH.

P_S = physiological tolerance index for salinity.

N_c = nutritional utilization index for carbohydrates.

N_a = nutritional utilization index for alcohols.

N_{ca} = nutritional utilization index for carboxylic acids.

N_{aa} = nutritional utilization index for amino acids.

N_h = nutritional utilization index for hydrocarbons.

N_T = nutritional utilization for all substrates.

H' = Shannon diversity index.

J' = equitability index.

face waters east and west of Kodiak Island; the mean P_S for western stations was 0.11, whereas the mean P_S for eastern stations was 0.61. In most cases, the temperature tolerance index (P_T) was greater than the indices for either the pH range or the NaCl concentration. This indicates that the majority of communities sampled are more tolerant to changes in temperature than they are to changes in either pH or salinity, at least for the ranges that were tested.

The high physiological tolerance indices for Gulf of Alaska bacterial communities are somewhat surprising considering that relatively low annual variations in temperature, salinity, and pH occur in these subarctic marine ecosystems. Most populations were quite tolerant of fluctuations in temperature, salinity, and pH, even for values that went beyond the limits to which they are ever naturally exposed. There are lower salinity tolerance indices for the western Gulf of Alaska than for Cook Inlet and the eastern Gulf. These lower indices correlate with areas where freshwater input is expected; little runoff should occur from the Aleutian Islands, while east of Kodiak Island there are major river sources of freshwater.

The salinity tolerance indices also indicate that intertidal communities are more tolerant of variations in salinity than offshore communities. This higher tolerance is adaptive, since the nearshore communities experience greater salinity fluctuations than the offshore communities. Extensive mixing in the water column, suggested by temperature and salinity (density) measurements taken at the time of sampling, may account for a lack of statistically significant differences between the water and the sediment communities as far as physiological tolerance indices are concerned.

The physiological tolerance indices showed significant differences for temperature, pH, and salinity between bacteria isolated on high- and on low-nutrient media (Table 8-4) (Horowitz *et al.* 1983). Although one might postulate that bacteria isolated on low-nutrient media would be able to grow only under greatly restricted conditions, the bacteria isolated on low-nutrient media were actually more tolerant to variations in salinity and pH. They were also less fastidious from a nutrition standpoint than bacterial populations isolated on rich media. The high physiological tolerance indices for the Gulf isolates contrast markedly with those indices calculated for salinity and temperature using the data of Mallory, Austin, and Colwell (1977) ($P_T = 0.44$ and $P_S = 0.20$ for Chesapeake Bay isolates). In the Gulf, it is obviously advantageous for indigenous bacteria to be versatile rather than specialized.

Nutritional Versatility

A nutritional versatility index (N_T) was developed by Hauxhurst *et al.* (1981) to describe the nutritional capabilities of the indigenous microbial populations. This index, which is essentially synonymous with the average carbonaceous compound index (UAI) developed independently by Martin and Bianchi (1980), is based upon first determining the numbers of different substrates that can be used as growth substrates by members of the microbial community, and then calculating the percentage of the substrates that can be used by one or more representative isolates. Average UAI

Table 8-4.

Comparison of physiological tolerance indices, nutrient utilization indices, and taxonomic diversities for bacterial populations isolated on high- and low-nutrient media.

	WATER		SEDIMENT	
	LOW NUTRIENT	HIGH NUTRIENT	LOW NUTRIENT	HIGH NUTRIENT
P_T	0.81	0.80	0.80	0.69
P_{Hl}	0.80	0.60	0.80	0.61
P_S	0.81	0.60	0.86	0.26
N_c	0.38	0.37	0.24	0.19
N_a	0.59	0.33	0.43	0.20
N_{ca}	0.71	0.36	0.68	0.22
N_{aa}	0.72	0.46	0.59	0.32
N_h	0.50	0.17	0.35	0.08
H'	2.8	4.1	2.6	5.2

P_T = physiological tolerance index for temperature.

P_{Hl} = physiological tolerance index for pH.

P_S = physiological tolerance index for salinity.

N_c = nutritional utilization index for carbohydrates.

N_a = nutritional utilization index for alcohols.

N_{ca} = nutritional utilization index for carboxylic acids.

N_{aa} = nutritional utilization index for amino acids.

N_h = nutritional utilization index for hydrocarbons.

H' = Shannon diversity index.

values for oligotrophic Mediterranean waters were found to be approximately 40% ($N_T = 0.40$) with increases in UAI values up to 52 to 57% during peak phytoplankton bloom. This indicates that higher UAI values occurred during periods of organic enrichment than under oligotrophic conditions. The mean N_T value of 0.53 for offshore Gulf of Alaska waters is somewhat higher than the UAI of 0.40 reported for oligotrophic Mediterranean waters. Direct comparison, however, is not possible in an absolute sense because different substrates were used for the calculations.

Carbohydrates and amino acids generally had the highest utilization indices (Table 8-3) (Hauxhurst *et al.* 1981). In the Gulf, saccharolytic bacterial populations appear to occur as frequently as proteolytic populations. There are two other noteworthy similarities that occur in the Gulf as well: 1) similar utilization indices for amino acids and carbohydrates, and 2) similar proportions of bacterial populations that exhibit extracellular proteolytic and saccharolytic activities. In other regions of the Pacific Ocean, proteolytic capacities have been found to far exceed saccharolytic activities for bacterial populations (ZoBell 1946). The nutritional utilization indices presumably reflect patterns of substrate use within the natural habitats of these communities. This reflection suggests that the bacterial communities may be deriving their energy from phytoplankton-produced nutrients that are rich in carbohydrates.

Although high-nutrient media have been used extensively in marine microbiology—ZoBell and others have found that a nutrient-rich medium supports the growth of higher numbers of marine microorganisms than media of other composition (ZoBell 1946; Carlucci 1974)—the recognition that most true marine bacteria grow in a nutrient-deprived environment has raised questions as to whether the use of low-nutrient media would be more appropriate (Jannasch 1967; Carlucci 1974; Carlucci and

Shimp 1974). High nutrient concentrations inhibit the growth of some marine bacteria; such bacteria grow best at low nutrient concentrations (Torella and Morita 1981).

The characteristics of bacteria that were isolated on either low- or high-nutrient media differ significantly, suggesting that the bacteria isolated on the different media represent bacterial populations occupying different ecological niches within their environment. In addition, isolates from low-nutrient media were nutritionally far more versatile than those isolated on high-nutrient media (Horowitz *et al.* 1983) (Table 8–4). Isolates from low-nutrient media could utilize two to three times more alcohol, carboxylic acid, amino acid, and hydrocarbon substrates than the isolates obtained from high-nutrient media. It is possible that in natural marine ecosystems some bacteria are associated with nutrient-rich particles such as detritus—including dead organisms and excretions—while other bacteria grow under conditions of near starvation on minimal concentrations of dissolved organic carbon (Morita 1982).

Comparing these results to those obtained by Mallory *et al.* (1977), it appears that for comparable tests, a higher proportion of the Alaskan isolates were euryheterotrophic, whereas the Chesapeake Bay isolates were more restricted in the substrates they used. For example, the nutritional utilization indices for the Chesapeake Bay isolates—calculated based on the data of Mallory *et al.* (1977)—are $N_c = 0.40$, $N_a = 0.20$, $N_{aa} = 0.10$, and $N_{ca} = 0.10$, which, with the exception of carbohydrates, are significantly lower than the comparable indices for the Alaskan Cook Inlet isolates that were obtained on low-nutrient media (Horowitz *et al.* 1983).

Diversity of Gulf of Alaska Bacterial Communities

A diversity index reflects both the number of different species and their relative abundances (distribution) within a given community, and hence the 'status' of the community. However, a diversity index does not define the specific factors responsible for establishing levels of informational heterogeneity (Atlas 1984a). Various diversity indices have been used to assess environmental stress caused by pollution (Patrick, Hohn, and Wallace 1954; Patrick 1963; Pielou 1975; and Cairns 1979). The Shannon index (H') accounts for both the numbers of different species and their relative abundances within a community. The index is calculated as $H' = -\sum P_i \log P_i$, where $P_i = n_i/N =$ importance probability for each species, $n_i =$ importance value for each species, and $N =$ total of importance values. The equitability index (J') describes the evenness of species distribution within the community and is calculated as $J' = H'/H_{\max}$, where H_{\max} is the theoretical maximum Shannon index for a community that contains a specified number of species.

The Shannon diversity indices for Gulf of Alaska bacterial communities show a high state of diversity (Hauxhurst *et al.* 1981). These findings are comparable to those reported by Martin and Bianchi (1980) for oligotrophic marine waters of the French Mediterranean region. The taxonomic diversity indices for the Gulf of Alaska bacterial communities were somewhat higher for the water column and were sim-

ilar for sediments when compared with those indices previously calculated for Arctic marine bacterial communities (Kaneko, Atlas, and Krichevsky 1977; Hauxhurst *et al.* 1981; and Atlas, in press). Although seasonal differences in taxonomic diversity were found in Arctic waters, no significant seasonal differences in taxonomic diversity indices were found for bacterial communities in those subarctic Gulf of Alaska waters sampled in March and October. Unlike the Beaufort Sea, where an inverse relationship between population size and taxonomic diversity was found (Kaneko *et al.* 1977), no significant correlation was found between population size and diversity for Gulf of Alaska bacterial communities (Hauxhurst *et al.* 1981).

The bacterial populations isolated on nutrient-rich media had higher diversities than bacteria isolated on low-nutrient media (Table 8–4) (Horowitz *et al.* 1983). The average Shannon diversity index for all isolates from high-nutrient media was 5.6, compared with an index of 3.1 for isolates from low-nutrient media. The Shannon diversity indices for isolates from sediment obtained on high-nutrient media were higher than indices for comparable isolates taken from water. There was no significant difference in diversity indices between sediment and water isolates obtained on low-nutrient media.

Pathogenic Microorganisms in the Gulf of Alaska

Fish Diseases

Most of the data on fish diseases in the Gulf of Alaska relate to the freshwater environments where salmonids are reared and released (see review by Dieterich 1981). For fish diseases in marine systems, Grischkowsky and Amend (1976) reported infectious hematopoietic necrosis virus in Alaskan sockeye salmon; the virus was isolated from moribund juveniles at Kitoi Bay and from adult spawning stock throughout Bristol Bay, Kodiak Island, Cook Inlet, and the southeast Gulf of Alaska areas.

McCain, Gronlund, Myers, and Wellings (1979) and McCain, Hodgins, Sparks, and Gronlund (1981) found that Gulf of Alaska flatfish show no lymphocystis disease, and although lymphocystis was not observed in the yellowfin sole (*Limanda aspera*) of the Gulf of Alaska, it was found in sole collected in the Bering Sea. In contrast to the absence of lymphocystis, Levings (1967) reported that 10% of the rock sole (*Lepidopsetta bilineata*) collected in the Western Gulf of Alaska had epidermal papillomas, which in some cases covered up to 50% of the body. Since such tumors were rarely detected in specimens from British Columbia, Levings proposed that differences in growth rates between fish in these regions might reflect differences in the frequency with which certain diseases occur in the two populations. Stich, Acton, Oishi, Yamazaki, Harada, and Moser (1977) conclude that lymphocystis and papillomatosis are mutually exclusive; even in the Bering Sea, where both diseases occur, individual flatfish are never afflicted with both of these diseases. Based upon the distributions of lymphocystis and papillomatosis, Stich, Acton, Dunn, Oishi, Yamazaki, Harada, Peters, and Peters (1977) hypothesized that the lym-

phocystis virus and the 'papilloma virus' are related. They further hypothesized that lymphocystis disease results when a complete infectious-replication cycle occurs, whereas papillomatosis occurs when a complete infection is aborted.

Crab Diseases

The commercially important Tanner crab (*Chionoecetes bairdi*) is susceptible to fungal infection by *Trichomaris invadens* which results in a disease called black mat syndrome (BMS). Sparks and Hibbits (1979) have shown that *T. invadens* can be found in most organs and tissues of infected Tanner crabs. Sparks (1982) has suggested that this disease could prove fatal to the infected crab, but before death occurs, it undoubtedly affects breeding and reproduction. A survey of natural Gulf of Alaska Tanner crab populations indicated that as many as 94.7% of the barren females had BMS (Hicks 1982), suggesting that *T. invadens* infections have a significant detrimental impact on reproductive success. Females showed the highest incidence of BMS with as much as 50% of the population infected in some areas. Black mat syndrome was more prevalent in offshore populations than in nearshore populations. The incidence of BMS shows large seasonal variations; Tanner crabs southwest of Kodiak Island had a 29% incidence of BMS one year and 2% incidence the next year (Hicks 1982). Although it is clear that BMS is an important factor controlling Tanner crab populations, we do not know enough about the conditions that enhance the rate of infection to offer solutions for reducing the incidence of this disease (Sparks 1982).

Potential Human Pathogens Associated with Edible Crabs

Pennington and Cronholm (1977) detected bacteria that are known human pathogens in crabs collected in the vicinity of Kodiak Island. They suggested that inadequately treated sewage was the source of this contamination. Faghri, Pennington, Cronholm, and Atlas (1984) examined the interaction between pathogenic bacteria and crabs from the Gulf of Alaska in greater detail. Their evidence indicates that certain bacteria from foreign contamination sources such as sewage can associate with crab tissue and survive in the marine environment for prolonged periods. Crabs obtained from near Kodiak Island contained bacteria that were identified as potential human pathogens. The isolates contained many taxa such as *Klebsiella* and *Citrobacter* that are normally associated with domestic sewage. These isolates were most frequently found in association with gill tissue, but in some cases bacteria were isolated from muscle tissue as well.

Yersinia enterocolytica, a human pathogen transmitted via the gastrointestinal tract and associated with several recent outbreaks of food poisoning, was among the isolates obtained from crabs collected near Kodiak Island; tests with laboratory mice confirmed the pathogenicity of the *Y. enterocolytica* and also of the *Klebsiella pneumoniae* isolates (Faghri *et al.* 1984). Crabs from the southern Bering Sea and those collected in the Gulf of Alaska away from Kodiak Island did not contain bacterial populations indicative of sewage contamination.

A standard indicator organism, *Escherichia coli*, was absent from crabs collected near Kodiak Island, but other bacteria associated with sewage were present. Previous studies have shown that standard coliform counts are inadequate as indicators either of fecal contamination of marine ecosystems, or of the safety of shellfish collected from areas impacted by sewage effluents. This is because *E. coli* is rapidly eliminated from seawater, whereas other bacteria in sewage effluents, including human pathogens, survive longer (Carlucci and Pramer 1959; Dutka 1973; and Rhodes, Anderson, and Kator 1983). Microcosm studies by Faghri *et al.* (1984) confirmed the rapid disappearance of *E. coli* from seawater at low temperatures and indicated that *E. coli* survival is not enhanced by association with crabs. Other bacteria such as *Klebsiella*, however, showed prolonged survival when in association with crab tissues.

In addition to examining the potential for the association of sewage bacteria with crabs, Faghri *et al.* (1984) examined the possibility that indigenous marine bacteria that may be human pathogens could accumulate in crab tissue. Several investigators have found *Vibrio* species associated with tissue in blue crabs collected in temperate waters (Colwell, Wicks, and Tubiash 1975; Sizemore, Colwell, Tubiash, and Lovelace 1975; Tubiash, Sizemore, and Colwell 1975; and Davis and Sizemore 1982). Recent studies have shown that *V. cholerae* occurs naturally in temperate estuaries (Kaper, Lockman, Colwell, and Joseph 1979) and that cases of cholera in the Gulf Coast region of the United States have resulted from eating contaminated shellfish, including inadequately cooked crab meat (Blake, Weaver, and Hollis 1980). While it has been suggested that *V. cholerae* is a ubiquitous inhabitant of estuarine ecosystems (Kaper *et al.* 1979), this organism was not found in association with the Alaskan crabs (Faghri *et al.* 1984).

Vibrio vulnificus, reported in association with eels and shellfish by Oliver, Warner, and Cleland (1982) and by Tison, Nishibuchi, Greenwood, and Seidler (1982), was found in the gill tissue of crabs collected off the Oregon/Washington coast. It was not found, however, in the tissues of crabs collected in Alaskan continental shelf regions (Faghri *et al.* 1984). Similarly *V. parahaemolyticus* was isolated from Dungeness crabs collected off the mouth of the Columbia River, but not from Alaskan crabs (Faghri *et al.* 1984). *Vibrio parahaemolyticus*, a human pathogen, has been found in association with crabs and other shellfish (Fishbein, Mehlman, and Pitcher 1970; Bartley and Slanetz 1981). In temperate estuaries, *V. parahaemolyticus* undergoes an annual cycle during which it becomes associated with the chitin exoskeletons of invertebrates (Kaneko and Colwell 1973, 1975a). It is apparently restricted to temperate waters that reach high enough temperatures for it to complete its annual cycle (Kaneko and Colwell 1975b, 1978). Previous surveys have failed to detect *V. parahaemolyticus* north of Petersburg in southeastern Alaska, but the closely related species, *V. alginolyticus*, has been isolated throughout the Gulf of Alaska (Baross and Liston 1970; Vasconcelos, Stang, and Laidlaw 1975). Thus, although *Vibrio* species are among the major bacterial species occurring in Alaskan waters, those of concern with respect to human health appear to be absent in cold marine waters.

Staphylococcus and *Micrococcus* species were frequently isolated from Alaskan crab tissues (Faghri *et al.* 1984); these Gram-positive cocci are much more abundant in crab tissue than they are in the surrounding water and sediment (Hauxhurst *et al.* 1980). Recent reports, however, have indicated that Gram-positive cocci are normally found in marine habitats (Gunn, Singleton, Peele, and Colwell 1982; Gunn and Colwell 1983). All the *Staphylococcus* isolates from crabs examined by Faghri *et al.* (1984) were coagulase-negative *S. epidermidis* and *S. hominis*; these species have also been isolated from other marine ecosystems (Gunn and Colwell 1983). Some coagulase-negative *Staphylococcus* species are human pathogens (Kloos 1982), and the *in vivo* pathogenicity tests showed that the crab isolates were pathogenic for mice (Faghri *et al.* 1984).

Besides examining field samples for contamination with human pathogen bacteria, Faghri *et al.* (1984) conducted microcosm studies to determine which, if any, bacteria could survive in seawater and become associated with crab tissues. An important question is whether the bacteria associated with crabs contaminate the edible muscle tissues. Scanning electron microscope observations and viable enumeration procedures indicate that most bacteria are associated with surface tissue of the gills and on the shell of crabs collected in the Gulf of Alaska. For example, Dungeness crabs had a diverse array of bacteria associated with gill tissue, and Alaskan king crabs collected near Kodiak Island showed higher numbers of viable bacteria on their gill tissue than crabs collected away from this populated area.

As the study by Faghri *et al.* (1984) showed, hemolymph and muscle tissues of Alaskan crabs normally have low bacterial populations. However, after death, high numbers of bacteria were found in hemolymph and muscle tissues; the muscle tissues of crabs that are either stressed by oxygen depletion or are injured and die within holding tanks can rapidly become contaminated with bacteria that include human pathogens. As long as the crab is healthy, the bacteria appear to be restricted to the shell and gill tissues. However, if the crab is injured, becomes weakened, or dies, bacterial contaminants on the surface rapidly penetrate the hemolymph, and human pathogens can enter the muscle tissues.

Microbial Processes

Carbon Cycling

In the classical scheme of large-scale marine biological processes, the major role of bacteria was thought to be that of mineralizer. Even though the role of the bacteria in the detrital food chain was known, it was thought to be of little importance to the total biological productivity of marine systems. By the early 1970s, however, enough radiotracer studies had been conducted to challenge many of the earlier concepts (Fenchel 1970; Mann 1972; and Fenchel and Jørgensen 1977). About the same time, Wetzel, Rich, Miller, and Allen (1972) redefined the working definition of the term detritus as "nonpredatory losses of organic carbon from any trophic level (includes egestion, excretion, and

secretion) or input from sources external to the ecosystem that enter and cycle in the system (allochthonous organic carbon)." This relatively liberal interpretation of what constitutes detritus includes such components as dissolved organic compounds that were normally not categorized in this way (Fenchel and Jørgensen 1977).

In light of both the above definition and observations that were being made using increasingly sensitive and sophisticated techniques, it was rapidly becoming evident that the relative importance of marine bacteria in the detrital food chain needed reevaluation. Pomeroy (1974) pointed out that bacteria had several roles to play in the detrital food chain: (1) converting dissolved organic carbon into bacterial biomass that could be used directly by higher trophic levels; (2) degrading relatively recalcitrant organic polymers that would not normally become available as a food source; and (3) colonizing both organic and inorganic particles, thus increasing the food value of these particles. Considering all these functions and using Wetzel's definition of detritus, Sibert and Naiman (1980) concluded that ecosystems derive their total productivity from two sources: photosynthesis and microbial processing of non-grazed plant material.

Although it is now generally acknowledged that the detrital food chain plays an important, if not major, role in overall productivity (Naiman and Sibert 1979) and that bacterial biomass is an important component of that system, the actual percentage of total organic carbon that is cycled through bacterial biomass is still difficult to estimate. Excluding all other sources of carbon, it has been estimated that between 10 and 15% of macrophytic carbon (Stuart, Newell, and Lucas 1982) and between 3 and 30% (Jensen 1983) or up to 33% (Laake, Dahle, and Hentzschel 1983) of phytoplankton carbon is converted to bacterial biomass. In another study, the investigators estimated that between 20 and 60% of the phytoplankton carbon that was fixed by primary productivity was consumed by microheterotrophs (Linley, Newell, and Lucas 1983).

Azam, Fenchel, Field, Gray, Meyer-Reil, and Thingstad (1983) concluded that between 10 and 50% of all the carbon that is fixed by photosynthesis in the water column is used by bacteria, and most of this carbon is subsequently cycled to the rest of the food chain via nanoplanktonic heterotrophic flagellates. Although their study concerned only free bacteria in the water column, they concluded that similar principles would apply to detrital particles as well. In another study of carbon cycling in Kiel Bight, Rheinheimer (1981) concluded that between 15 and 30% of the yearly primary production was transformed to bacterial biomass.

The above studies were conducted in various geographical areas using different techniques, and the conclusions were often based on different assumptions. However, it does seem clear that in general terms, approximately 10 to 50% of all primary production in the marine environment is cycled through bacteria.

The relative importance of bacterial biomass production will depend to a large extent on the population being considered. When considering the diets of marine herbivores, bacterial biomass is probably relatively unimportant. On the other hand, the high correlation found between

nematode biomass and microbial biomass by Hanson, Tenore, Bishop, Chamberlain, Pamatmat, and Tietjen (1981) and the close predator-prey relationship observed by Azam *et al.* (1983) between nanoplanktonic heterotrophic flagellates and bacteria suggest that both nematodes and nanoplanktonic heterotrophic flagellates are very much dependent on bacterial biomass. This principle is also well illustrated in the case of the food chain dynamics of chum salmon fry. During their first few weeks in saltwater, chum salmon feed heavily on harpacticoid copepods. Sibert, Brown, Healey, Kask, and Naiman (1977) found that harpacticoid copepods are primarily dependent on bacteria as a food source. Their findings strongly suggested that the high microbial productivity that they observed in an estuary in British Columbia was critical to the high salmonid productivity of the region. Areas of high microbial activity may also be important in relation to salmonid production in the Gulf of Alaska.

Carbon Cycling in the Water Column

The pelagic microbial community is generally classified as either free-living or particulate-associated. While there is still considerable controversy concerning the relative roles of these two populations in the marine environment, it is generally accepted that their relative importance varies with the environment (Azam and Hodson 1977; Hanson and Wiebe 1977; Bell and Albright 1981; Bent and Goulder 1981; and Wright and Coffin 1983). Although these two populations were not differentiated in studies of the Gulf of Alaska, a very high positive correlation was observed in Cook Inlet pelagic waters between water turbidity and relative heterotrophic activity using both glucose and glutamate (Griffiths, McNamara, Steven, and Morita 1981). The relatively high microbial activity associated with suspended particulates in Cook Inlet suggests that these particles could be an important food source for any organisms that can trap them and then digest the associated microheterotrophs.

Since most of the major rivers emptying into the Gulf of Alaska contain a high sediment load, bacterial biomass production associated with sediment particles may be an important feature of nearshore biological activity. Even without these particles, bacterial biomass production is generally greater nearshore than offshore and is greatest in areas directly influenced by major river plumes. Not only is the rate of organic carbon uptake elevated, but there is also an elevation in microbial biomass production in the plumes when compared with the surrounding seawater (Griffiths, McNamara, Steven, and Morita 1981; Griffiths, Caldwell, and Morita 1984). This phenomenon was observed in essentially every major river input that was studied in Alaskan nearshore waters. In the Gulf of Alaska, it was observed on a very large scale in Cook Inlet and on a smaller scale within Kachemak Bay (Griffiths *et al.* 1984).

The stimulation of microbial activity in areas where freshwater from terrestrial runoff and marine waters intermix has also been reported by others (Stevenson and Erkenbrecher 1976; Valdes and Albright 1981; and Albright 1983). The exact mechanism for this stimulation is not known, but it has been hypothesized by Albright (1983) that

organic nutrients from both sources complement each other to provide a more complete nutrient for the microheterotrophs. The stimulation of microbial biomass production under these conditions may help explain the sources of the bacterial biomass that is required to feed young chum salmon as suggested by Naiman and Sibert (1979). It is probable that similar food chain dynamics take place in most major estuarine systems within the Gulf of Alaska.

The relative microbial activities found in the Gulf of Alaska have been found to be similar to those observed in more temperate climates (Griffiths, Hayasaka, McNamara, and Morita 1978), as well as being similar to those observed in Arctic waters (Atlas and Griffiths 1984). Measurements of the uptake of ^{14}C -labeled organics by bacteria do not take into account the tracer dilution due to ambient concentration of the substrate—dilution which can seriously affect measured uptake values. However, the data support the conclusion that the microbial biomass in the food chain of the Gulf of Alaska is comparable to the microbial biomass in the food chains of other regions of the world's oceans.

During studies of relative microbial activities in the waters of Kachemak Bay, Griffiths, Caldwell, and Morita (1982) observed seasonal trends that indicate that the pelagic microorganisms change both qualitatively and quantitatively. From the results of this study and from patterns of relative microbial heterotrophic activity observed during several cruises in Cook Inlet (Griffiths and Morita 1981), it was concluded that the major seasonal variation observed in pelagic microbial communities is directly related to phytoplankton bloom activity. These seasonal variations strongly suggest a link between the release of dissolved organic compounds by phytoplankton during a bloom cycle and the incorporation of this material into microbial biomass (Griffiths, Caldwell, and Morita 1982). The same relationship was suggested by the nutritional data reported by Hauxhurst *et al.* (1981).

During these studies, Griffiths, Caldwell, and Morita (1982) detected a shift in the qualitative characteristics of the microbial population as the population responded to the phytoplankton bloom. During periods when phytoplankton activity was relatively low, the ratio of the glucose uptake rate to the glutamate uptake rate was approximately 0.1, indicating that the potential rate at which glutamate could be utilized was approximately 10 times greater than that for glucose. During an active phytoplankton bloom the ratio was approximately 1.0. Quantitative shifts in bacterial populations during phytoplankton blooms have also been reported by Lelong, Bianchi, and Martin (1980) and Rieper (1976).

The link between both qualitative and quantitative changes in pelagic microbial communities and phytoplankton bloom cycles is well established (Saunders and Storch 1971). Typically these changes occur either in response to the extracellular carbon produced by the phytoplankton (Smith, Barber, and Huntsman 1977; Hollibaugh 1979; and Larsson and Hagström 1979, 1982) or in response to injured or decomposing phytoplankton (Fuhrman, Ammerman, and Azam 1980; Fukami, Simidu, and Taga 1981). Both qualitative and quantitative changes may also

occur in response to sedimentation of the starch particles produced by phytoplankton (Bursa 1968). The fact that similar phytoplankton-microbial interactions have been found in other marine systems again suggests that the bloom responses that were observed in the Gulf of Alaska are not unique to this region.

Carbon Cycling in the Sediments

In shallow nearshore environments, cycling of organic carbon through the benthic community is undoubtedly an important feature of this area's biological productivity. Unfortunately, there are no standardized methods for measuring relative microbial heterotrophic activity in marine sediments. Therefore, it is difficult to make direct comparisons between those rates observed in the Gulf of Alaska and rates observed in other marine systems. However, comparisons can be made with rates observed in more northern Alaskan waters (Table 8-5). Although differences were observed in the mean values of samples from different regions that were collected at different times, none of these differences was statistically significant. Of greater interest and significance were the seasonal changes that were observed in the sediments from Kachemak Bay (Fig. 8-1; Table 8-6), which were analyzed using methods described by Griffiths, Caldwell, Broich, and Morita (1983).

In contrast to the seasonal variation in the water column, where there is a variation factor of 10, the relative microbial activities observed in the sediments collected near Kasitsna Bay were relatively constant with a seasonal variation factor of about three. The increased microbial activity observed in July 1979 could have been caused by either a seasonal increase in temperature or by the input of detrital carbon into the system. Temperature has been discounted as a significant factor in this increase, since the correlation between temperature and glutamate uptake was not significant and the correlation with glucose uptake was very low. Additionally, the maximum mean sediment temperature was found in November when the mean rate of substrate uptake was again reduced to a more normal level (Table 8-6).

It is much more likely that this elevated activity was related to an elevated input of detrital carbon. This detrital input could have been from terrestrial sources but it was more likely in response to the early and intense phytoplankton bloom that had occurred in the spring of that

Table 8-5.
Comparison of microbial uptake rates (ng/g·h) found in Arctic and subarctic marine sediments.

LOCATION	TIME	GLUCOSE UPTAKE		GLUTAMATE UPTAKE	
		MEAN	RANGE	MEAN	RANGE
Beaufort Sea	Summer 1976	4	1-15	80	20-180
Beaufort Sea	Summer 1978	9	1-24	96	7-262
Norton Sound	Summer 1979	28	0.1-154	127	3-1063
Bristol Bay	Spring 1981	-	-	215	149-345
Cook Inlet	Fall 1976	12	1-56	220	70-1190
Cook Inlet	Spring 1977	8	1-18	217	80-370
Cook Inlet	Fall 1977	4	0.4-22	63	20-252
Cook Inlet	Spring 1978	4	0.1-38	89	5-595

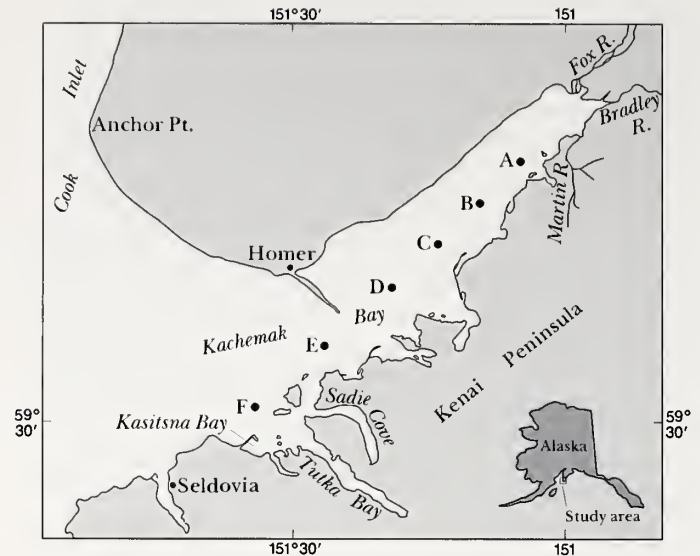


Figure 8-1. Microbiological sampling locations within Kachemak Bay.

Table 8-6.
Glucose and glutamate uptake rates (ng/g·h) in sediments collected in and near Kasitsna Bay.

TIME	GLUCOSE UPTAKE		GLUTAMATE UPTAKE	
	MEAN	RANGE	MEAN	RANGE
Winter 1979	25	3-110	340	32-1860
Spring 1979	27	5-73	320	35-940
Summer 1979	140	20-360	1070	180-3600
Fall 1979	57	4-180	320	41-1260
Winter 1980	46	11-120	380	110-1110
Spring 1980	53	10-140	380	130-780
Summer 1980	50	9-150	470	120-960

year (Griffiths, Caldwell, and Morita 1982). During the second season of the study, the spring phytoplankton bloom occurred two months later and there was no stimulation in samples collected in the first week of July. An apparent relationship between a phytoplankton bloom and increased microbial activity in marine sediments has also been found in the Baltic Sea (Graf, Bengtsson, Diesner, Schulz, and Theede 1982).

A number of studies have shown that organic nutrients are introduced into marine sediments either during or after a major phytoplankton bloom. This carbon source forms a major portion of the carbon required to maintain the benthic community (Iturriaga 1979; Hargrave 1980; and Wassmann 1983). Chester and Larrance (1981) concluded that the extremely high productivity of both benthic and pelagic animals in Kachemak Bay (located within Cook Inlet) was the direct result of a high flux of organic matter consisting mostly of phytoplankton and phytoplankton-derived material that was incorporated into the sediments of the Bay. A lag that occurs between the time of the phytoplankton bloom and the elevated microbial activity may be related to the time it takes the bioturbation process to incorporate this carbon into the sediments (Yingst and Rhoads 1980).

Table 8-7.

Enzyme activities found in sediments collected at locations illustrated in Figure 8-2. Mean values are given on first line; ranges of variation are given in parentheses. Amylase and cellulase activities are μg glucose/g-h; phosphatase and arylsulfatase activities are μM p-nitrophenol/g-h; nitrogenase activities are $\text{ng N}_2/\text{g-h}$.

TIME	AMYLASE	CELLULASE	PHOSPHATASE	ARYLSULFATASE	NITROGENASE
Winter 1979	32 (11-62)	16 (4-31)	0.27 (0.03-0.81)	0.50 (0.01-1.41)	0.7 (0-2.3)
Spring 1979	28 (11-83)	14 (7-35)	0.22 (0.13-0.41)	0.37 (0.08-0.62)	0.9 (0-2.1)
Summer 1979	26 (10-45)	18 (8-38)	0.31 (0.14-0.48)	0.60 (0.30-1.12)	0.9 (0-4.2)
Fall 1979	32 (11-100)	12 (2-49)	0.27 (0.15-0.62)	0.18 (0.09-1.04)	1.7 (0-7.5)
Winter 1980	19 (6-51)	10 (4-20)	0.28 (0.14-0.50)	0.63 (0.21-1.13)	0.9 (0.3-1.8)
Spring 1980	30 (14-75)	14 (8-33)	0.23 (0.12-0.44)	0.41 (0.14-0.85)	0.9 (0-1.7)
Summer 1980	28 (10-73)	21 (8-43)	0.34 (0.19-0.70)	0.56 (0.16-1.19)	1.3 (0.2-3.1)

Chester and Larrance (1981) also measured microbial activity by assaying potential activities for five enzymes: phosphatase, amylase, hydrolase, arylsulfatase, and cellulase (Table 8-7). Phosphatase and arylsulfatase activities were measured as indicators of general microbial activity. Amylase and cellulase activities were measured as indicators of potential hydrolase activities for the degradation of starch and cellulose, respectively. For those sediments that were tested, no significant seasonal changes took place in any of these enzymes. This relative seasonal consistency in microbial activities may be attributed to a relatively constant source of usable organic carbon throughout the year. During the winter months, the major contributor of detrital carbon is probably *Laminaria* and related macrophytes (Lees 1978). This *Laminaria* growth is likely based both upon algal organic carbon produced during the summer and upon inorganic nutrients released from sediments by bacterial activity during fall and winter periods. It has been estimated that the biomass produced annually by the macrophytes in Kachemak Bay equals the biomass produced by phytoplankton in the same region (Lees 1978). To supplement this source of carbon, there is some freshwater runoff during most of the winter. Presumably, this provides terrestrial carbon input throughout the year.

This pattern of seasonal consistency is in stark contrast to the seasonal differences observed in Arctic marine sediments and in the mouth of Kachemak Bay. For example, Griffiths *et al.* (1978) observed a 10-fold seasonal variation in the relative heterotrophic activities between summer and winter in Beaufort Sea sediments and in the mouth of Kachemak Bay (Table 8-8). This seasonal difference was attributed to seasonal changes in the input of detrital carbon into the two systems. During the winter months, the Beaufort Sea has little or no light for photosynthesis, no terrestrial runoff, and very few areas where significant macrophytic carbon can come into the system. This reduction in activity also accounts for the 10-fold reduction in adenylate concentrations in Elson Lagoon sediments (Beaufort Sea) (Atlas and Griffiths 1984). In Kasitsna Bay sediments no seasonal changes were observed in total adenylates. The Elson

Lagoon data suggest that during the winter, there is a reduction both in microbial biomass and in total benthic biomass for all organisms smaller than 2 mm residing in Arctic sediments. This does not seem to occur in the more temperate subarctic marine sediments of Kasitsna Bay.

It has been known for some time that there is an inverse correlation between microbial activity and the distance from shore. There are also two other generalizations that can be made about microbial activities in marine sediments. As Griffiths *et al.* (1983) observed in Bristol Bay, there is elevated microbial activity in areas where fine particles settle out of the water column and are incorporated into the sediments. In the Gulf of Alaska there are various geological features such as Prince William Sound and areas near Kayak Island which should allow extensive settling of fine-grained

Table 8-8.

Rates of various microbial activities observed along the Kachemak Bay transect. All values are the means of three observations. Station locations are shown in Figure 8-1. Glucose and glutamate uptakes and alginase activities are in μg glucose/g-h; phosphatase and arylsulfatase activities are shown as a ratio of these two activities; and nitrogenase activities are $\text{ng N}_2/\text{g-h}$.

STATION	GLUCOSE UPTAKE	GLUTAMATE UPTAKE	NITROGEN FIXATION	ARYLSULFATASE/PHOSPHATASE	ALGINASE
WINTER 1979					
A	10	104	0.03	0.52	
B	46	384	0.10	0.49	
C	25	200		0.61	
D	12	138	0.46	1.16	
E				1.51	
F	5	104	0.76	3.95	
SUMMER 1979					
B	16	146	0.00	0.69	5.3
C	30	208	0.70	0.75	7.0
D	47	402	1.38	1.04	9.8
E	69	535	1.56	1.26	9.9
F	82	662	2.57	2.37	11.7

particles. From the known geographical distributions of relative microbial heterotrophic activity, it is possible to predict that areas like Prince William Sound are areas of high microbial biomass productivity and are therefore important features of secondary productivity in the Gulf of Alaska.

Gulf of Alaska studies have also shown that microbial activity is elevated in the soft sediments that lie within the normal plume pattern of major rivers (Atlas *et al.* 1983). However, the areas of highest activity may not be those areas closest to the mouth of the river. A good example of this is where the Yukon River empties into Norton Sound. Most of the sediments near the major outlets of the Yukon are sandy and do not have elevated microbial activities (Atlas *et al.* 1983). In areas to the east and northeast (where prevailing currents presumably carried fine-grained terrestrial detritus), microbial activities were greatly elevated. Elevated microbial activities have also been found in sediments near the major rivers in the Beaufort Sea (Atlas and Griffiths 1984).

Kachemak Bay may serve as a model for many embayments within the Gulf of Alaska because of the seasonal and geographic variations in the sources of detrital carbon that occur within it. As indicated above, the major detrital inputs are from phytoplanktonic, macrophytic, and terrestrial carbon. Although all of these carbon sources can be found throughout the Bay, one of these sources probably dominates in each area. The major source of terrestrial carbon in the region should be the Fox, Bradley, and Martin Rivers which flow into the head of Kachemak Bay. The bulk of the macrophytic community is found along the entire southeastern shoreline and must represent the major input of organic carbon into the soft sediments along this shoreline (Lees 1978). Although phytoplankton undoubtedly flourish throughout the Bay, their productivity is particularly high at the mouth of the Bay seaward of the Homer Spit (Chester and Larrance 1981). The waters in the inner Bay are often very turbid and thus primary productivity is reduced.

Terrestrial carbon should also be a relatively constant source of detrital carbon to the benthic community. Although river flow rates and detrital carbon input rates can vary seasonally, there is at least some flow during most of the year in this area. Since most of the particulate terrestrial carbon requires some processing by marine invertebrates and bacteria before it can become useful as food for higher trophic levels, the seasonal pulses of new carbon should be buffered in their effects on microbial activities.

The carbon input from phytoplankton blooms should have entirely different characteristics. Because phytoplankton represent a readily degradable source of high-quality food, they should provide a relatively transient source of high-quality, carbon-containing compounds (*e.g.*, simple carbohydrates). This results in a pulse of elevated microbial activity after a major bloom. During studies on Kachemak Bay, sediment samples were collected and analyzed along two transects; one was sampled in July after a large early phytoplankton bloom in the area (Griffiths, Caldwell, and Morita 1982) and the other was sampled in January. If the above assumptions are correct, one would expect to find maximum microbial activity in the sediments collected near the major rivers, and much lower activity in sediments

collected outside of Homer Spit during January. This, indeed, is what was found when relative microbial activity was measured using either glucose or glutamate (Table 8-8).

In the summer, on the other hand, one would expect to find a gradient of increasing microbial activity from the area near the river input to the outside of the spit where phytoplankton biomass should have recently sedimented out of the water column. Again, this is the pattern that was found in July (Table 8-8). Additionally, if these assumptions are correct, one would also expect to find greater seasonal variability in microbial activity in the offshore stations where phytoplankton carbon should dominate than in stations where terrestrial carbon should dominate. Again, the observations support these assumptions.

Arylsulfatase, phosphatase, and alginase activities were also measured during these studies. Measurements were made to determine if the microbial function in the Bay was influenced by differing sources of detrital carbon. In these studies, phosphatase activity was assumed to act as a general indicator of microbial activity (Kobori and Taga 1974; Kaneko *et al.* 1978) even though other organisms are known to produce this enzyme (Rivkin and Swift 1979; Griffiths *et al.* 1983). The arylsulfatase activity, on the other hand, should reflect a more specific microbial population, such as bacteria that have adapted to using particulate carbon from a marine source (Oshrain and Wiebe 1979). If these assumptions are correct, and if there is a gradient of terrestrial carbon from the head to the mouth of Kachemak Bay, an increase in the ratio of arylsulfatase to phosphatase should have been observed in sediments collected along this gradient. This was found (Table 8-8). These same trends were found on a smaller scale in two side bays where there was a source of terrestrial carbon at the heads of both bays (Fig. 8-2).

Alginase activity was also measured. If the assumptions about the terrestrial carbon gradient along Kachemak Bay are correct, there should be a positive correlation between the marine algal alginin input into sediment detritus and the distance from the head of the Bay. If this is true, and

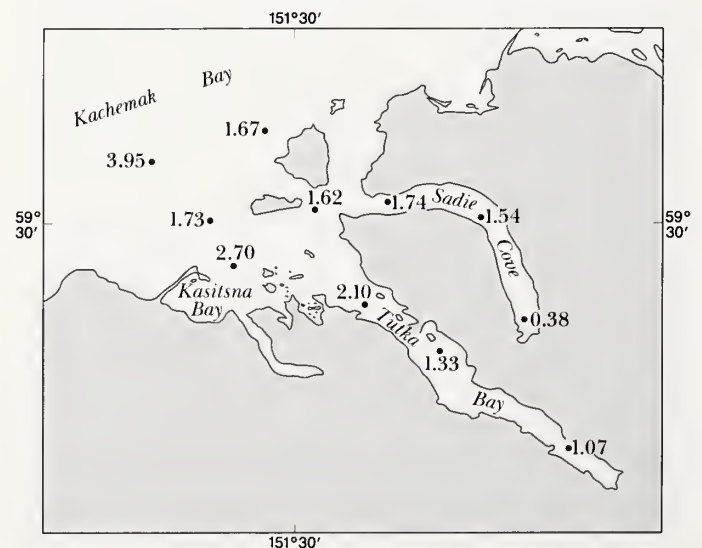


Figure 8-2. Ratios of arylsulfatase to phosphatase activities in sediments near Kasitsna Bay.

microbial enzymatic activities adjust to the presence of this compound, an increase in alginase activity along the Kachemak Bay head-to-mouth transect would be expected. This was found (Table 8-8).

These studies in Kachemak Bay showed that the characteristics of carbon cycling in Bay sediments depend heavily upon the source of the detrital carbon. The patterns that were found at the mouth of Kachemak Bay are probably typical of many shallow nearshore environments where phytoplankton carbon provides most of the carbon for the detrital food chain. In such a system, organic carbon should be cycled very rapidly and there are undoubtedly long periods when secondary productivity is low in the benthic communities. The sediments near the head of Kachemak Bay are typical of the soft sediments found adjacent to the mouths of large rivers. Here most of the carbon is in a relatively recalcitrant form that provides a constant source of organic carbon for the detrital food chain throughout the year.

The areas which have the highest and most consistent input of carbon for the detrital food chain should be found in small bays such as Sadie Cove and Tutka Bay (see Fig. 8-2). These areas do not have a large water column particulate load due to either terrestrial runoff or to sediment resuspension from wave or tidal action. In bays such as these, there is carbon input under essentially ideal conditions from all major sources. The water is clear enough to allow spring phytoplankton blooms to occur, there is some terrestrial input from the surrounding watershed, and there is ample rocky substrate to allow extensive macrophytic growth (Lees 1978). The end result is that a high constant level of good-quality detrital carbon flows through the system, allowing it to support a highly productive marine assemblage (Lees 1978). These bays are probably good systems to use as models for most of the southeastern Alaskan coastline.

Nitrogen Cycling

Insufficient quantities of either fixed nitrogen or phosphorus can be a limiting factor in the growth of marine phytoplankton. Therefore, these compounds are an important feature of overall biological productivity. Both the mineralization of these compounds from organic matter and the equilibria between atmospheric and combined nitrogen are greatly affected by microbial processes. Nitrogen recycling by microorganisms both in nearshore sediments and in marine waters plays a vital role in providing nutrients to the phytoplankton.

A study of 'whole phytoplankton debris' degradation by marine microorganisms has shown that as much as 30.8% of the carbon is mineralized and returned to the environment within three days (Newell, Lucas, and Linley 1981). Even the more recalcitrant carbon (64.4%) was mineralized by bacteria within 11 days. In studies of nitrogen mineralization in Saanich Inlet, British Columbia, Harrison (1978) found usable nitrogen turnover rates of between 3 and 16 days and observed that 'microplankton' were the primary nitrogen mineralizers. While conducting studies of ammonium regeneration rates in Nova Scotia, LaRoche (1983) found

that rapid mineralization in the water column could account for 36% of the ammonia needed for phytoplankton growth. Bacterial mineralization is also an important factor in kelp bed productivity (Newell, Field, and Griffiths 1982).

Although microbial mineralization of organic matter may be an important mechanism for sustaining phytoplankton productivity in the water column, it is becoming increasingly clear that mineralization by benthic microorganisms is not only important for benthic productivity, but is also a potentially important source of inorganic nutrients for the water column as well (Hattori 1982). Studies of nearshore environments indicate that most phytoplankton inorganic-nutrient requirements could be met by the nitrogen and phosphorus released from the sediments. While studying phosphorus mineralization in Narragansett Bay, Rhode Island, Nixon, Kelly, Furnas, Oviatt, and Hale (1980) found that the Bay released enough phosphorus to provide 50% of the phosphorus requirement for phytoplankton productivity. Fisher, Carlson, and Barber (1982) reported that between 28 and 35% of both the nitrogen and the phosphorus requirements for the primary productivity in three North Carolina estuaries came from mineralization in nearshore sediments. From their analysis of mid-American coastal waters, Sharp and Church (1981) concluded that one-third to two-thirds of all nitrogen required for primary productivity was mineralized from the sediments. Similar conclusions have also been reached by Davies (1975) in studies of a Scottish sea loch, and by investigators in earlier works summarized in a review by Zeitzschel (1980). The most vigorous mineralization rates probably occur at the sediment-water interface (Kemp, Wetzel, Boynton, D'Elia, and Stevenson 1982; Garber 1984).

When one considers nitrogen cycling as it relates to the mineralization process, one must also account for both the conversion of atmospheric nitrogen to combined nitrogen (nitrogen fixation) and the loss of combined nitrogen to atmospheric nitrogen (denitrification). Although these processes may be relatively insignificant relative to the total nitrogen flux in nearshore environments (Marsho, Burchard, and Fleming 1975), these processes can be locally important. While studying nitrogen fixation in a salt marsh, Teal, Valiela, and Berlo (1979) observed that nitrogen fixation could account for somewhat less than a third of the total nitrogen requirement for the local marsh grass. Capone, Penhale, Oremland, and Taylor (1979) and Zuberer and Silver (1978) reached the same conclusion in studies of two other marine systems.

At least two factors can greatly influence nitrogen fixation rates in marine sediments: 1) the presence of inorganic combined nitrogen tends to suppress the rates, and 2) the availability of readily degradable sugars tends to stimulate the rates. Two studies have reported the effect that combined nitrogen has on nitrogen fixation in salt marsh sediments. Hanson (1977) found that nitrate inhibited nitrogen fixation more than ammonium did, and that ammonium inhibited nitrogen fixation more than organic nitrogen. Dicker and Smith (1980) made similar observations, but they also found a seasonal component to the degree in which ammonium inhibited nitrogen fixation. It is generally agreed, however, that the primary limiting factor for nitro-

gen fixation in marine sediments is a readily oxidizable carbon source (Herbert 1975; Marsho *et al.* 1975; Hartwig and Stanley 1978; and Jones 1982).

Of perhaps greater ecological significance than nitrogen fixation is the process of denitrification. Whenever nitrate is present in microaerophilic marine environments, either in the water column or in sediments, it can be converted to N_2O or N_2 by microbial denitrification. Denitrification may be one of the major mechanisms for releasing inorganic nitrogen from sediments. Nishio, Koike, and Hattori (1982) reported that denitrification accounted for between 27 and 57% of nitrate consumption in three bays along the Japanese coast. In a study of denitrification in Narragansett Bay, Seitzinger, Nixon, and Pilson (1984) concluded that 35% of all mineralized nitrogen was removed from the sediments by this process.

At the present time, relatively little is known about the dynamics of nitrogen cycling in the Gulf of Alaska. Most of what is known comes from relatively few sources: a study of amino acid uptake and regeneration by phytoplankton communities in Southeast Alaska (Schell 1974), a study of nitrogen fixation and denitrification in Cook Inlet and Shelikof Strait (Haines, Atlas, Griffiths, and Morita 1981), and studies of glutamate metabolism, nitrogen fixation, and denitrification in Kachemak Bay (reported in this chapter).

If one assumes that relative microbial activity measurements using an amino acid as the test substrate reflect relative levels of nutrient mineralization, then one can make certain statements concerning relative mineralization rates in both the waters and the sediments of the Gulf of Alaska. As this and other reports show (Griffiths *et al.* 1978; Griffiths, McNamara, Steven, and Morita 1981; Griffiths, McNamara, Caldwell, and Morita 1981; Griffiths, Caldwell, and Morita 1982; Griffiths, Caldwell, Broich, and Morita 1982a; Griffiths *et al.* 1983; and Atlas and Griffiths 1984), glutamate mineralization rates both in Arctic and subarctic sediments and in Arctic and subarctic waters are comparable to those in other parts of the world. This is because the presence of a suitable substrate is more ecologically important than temperature. In other words, if a suitable substrate is present (*i.e.*, amino acids for mineralization, simple sugars for nitrogen fixation, and/or nitrate for denitrification), bacteria adjust to the colder conditions so that glutamate-mineralization dynamics end up being very similar to those found in warmer waters.

Using the report by Schell (1974) and observations by Griffiths, Caldwell, and Morita (1982), we can conclude that mineralization rates in the water column are closely tied to the phytoplankton bloom. In the waters of southeastern Alaska, Schell (1974) found that inorganic nitrogen sources were much more important to phytoplankton growth than dissolved organic nitrogen (DON). Therefore, we assume that mineralization by microheterotrophs is important to maintaining productivity during spring phytoplankton blooms. Any link between primary productivity and nutrient mineralization should result in cycles of increased dissolved inorganic nitrogen (DIN) and in surges of primary productivity following the initial intense spring bloom. This is essentially what Schell (1974) found in his study. There is now a large body of data (reviewed by Hattori 1982), which

indicates that the mineralization process carried out by microheterotrophs can be extremely important in maintaining primary productivity in the marine environment once the initial bloom has consumed most of the available inorganic nutrients.

In addition to the elevated mineralization rates associated with the phytoplankton bloom, Griffiths, McNamara, Steven, and Morita (1981) and Atlas *et al.* (1983) found elevated mineralization rates in major river plumes. Mineralization of terrestrial organic material by marine heterotrophs may contribute significantly to the high biological productivity associated with these plumes (Griffiths, Caldwell, and Morita 1984). Based on observations made in Cook Inlet, it is reasonable to assume that heterotrophic mineralization is an important feature of all major river plumes in the Gulf of Alaska.

In Gulf of Alaska sediments, important inorganic nutrients are recycled via mineralization at rates that depend on both the quality and quantity of the carbon coming into the system. As was the case for marine waters that were affected by major river plumes, elevated mineralization rates have been found in sediments that are affected by the same plumes (Atlas *et al.* 1983; Atlas and Griffiths 1984). The impact that carbon has on mineralization rates has been graphically illustrated in sediment samples from both the Beaufort Sea and Kachemak Bay. Large seasonal differences in mineralization rates were found in the Beaufort Sea study (Griffiths *et al.* 1978). It was hypothesized that the differences resulted from extreme seasonal differences in the amount of organic carbon being introduced from all sources.

Similar seasonal changes in mineralization rates were found in the mouth of Kachemak Bay (Table 8-8) where most of the new organic carbon probably comes from spring and summer phytoplankton blooms (Chester and Larrance 1981). In sediments where organic carbon supplies should be more constant, such as in Kasitsna Bay and at the head of Kachemak Bay, mineralization rates showed much greater seasonal consistency (Tables 8-6 and 8-8).

The nitrogen fixation and denitrification rates for sediments from Cook Inlet and Shelikof Strait and the rates for sediments from other Alaskan marine waters (Table 8-9) agree with those rates reported by other investigators working in other regions (Haines *et al.* 1981). In addition to these studies, both nitrogen fixation and denitrification have

Table 8-9.
Comparison of mean rates of nitrogen fixation and denitrification in sediments from different regions of the Alaskan continental shelf.

REGION	N_2 FIXATION (mg-at N_2 -N/m ² h)	DENITRIFICATION (mg-at N_2 -O-N/m ² h)
Upper Cook Inlet	0.3	0.1
Kamishak Bay	1.0	25.6
Shelikof Strait	2.4	2.1
Norton Sound	0.8	4.3
Elson Lagoon		
Winter	0.4	0.3
Spring	4.6	<0.1
Summer	2.1	<0.1

been measured for sediment from Kachemak Bay to determine seasonal and geographical patterns for this area.

Measurements of denitrification rates were conducted on Kachemak Bay sediments collected at various locations and at different times of the year. Using a standard acetylene block technique, N_2O production was rarely detected from nonamended sediments, even though the minimum sensitivity for this method is $0.002 \text{ ng } N_2/g \cdot h$. We are unclear as to why significant natural denitrification rates were not detected in these particular sediments, even though relatively high denitrification rates were found in sediments from across Cook Inlet in Kamishak Bay (Haines *et al.* 1981). It may be related to the availability of nitrate in these sediments. Very high denitrification rates were found when nitrate was added to the assayed sediments (Griffiths and Morita 1981). This indicates that Kachemak Bay sediments had the potential to denitrify, but that there was very little available nitrate present. Since the denitrification rates observed by Haines *et al.* (1981) were of the same magnitude as those reported by others, one must assume that the denitrification process works in Gulf of Alaska sediments in the same manner that it does in other marine system sediments.

As discussed earlier, there are reports indicating that nitrogen fixation provides significant combined nitrogen for salt marsh plants that grow in more temperate waters (Zuberer and Silver 1978; Capone *et al.* 1979; and Teal *et al.* 1979). McRoy, Goering, and Chaney (1973), however, found no nitrogen fixation associated with seagrasses taken from both Izembek Lagoon (Alaska Peninsula) and Prince William Sound and concluded that nitrogen fixation was an unimportant source of nitrogen for these grasses.

Nitrogen fixation levels in the sediments of Cook Inlet and Shelikof Strait suggest that rates for these sediments are comparable to those reported elsewhere. In addition, nitrogen fixation rates found in Kachemak Bay suggest that characteristics of the detrital carbon that comes into the system influence nitrogen fixation. No significantly consistent seasonal changes in nitrogen fixation rates were found for sediment collected near Kasitsna Bay (Table 8-7). This appears to be another indication that these sediments receive a relatively consistent input of detrital carbon throughout the year.

The lack of seasonal variability in the nitrogen fixation rates for Kasitsna Bay sediments contrasts sharply with the wide variation we found in the rates for sediments collected near the mouth of Kachemak Bay (Table 8-8). In the same study, we also found that nitrogen fixation rates increased as the distance from the head of Kachemak Bay increased (Table 8-8). It is possible that both the elevated seasonal variability and the gradients can be explained in terms of phytoplankton as a carbon source for the system. Phytoplankton represent a relatively high quality food source in the marine environment. This food source includes not only cytoplasm but starch granules that settle out of the water column (Bursa 1968). Carbon input from phytoplankton is seasonal in nature, which may explain the seasonal changes in the nitrogen fixation rates found in sediments taken from the mouth of the Bay. How distance from the head of the Bay affects nitrogen fixation could be

explained in terms of the relative food value of phytoplankton versus the food value of leaves and woody debris that are presumably the major components of the detrital carbon found in the sediments near the head of the Bay.

Microbial Activities and Pollutants in the Gulf of Alaska

Biodegradation of Petroleum Hydrocarbons

Oil and gas development within the Gulf of Alaska, coupled with petroleum transportation from Valdez, acts to raise the chances that petroleum pollutants will be accidentally introduced into the Gulf. After petroleum pollutants are introduced into marine environments, they are subject to microbial biodegradation. The rate of that biodegradation is influenced by a number of factors, including the abundance of hydrocarbon-degrading microorganisms, the composition of the oil, and the environment (temperature, dissolved oxygen levels, and nutrient concentrations) (Karrick 1977; Atlas 1981, 1984c).

Although there have been no major oil spills in the Gulf of Alaska, the wreck of the ship *Irish Stardust* in 1973 spilled ~180 mt of heavy fuel oil into a British Columbia embayment. Cretney, Wong, Green, and Bawden (1978) reported that biodegradation accounted for almost complete removal of *n*-alkanes in this oil during the first year after the spill, and although pristane and phytane were biodegraded more slowly, they were almost completely gone after 4 years. The non-*n*-alkane components of the C_{28} to C_{30} range appeared to be the most resistant to degradation of all the components of the fuel oil.

Roubal and Atlas (1978) reported that hydrocarbon utilizers were ubiquitously distributed, with no significant concentration differences between Arctic and subarctic sampling regions nor between surface water and sediment samples. Counts of hydrocarbon degraders for various regions of Alaska are listed in Table 8-1 (Atlas 1982). Robertson, Arhelger, Law, and Button (1973) and Robertson, Arhelger, Kinney, and Button (1973) reported 1/ml concentrations of hydrocarbon degraders in Cook Inlet and Port Valdez. The distribution of hydrocarbon utilizers within Cook Inlet was positively correlated with the occurrence of hydrocarbons in the environment (Roubal and Atlas 1978). Areas of hydrocarbon accumulation within Cook Inlet and surrounding waters had elevated abundances of hydrocarbon-degrading microorganisms (Atlas *et al.* 1983). These findings are in agreement with studies indicating that the distribution of hydrocarbon-utilizing microorganisms reflects the environment's historical exposure to hydrocarbons (Atlas 1981; Floodgate 1984; and Vestal, Cooney, Crow, and Berger 1984).

Roubal and Atlas (1979) reported that water samples from Cook Inlet showed low potential for natural biodegradation in both spring and fall. Cook Inlet sediment showed somewhat higher natural biodegradation potentials in summer-through-fall samples than in winter-through-spring samples. Biodegradation potentials followed the order: naphthalene > hexadecane > pristane \geq benzanthracene,

and natural biodegradation potentials for pristane and benzanthracene were often zero. Kinney, Button, and Schell (1969) reported that hydrocarbons within Cook Inlet biodegrade rapidly and that concentrations of nitrogen and phosphorus nutrients do not limit the rate of microbial hydrocarbon degradation in this region.

Arhelger, Robertson, and Button (1977) compared Arctic and subarctic hydrocarbon biodegradation and found that dodecane oxidation rates were: Port Valdez, 0.7 g/d; Chukchi Sea, 0.5 g/d; and Arctic Ocean, 0.001 g/d. This study indicates that hydrocarbon degradation rates show a definite climatic shift and are higher in the Gulf of Alaska region than in the Arctic Ocean. Button, Robertson, and Craig (1981) found that toluene oxidation rates in the Port Valdez estuary were in the range of 1 to 30 pg/l. Near the ballast-water injection site of the trans-Alaska pipeline's loading facility, the bacterial biomass was elevated by a factor of 10; the origin of bacteria in this layer was traced to growth in oil-tanker ballast water during shipments.

Effects of Hydrocarbons on Microbial Activities

Currently available information indicates that the long-term impact that petroleum hydrocarbons have on microbial activity in marine sediments is greater than the impact in marine waters. The extent of that impact may also vary with the latitude at which the impact occurs.

An early study (Hodson, Azan, and Lee 1977) reported on the effects that petroleum hydrocarbons have on the uptake of organic substrates by microplankton. As a part of the Controlled Ecosystem Pollution Experiments (CEPEX) program, these investigators examined the effects that Kuwait and Louisiana crude oil, No. 2 fuel oil, and Bunker C oil had on the assimilation and mineralization of glucose by microbial populations from Saanich Inlet, British Columbia, Canada. They demonstrated that all types of oil inhibited glucose use, although refined petroleum products inhibited glucose use significantly more than either of the crude oils. Glucose uptake and mineralization both appeared to be inhibited to a similar extent by No. 2 fuel oil.

Griffiths, McNamara, Caldwell, and Morita (1981) collected over 200 water samples from both Arctic and subarctic regions. Most of the subarctic samples were collected in Cook Inlet. In samples that were exposed to crude oil, glucose uptake rates were reduced 37 to 50% when compared with a control group of samples that were not exposed to oil. When glutamate was used as the test substrate, the mean reduction was 33 percent. For these studies, incubation times were less than 12 hours and, therefore, there was little time for hydrocarbon utilizer populations to multiply. In the same paper, Griffiths, McNamara, Caldwell, and Morita (1981) followed the response of natural microbial populations to crude oil over extended exposure (up to 10 days). These studies demonstrated that after an initial period when the substrate uptake was inhibited, uptake rates increased in the treated samples until their rates greatly exceeded the rates observed in the non-oiled controls. This adjustment to the presence of petroleum hydrocarbons was also observed indirectly during the same study; samples that came from areas near natural oil seeps or in

shipping lanes were less affected by crude oil than samples collected in areas that were not previously exposed to petroleum hydrocarbons. It was therefore concluded that the adverse effects that crude oil has on microbial heterotrophic activity (substrate uptake rates) are short lived and those effects would have relatively little impact in overall biological activity under most circumstances.

Although the initial impact of crude oil on benthic microbial activity was found to be somewhat less than its impact on water samples (between 14 and 36% reduction in diluted sediment samples versus reductions between 37 and 85% in water samples), the long-term effects were of much greater importance (Griffiths, McNamara, Caldwell, and Morita 1981; Griffiths, Caldwell, Broich, and Morita 1981, 1982a, 1982b). This conclusion is based on an extensive study of crude-oil effects on microbial activities and of other variables in Kachemak Bay sediments. During the study, investigators mixed either fresh or weathered crude oil into natural sediments collected at the study sites. The sediments were loaded into plastic trays which were then placed on the bottom by SCUBA divers. Subsamples from these trays were collected for up to 18 months to assess the impact of the petroleum hydrocarbons. A large number of microbial functions were affected by both the fresh and the weathered crude oils for periods of up to 18 months. The oils were at concentrations which have been reported in marine sediments collected at spill sites (from 0.1–50‰). The microbiologically mediated transformations found to be affected are summarized in Figure 8–3. As the figure shows, crude oil interfered with portions of all major geochemical processes.

The changes have several possible explanations. They may have been caused directly by toxicity of oil components or degradation products or indirectly by secondary factors such as reduced oxygen availability. When investigators interpreted the microbiological data in terms of what they

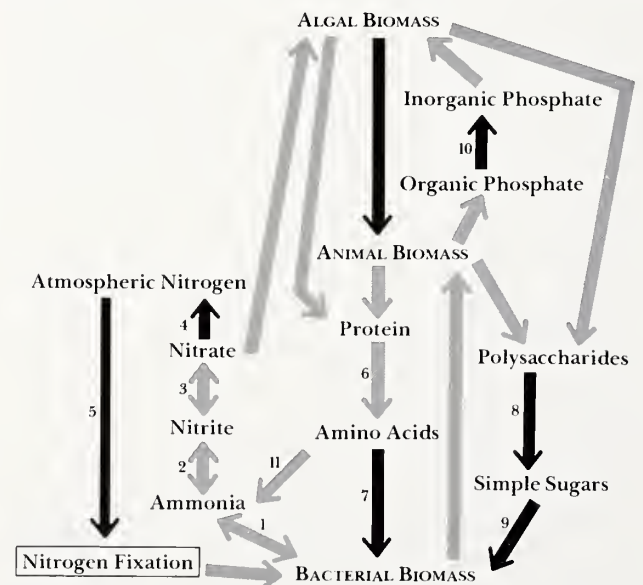


Figure 8–3. Diagram of nutrient cycling in the marine environment. Transformations marked with black arrows are adversely affected by crude oil. Transformations labeled with numbers are primarily mediated by bacteria.

learned about the hydrocarbon chemistry of these sediments, they concluded that the benthic microbial communities had the capacity to use the crude oil and return the sediment to its approximate original condition if the crude oil component was less than 1‰ (Griffiths and Morita 1981). Hydrocarbon chemistry in both the treated samples and the non-treated controls looked essentially the same after 18 months—even in the sediments that had been treated with 0.1‰ crude oil—yet the redox potential was still 89% lower in the treated sediments than in the control. All other variables appeared normal, however.

It was abundantly clear from data by Griffiths and Morita (1981) that the self-cleansing capacity was severely impaired in sediments which were treated with 50‰ crude oil. After 18 months, hydrocarbon chemical analyses strongly indicated that little biodegradation had taken place in the sediments. The temporal trends in the microbiological studies suggested that it would take between 6 and 8 years to re-establish normal function.

There is little information presently available for comparing the effects that Griffiths and his associates observed in Kachemak Bay with effects of crude oil on marine sediments taken from temperate waters. A study of hydrocarbon effects in a wide variety of locations led Pfaender and Buckley (1984) to conclude that petroleum hydrocarbons have a greater impact on Arctic and subarctic environments than they have on tropical and temperate environments. Griffiths, Caldwell, Broich, and Morita (1981) compared the effects of crude oil on Kachemak Bay sediments with the effects on sediment collected near Point Barrow, Alaska (well above the Arctic Circle). The comparison showed distinct differences in the time required for microbial changes to take place after exposure to crude oil. In the Kachemak Bay sediments, large reductions in glucose and glutamate uptake rates were found within the first 6 weeks of exposure. In the Arctic sediment samples, no reduction was found for over a year after sediments had been exposed. Even after exposure for 2 1/2 years, glucose and glutamate uptake rates were still greatly reduced. This study showed that the effects of crude oil on the benthic microflora were similar in both Arctic and subarctic sediments, but the time it took for the changes to become manifest was much different. If most of the adverse effects of crude oil contamination result from biological activity (*i.e.*, the production of toxic metabolic byproducts and oxygen depletion), it is possible that both the timing and the duration of the effect may be related to hydrocarbon biodegradation rates. There may also be a direct correlation between the mean environmental temperature and hydrocarbon degradation rates as suggested by Pfaender and Buckley (1984).

Conclusions

Investigators are using modern methods to formulate the beginnings of a quantitative understanding of the role microorganisms play in marine systems. Microbiological studies of the Gulf of Alaska show that microorganisms are critical in establishing and regulating ecosystem dynamics. By studying factors such as the microbial community struc-

ture as well as both the physiological and nutritional properties of microbial populations, investigators have discovered the versatility of the indigenous microorganisms, along with the adaptive properties that have evolved within communities in response to environmental factors in various parts of the Gulf. These studies have also revealed the close link between microorganisms and other biota in the Gulf.

Rate measurements of microbial metabolic activities indicate that microbially based detrital food webs are essential for supporting the productivity of higher organisms. This productivity is closely tied to a number of factors, including:

- relationships between bacterial and phytoplankton populations
- microbial nutrient-cycling activities
- microbial biomass production.

New marine study methods should lead to a better understanding of the factors controlling productivity in the Gulf. These methods should also produce a more precise comprehension of the overall functioning of the ecosystems in the Gulf including the microbially mediated pathways and the rates of transfer involved in interpopulation dynamics. Developing such a fundamental understanding will let us do a better job of predicting the impact of human activity on Gulf productivity as well as on the general functioning of the Gulf ecosystem.

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ABSTRACT

Changes in both the amount of daily light and in the depth of mixing initiate a predictable, positive response in phytoplankton productivity throughout the subarctic Gulf of Alaska during the spring. In the oceanic regions, however, this productivity increase is not accompanied by a commensurate increase in the phytoplankton standing crop. Chlorophyll *a* levels in this region usually do not exceed 1 mg/m^3 , diatom cells are not especially numerous, and the phytoplankton community is numerically dominated by microflagellates. The discrepancy between increased productivity and the size of the standing crop is generally attributed to the rapid rate with which phytoplankton cells are removed from the surface water by endemic North Pacific macrozooplankton.

Recent measurements suggest that in addition to the macrozooplankton's influence, grazing by microzooplankton coupled with the number of phytoplankton cells that sink are also important loss factors. Seasonal ^{14}C productivity measurements at Ocean Station 'P' (50°N , 145°W) vary from winter values that are generally less than $50 \text{ mg C/m}^2\text{d}$ to summer values that range between 200 and $400 \text{ mg C/m}^2\text{d}$ and suggest annual productivity of $\sim 50 \text{ g C/m}^2$. However, a mass balance of phytoplankton nutrient consumption indicates that the yearly production may actually exceed 100 g C/m^2 for the Central Subarctic Domain.

The Gulf of Alaska shelf is extremely productive and in the areas near Adak Island, lower Cook Inlet, and the Kenai shelf, annual production is $\sim 300 \text{ g C/m}^2$. Production in these areas may be associated with upwelling that is induced by both coastal and near-shelf water movements. Such productivity suggests that previous estimates of the Gulf's productivity may need to be adjusted upward.

Coastal areas are environmentally heterogeneous, and measurements suggest that the annual production in the various embayments ranges from 140 to over 200 g C/m^2 . Large standing crops of phytoplankton build up near the shore. Dense chlorophyll *a* concentrations usually appear briefly in surface waters, although subsurface chlorophyll *a* layers may persist throughout the summer.

Introduction

For the purpose of our discussion, we have separated the oceanic regions from both the coastal and the shelf waters in the Gulf at the shelf break (roughly the 200-m isobath in Fig. 9-1). The coastal area stretches from the Queen Charlotte Islands in the east to 176°W in the Aleutian Islands.

The earliest comprehensive coastal studies began both in Cook Inlet (Hood, Natarajan, Rosenberg, and Wallen 1968) and in Prince William Sound (Goering, Shiels, and Patton 1973). However, the Alexander Archipelago of the southeast Gulf, Yakutat Bay, Kodiak Island, and the large estuary formed by the Copper River are also an important part of the extremely long and physiographically diverse coast.

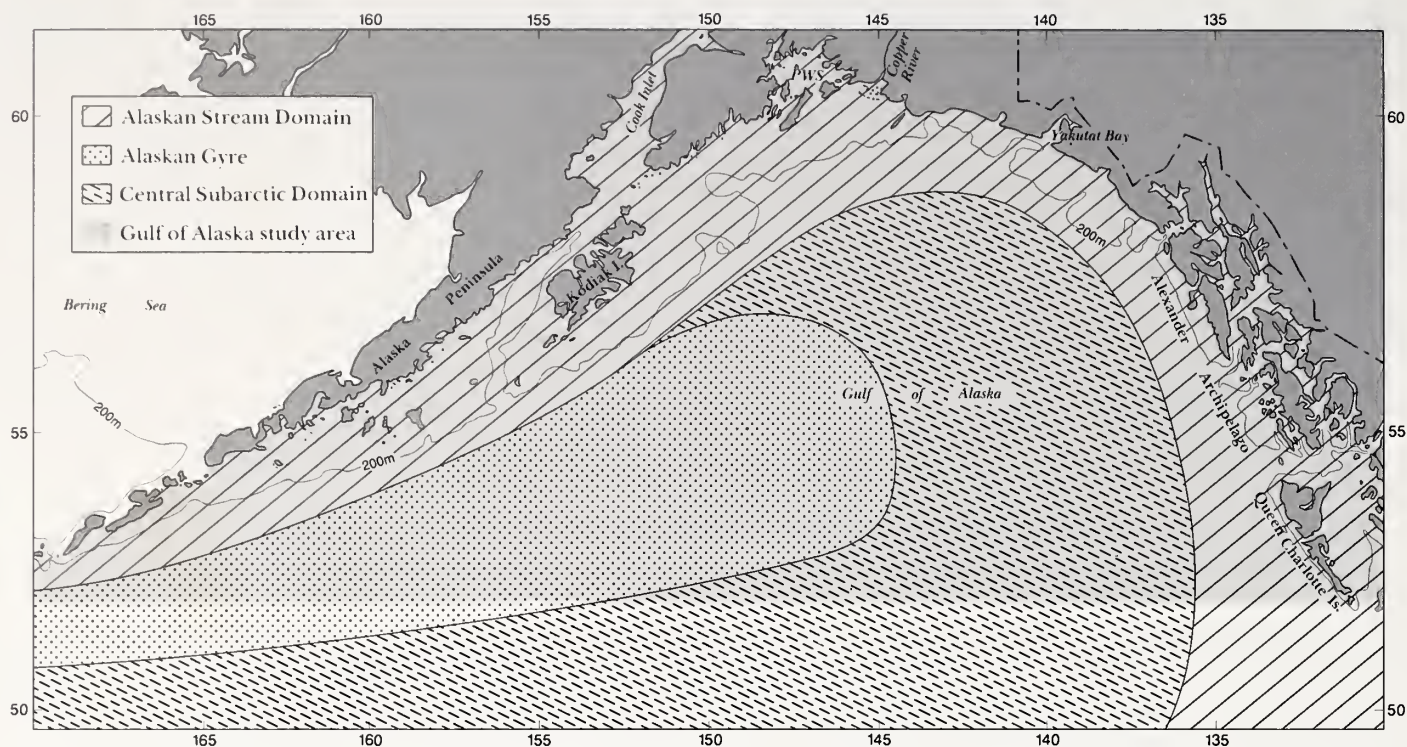


Figure 9-1. Overview of the Gulf of Alaska that indicates the 200-m isobath and selected coastal features. Superimposed on the figure are surface-water domains delineated by Dodimead *et al.* (1963) on the basis of measurements of temperature, salinity, and oxygen.

This means that phytoplankton studies done in the coastal areas of the Gulf have generally been more scattered than those conducted in the oceanic area.

The width of the Gulf's continental shelf varies greatly—from less than 15 km off Southeast Alaska to over 100 km south of Cook Inlet and on the Kodiak and Aleutian shelves (Fig. 9-1). Historically, phytoplankton and primary production on the Gulf's continental shelf have received little attention. However, information on the phytoplankton of the central Gulf shelf was significantly expanded during the United States Department of the Interior's Outer Continental Shelf Environmental Assessment Program (OCSEAP) (Larrance, Tennant, Chester, and Ruffio 1977).

Limited measurements for phytoplankton occurrence and growth in the oceanic region of the Gulf began in the late 1950s (McAllister, Parsons, and Strickland 1960; Holmes 1958). North American workers collected more extensive data in this area during the subsequent two decades (Anderson, Parsons, and Stevens 1969; Parsons and LeBrasseur 1967; Parsons and Anderson 1970; and Larrance 1971 a, b).

The work by the North Americans has been supplemented not only by a substantial body of information collected during Japanese cruises (Faculty of Fisheries, Hokkaido University 1960-1983; Takahashi, Satake, and Nakamoto 1972) but also from ships that traversed the area during Pacific crossings (Anderson and Munson 1972). In addition to information from these sources, we have also included data from the Canadian Ocean Weather Station P (50°N, 145°W) in our discussion. Although it is south of the current Gulf of Alaska definitional boundary (52°N), Station P has been the site of many process-oriented produc-

tion studies relevant to the oceanic Gulf area. Therefore, these results are included in our discussion.

Generally, phytoplankton studies in the Gulf of Alaska focus on the analyses of two major processes: 1) the productivity of commercially important food chains (OCSEAP Staff, Ch. 14, this volume) and, increasingly, 2) the association of phytoplankton growth with the vertical flux of material from the ocean's surface layers (Eppley and Peterson 1979). Each of these two processes ultimately depends on both the physical and the biological influences that govern phytoplankton growth in a particular area. Generally, these influences include several semi-independent factors such as the interaction of light and mixing processes (Sverdrup 1953), nutrient limitation (Dugdale 1967), and herbivore grazing (Steele and Frost 1977).

In the Gulf of Alaska, situations have been found in which each one of these influences dominates the local phytoplankton growth. In our review of the literature concerning phytoplankton and phytoplankton growth, we have presented the material in the context of these environmental influences whenever possible.

Methods

Phytoplankton identification and cell counts for the Gulf have usually been made using samples of preserved seawater. A set volume (typically 50 or 100 ml) of seawater was often collected and then preserved with Lugol's solution (Rodhe, Vollenweider, and Nauwerick 1958). While this preservation technique works well for diatoms, the acetic acid component of the preservative may destroy calcareous

material such as coccolithophorids (Hobro and Willén 1977). Conversely, preservation using a formalin solution damages naked flagellates (Hasle 1959). The most reliable analysis of delicate small phytoplankton forms (<20- μ m cells) in the Gulf employed glutaraldehyde as a preservative and avoided the mechanical damage caused by direct filtration (Booth, Lewin, and Norris 1982). However, even with these refined techniques, some loss of the naked cell forms takes place. This means that both the preservation and the sample-handling techniques that are used to identify and enumerate phytoplankton have a direct effect on the results.

In most studies, the cell counts were usually done using the inverted microscope method developed by Utermöhl (1931). Diatom identification in most studies was based on Cupp (1943). The use of scanning electron microscopes (SEM) on phytoplankton samples allowed researchers to identify species based on previously ignored features (Booth *et al.* 1982). Humm and Wicks (1980) has been used as a guide to the bluegreen algae. Cell measurements and geometric formulae were used to estimate plasma volumes (Larrance 1964) from which cell carbon could be estimated for individual species (Strathmann 1967).

Most primary production measurements have involved modification of the ^{14}C -uptake tracer method developed by Steemann Nielsen (1952). Typically, water from several depths throughout the euphotic zone (the depth at which 99% of the available sunlight is absorbed) was first collected and then incubated with ^{14}C -labeled sodium bicarbonate (*e.g.*, Parsons and Anderson 1970). Although some incubations took place under artificial light (Faculty of Fisheries, Hokkaido University 1960), most carbon productivity estimates were based upon on-deck simulations of *in situ* light conditions. In addition to the interpretive problems posed by the ^{14}C technique itself (Peterson 1980), incubation periods varied according to who conducted the tests. Therefore, estimates for daily primary production were often extrapolated from shorter incubation periods and were based on the relative amount of daylight received.

Two studies conducted in the Gulf have used ^{15}N as a tracer for phytoplankton nitrogen uptake (Goering, Shiels, and Patton 1973; Hattori and Wada 1972). The ^{15}N tracer technique is an alternative to the carbon method for measuring marine production. In addition, it has the added capability of distinguishing between 'new' production (fueled by nitrate uptake) and regenerated production (fueled largely by ammonium uptake) (Dugdale and Goering 1967). Phytoplankton production in the Gulf can also be estimated from a mass balance of the dissolved inorganic nutrients. This method can be used as an alternative to tracer methods or can be used to cross-check results. As phytoplankton grow, they consume carbon, nitrogen, and phosphorus in predictable proportions (Redfield, Ketchum, and Richards 1963). In theory, therefore, carbon production can be estimated from the measured consumption of carbon, nitrogen, or phosphorus.

Seawater nitrate is a phytoplankton nitrogen source that has been extensively measured in the ocean (Reeburgh and Kipphut, Ch. 4, this volume), and which can be used as a basis for estimating carbon production. The methodology involved is strictly chemical in nature. (Details on the spe-

cific methods used are found in Parsons, Maita, and Lalli [1984].) Both the amount of total carbon dioxide and the partial pressure of surface-water carbon dioxide are sensitive indicators of phytoplankton photosynthesis (Kelley, Longrich, and Hood 1971; Hood and Codispoti 1984).

The most widely used index of phytoplankton biomass in the Gulf—as in other marine areas—has been the measurement of the photosynthetic pigment chlorophyll *a*. Typically, this involves the extraction of the pigment into an organic solvent and its detection either by spectrophotometry (*e.g.*, Anderson 1969) or by fluorometry (Yentsch and Menzel 1963). A similar technique has been used to measure chlorophyll degradation products found in seawater. These products are formed mainly as a result of the activities of herbivorous grazers (Shuman and Lorenzen 1975). The particulate material from this activity falls through the water column and can be captured in sediment traps suspended at depth. These sediment traps have been used to measure particulate flux in the Gulf of Alaska (Larrance, Chester, and Milburn 1979).

The amount of phytoplankton removed from surface waters has been estimated by a combination of these various methods. Using a pigment budget, phytoplankton losses can be partitioned among three causes: 1) microzooplankton grazing (suspended degradation products), 2) macrozooplankton grazing (degradation products from sediment traps), and 3) phytoplankton sinking (chlorophyll *a* losses). The methodology is introduced here because we will present some preliminary results from Station P that are based on this technique. A more complete description of the methodologies and rationales used in this approach can be found in Welschmeyer and Lorenzen (1985).

Other measurements that are important to phytoplankton studies in the Gulf are surface-water mixing and light measurements. Most often, the amount of surface-water mixing has been determined by the depth of the mixed layer (the depth to the top of the major thermocline) (Giovondo and Robinson 1965). Incident solar radiation was often measured with a shipboard pyranometer, while an underwater quanta sensor was used in some cases to measure the extinction coefficient of light in the surface water. In most cases, however, a Secchi disk was used to estimate light extinction coefficients. An approximate conversion between the Secchi disk depth (Z_m) and the extinction coefficient (k_c) can be obtained from the following relationship (Walker 1980):

$$k_c = 1.45/Z_m \quad (1)$$

Oceanic Gulf of Alaska

We will first consider studies that have been done in oceanic areas. Table 9-1 lists the background data as reviewed by Anderson, Lam, Booth, and Glass (1977), together with more recent cruise listings for the oceanic Gulf.

Broad geographic divisions of the subarctic Pacific domain were defined by Dodimead, Favorite, and Hirano (1963) (Fig. 9-1). The three areas indicated in Figure 9-1 are not water masses *per se*, but reflect the prevailing circulation

Table 9-1.

Background biologic and oceanographic data collected in the oceanic Gulf of Alaska. The list is taken largely from Anderson *et al.* (1977) and has been modified and updated.

OPERATION	PERIOD	ZONES ^a	DATA TYPE ^b	SOURCE
Weather Station P				
Cruises 593 to 614	1959 to 1961	33	1,3,6,9	McAllister 1962
Cruises 615 to 634	1961 to 1963	33	1,3,6,9	Stephens 1964
Cruises 635 to 655	1964 to 1966	33	1,3,6,7,9	Stephens 1966
Cruises 661 to 674	1966 to 1967	33	1,3,6,7,9	Stephens 1968
Cruises 681 to 706	1968 to 1970	33	1,3,6,7,9	Stephens 1970
Ships of Opportunity				
Cruises 02 to 43	1968 to 1972	15,19, 22-32,34, 36	1,3,5,7,8,9	G.C. Anderson, University of Washington, unpubl. data
1958				
<i>H.M. Smith</i> 46	August-September	24,25,29, 30,31	1,3,6	McGary and Graham 1960
<i>Vityaz</i> 29	October-December	19-21,24, 27,29,30, 35	3,7,9	Koblentz-Mishke 1969
1959				
<i>Oshoro Maru</i> 44	June	22,25,29	6	Faculty of Fisheries, Hokkaido University 1960
<i>Brown Bear</i> 235	July-August	15,19,23, 24,27,28, 34,36	1,6	Stephens 1964
1960				
<i>Oshoro Maru</i> 46	June-August	18,19,22- 24,29-31, 35	5,6	Faculty of Fisheries, Hokkaido University 1961; Motoda and Kawamura 1963
1961				
<i>Oshawa</i> 1961	June	19,33,36	1,6,7	Antia <i>et al.</i> 1962
<i>Pioneer</i> 66	September-October	22,23,26, 29,30	1,3	Doty 1964
1964				
<i>G.B. Reed</i> 164	January-February	19,21,24, 27,28,31- 36	1	Stephens 1964
<i>Agassiz Ursa Major</i>	August-September	16,24,27,31	1,5,6	University of California 1967; Venrick 1971
1966				
<i>Argo Zetes</i> 1	January	16,24,27,31	1,2,5,6,7	University of California 1970; Venrick 1969
<i>Kelez</i> 166	March	22,25,29	1,3,8,9	Larrance 1971b
<i>Paragon</i> 266	June	22,25,29	1,3,8,9	Larrance 1971b
<i>Kelez</i> 366	September	20,22,29-31	1,3,7,8,9	Larrance 1971b
1967				
<i>Kelez</i> 167	January-February	23,26,30	1,3,7,8,9	Larrance 1971b
<i>T.G. Thompson</i> 12	February-March	17-19,24, 27,28,34-36	1,3,6,7	G.C. Anderson, University of Washington, unpubl. data
<i>Kelez</i> 367	April	19,36	1,8	Larrance 1971b
<i>Kelez</i> 667	July	22	1,3,7,8,9	Larrance 1971b
<i>Kelez</i> 767	August	22,25,29	1,3,7,8,9	Larrance 1971b
1968				
<i>Kelez</i> 268	May	23,26,30	1,8	Larrance 1971b
<i>Oshoro Maru</i> 28	June-July	17,18,22	6	Faculty of Fisheries, Hokkaido University 1969
1969				
<i>Endeavour</i> (trans-Pacific)	March-April	20,29-31	1,3,7,8,9	Anon. 1970
<i>Vityaz</i> 45	May-June	17,18,23,35	1,3	Anon. 1973
<i>Hakuho Maru</i> 694	August	31	1,5	Takahashi <i>et al.</i> 1972; T. Asaoka, University of Tokyo, unpubl. data
1970				
<i>Hakuho Maru</i> 702	May	19,34	6,7	Horibe 1971
<i>Oshoro Maru</i> 37	June-July	16,17,18, 22-24,27, 31,33,34	1,6	Faculty of Fisheries, Hokkaido University 1972

OPERATION	PERIOD	ZONES ^a	DATA TYPE ^b	SOURCE
1971 <i>T.G. Thompson 59</i>	May-June	22,23,25, 26,27	1,6,7	G.C. Anderson, University of Washington, unpubl. data
1972 <i>T.G. Thompson 72</i>	September	24,27,31	1,2,3,6,7,9	G.C. Anderson, University of Washington, unpubl. data
1973 <i>T.G. Thompson 82</i>	August	33	1,2,3,6,7,9	G.C. Anderson, University of Washington, unpubl. data
1974 <i>Hakuho Maru 742</i> <i>T.G. Thompson 91</i>	May July	29 36	1,6,7 1,2	Kuroki 1975 G.C. Anderson, University of Washington, unpubl. data
1975 <i>Discoverer</i> (OCSEAP- RP4-D1-75C Leg 1)	October	17	1,2,3,5,7,9	Larrance <i>et al.</i> 1977
1976 <i>Discoverer</i> (OCSEAP- RP4-D1-76A Leg III)	April	16,17	1,2,3,5,7,9	Larrance <i>et al.</i> 1977
<i>Discoverer</i> (OCSEAP- RP4-D1-76A Leg V&VI)	May	16,17	1,2,3,5,7,9	Larrance <i>et al.</i> 1977
<i>Acona</i> (OCSEAP- RP4-AC-76 Leg 11)	July	16,17	1,2,3,5,7,9	Larrance <i>et al.</i> 1977
<i>Surveyor</i> (OCSEAP- RP4-SU-76B Leg 11)	August	16,17	1,2,3,5,7,9	Larrance <i>et al.</i> 1977
1978	July-August	18,28,35	5	Booth <i>et al.</i> 1982
1980 <i>Oshoro Maru 80</i>	July	33,34,35	6,7	Faculty of Fisheries, Hokkaido University 1981
1981 <i>Oshoro Maru 85</i>	July	33,34,35	4,6,7	Faculty of Fisheries, Hokkaido University 1982; J.J. Goering, University of Alaska, unpubl. data
1982 <i>Oshoro Maru 90</i>	July	27,28,35	1,2,4,6,7,9	Faculty of Fisheries, Hokkaido University 1983; R.A. Sambrotto and J.J. Goering, University of Alaska, unpubl. data
<i>Wecoma</i>	July-August	33	1,2,3,8,9	Lorenzen 1984a, b, unpubl. data

^a The zones correspond to the geographic areas labeled in Figure 9-9.

^b Data type codes indicate the following parameters were measured: 1 = chlorophyll *a*, 2 = phaeopigments, 3 = primary productivity (carbon), 4 = primary productivity (nitrogen), 5 = phytoplankton species, 6 = oxygen, 7 = nitrate, 8 = mixed-layer depth, 9 = total incident radiation.

and weather patterns in the Gulf. For example, the Central Subarctic Domain is largely the path of the Subarctic Current as it turns north to form the Alaska Current. Although the Alaska Current is not properly called the Alaskan Stream until west of Kodiak Island (Reed and Schumacher, Ch. 3, this volume), the entire near-shelf circulation in Figure 9-1 is labeled Alaskan Stream Domain.

Precipitation exceeds evaporation in the Gulf of Alaska, and this maintains the surface salinity at less than 34 parts per thousand. This relatively fresh water results in a permanent halocline at ~100 to 120 m that limits winter convective circulation to relatively shallow depths, compared with the winter mixing depths in the North Atlantic.

Relevance of Ocean Station P Data

Available oceanographic data from the Gulf of Alaska are not evenly distributed, and by far the greatest number of measurements have been taken at Station P (Anderson *et al.* 1977). These measurements form the most reliable time series to use when addressing the seasonal variation and associated environmental influences on oceanic phytoplankton near the Gulf. Like the rest of the Gulf, Station P is north of the subarctic boundary and, consistent with the domains specified by Dodimead *et al.* (1963) (Fig. 9-1), is also under the influence of the North Pacific Current. This means that at Station P properties are probably representative of those found farther north as this flow continues in

the form of the Central Subarctic Domain. Therefore, the results of phytoplankton studies at Station P are generally relevant to large areas of the eastern oceanic Gulf of Alaska.

Another factor that suggests a relative homogeneity for phytoplankton growth in the Gulf is the siliceous ooze that dominates the sediments of the entire area (Lisitzin 1971). The diatom composition in the surface sediments coincides closely with the composition in the overlying water masses, and the sediments reflect the boundary between subarctic and transitional water (Kanaya and Koizumi 1966). Local diatom growth is ultimately responsible for the sediment patterns, although the biological factors that are involved are poorly known. For example, it is not clear how differences in the composition of local phytoplankton communities, differences in growth rates, and the various vertical-transport mechanisms such as the grazing and sinking bring about such sediment patterns. Although a quantitative answer to this question for the Gulf is not possible, the question serves as a useful framework for our discussion of oceanic phytoplankton.

Seasonal Pattern of Phytoplankton Growth at Ocean Station P

Anderson *et al.* (1977) compiled measurements from Station P that summarized the average seasonal changes in chlorophyll *a* (Fig. 9-2) and nitrate (Fig. 9-3) based on data collected from 1959 through 1970. The average chlorophyll *a* data (Fig. 9-2) indicate that the phytoplankton standing crop at Station P typically increases from winter values of $\sim 0.2 \mu\text{g/l}$ to maximum summer values of less than $0.5 \mu\text{g/l}$. From March to September, nitrate concentrations in surface waters decrease steadily from over $15 \mu\text{M/l}$ to less than $7 \mu\text{M/l}$, reflecting the seasonally changing supply and consumption of this important phytoplankton nutrient.

Nitrate is brought to the surface as a result of the vertical mixing of the deeper, nutrient-rich water throughout the

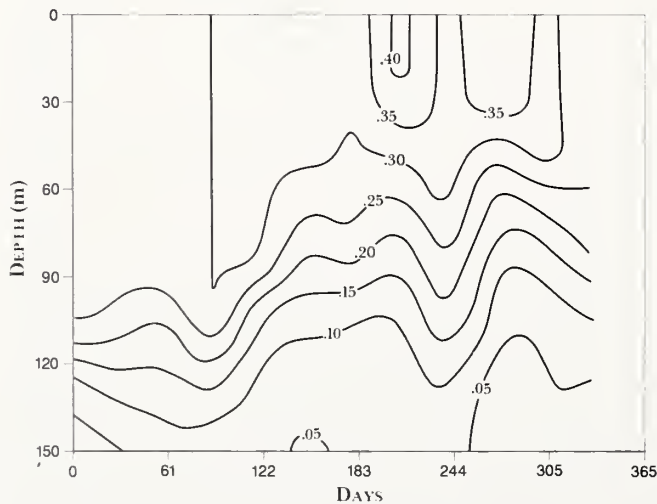


Figure 9-2. Average changes in chlorophyll *a* concentration (mg/m^3) according to both time and depth at Station P (50°N , 145°W). This is a composite from several sources. (Modified from Anderson *et al.* 1977.)

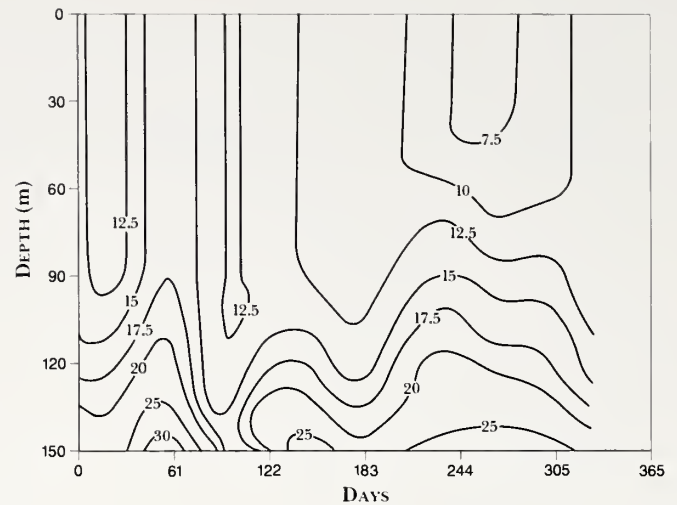


Figure 9-3. Average changes in nitrate concentration ($\mu\text{M/l}$) according to both time and depth at Station P. This is a composite from several sources. (Modified from Anderson *et al.* 1977.)

year. The mixing rate is greater during winter when vertical mixing is at its most vigorous. Conversely, the consumption of nitrate during phytoplankton growth is greatest in the summer months. These two processes result in the observed winter nitrate maximum and summer minimum in surface waters at Station P.

Although nitrate levels are reduced in the summer, the average concentrations are still larger than the minimum levels that are required for phytoplankton growth ($> 1 \mu\text{M/l}$) (Dugdale 1967; Hattori and Wada 1972). Other plant nutrients such as phosphorus (in the form of phosphate) are also plentiful during the summer, and therefore a lack of nutrients does not appear to be the factor that prevents greater amounts of plant biomass from accumulating in surface waters.

The seasonally consistent level of the phytoplankton standing crop at Station P is very similar to the uniformly low levels found in the high latitude southern ocean (El Sayed 1978). However, the relatively small vernal phytoplankton increase in the Gulf is very different from the situation found at comparable latitudes in the North Atlantic, where a much more dramatic increase in phytoplankton occurs during spring. Also, no pronounced subsurface chlorophyll *a* layers are found in the North Atlantic. Such layers appear to be a common feature in lower latitude waters of the North Pacific (Anderson 1969).

The consistency in the Station P phytoplankton biomass is striking, but not absolute. A weak seasonal signal in chlorophyll *a* can be observed at Station P (Fig. 9-2). Also, Anderson *et al.* (1977) presented the averaged chlorophyll *a* data for individual seasons (Fig. 9-4) and showed that in certain periods (*e.g.*, the summers of 1964 and 1965) greater than mean chlorophyll *a* levels were present. Also, the standard deviations of the means appear to increase with the sample size. This suggests that the actual chlorophyll *a* levels are not normally distributed around a constant value and that the mean values actually mask episodic departures from typical conditions.

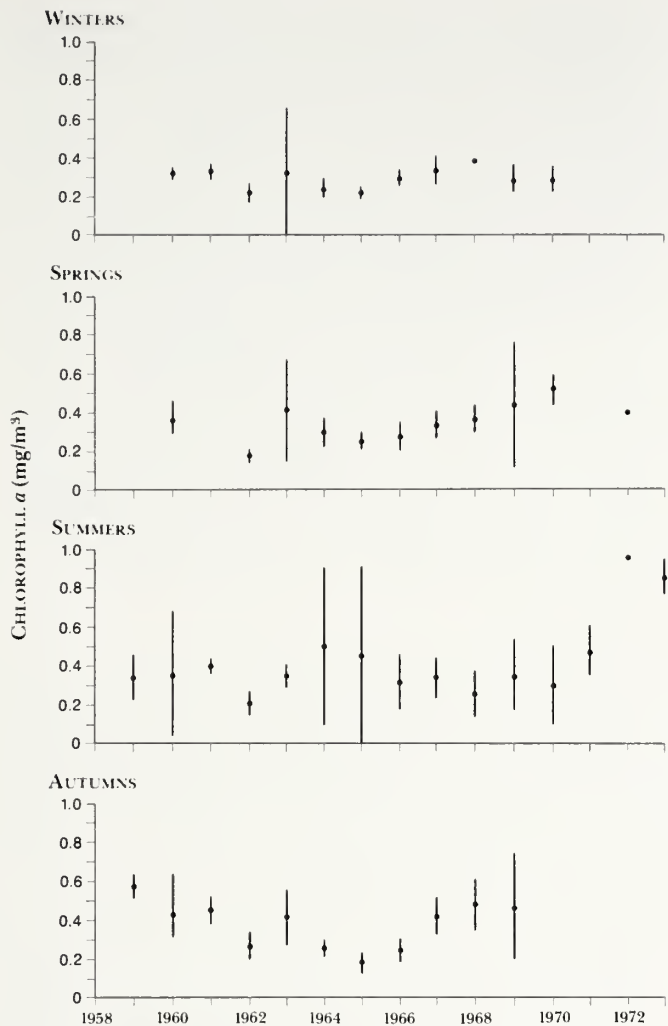


Figure 9-4. Mean seasonal concentrations of chlorophyll *a* found at Station P (± 1 SD) from 1959 to 1973. This is a composite from several sources. (Modified from Anderson *et al.* 1977.)

Unlike chlorophyll *a* levels, the rates of primary production at Station P increase significantly in spring and summer (Fig. 9-5). The seasonal increase in the amount of daily light certainly contributes to this increase. However, Parsons, Giovondo, and LeBrasseur (1966) have shown that the triggering mechanism for increased spring productivity is actually made up of more than this one variable. These authors applied a production model based on the critical depth (Z_{cr}) as defined by Sverdrup (1953):

$$Z_{cr} = \frac{I_c}{k_c \cdot I_c} \quad (2)$$

The critical depth formula expresses a depth in meters that can be compared directly to the mixed layer depth (MLZ). Importantly, in addition to incident light (I_c), the critical depth model considers the light intensity needed for net photosynthesis (the compensation light intensity, I_c) and the light extinction coefficient of the surface water (k_c). The changes in Z_{cr} relative to the mixed layer depth indicated

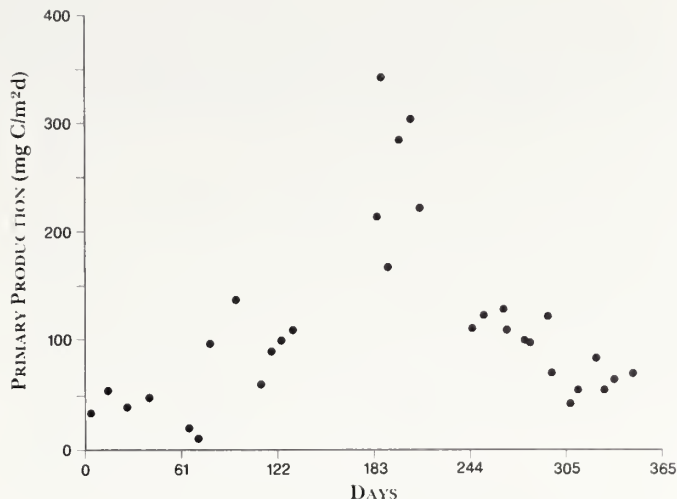


Figure 9-5. Seasonal changes in vertically integrated (0-50 m) primary production measured by the ^{14}C method at Station P. These are several years' worth of combined data. (Modified from Anderson *et al.* 1977.)

that suitable conditions for phytoplankton growth (low MLZ: Z_{cr} ratios) first occurred at Station P in May (Fig. 9-6).

During May, the mixed layer rises abruptly from its winter depth at the permanent halocline. These physical changes in upper water column properties coincide with increases in the local production rate (Fig. 9-5). The exact timing of when the spring mixed layer rises and phytoplankton productivity begins to increase varies from year to year, and this variation may then influence zooplankton growth (Parsons and LeBrasseur 1969).

Phytoplankton growth conditions remain favorable throughout the summer because the mixed layer usually remains within the euphotic zone at ~ 50 m during this season. Carbon productivity rates on the order of 200 to 400 mg C/m²d are typical during the summer months. These rates are maintained until fall when vertical stability becomes

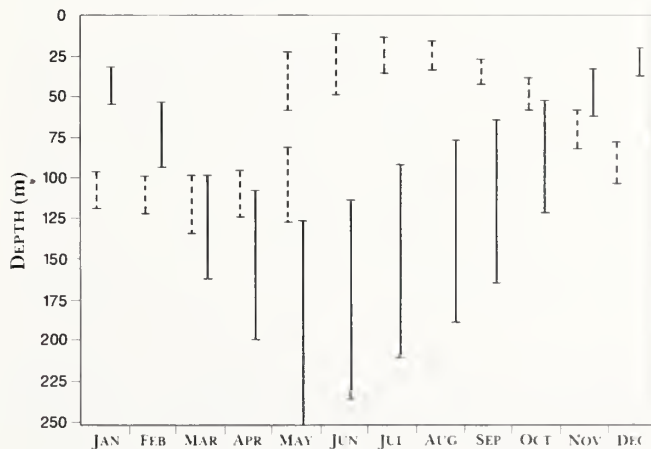


Figure 9-6. Comparison of the seasonal changes in both the critical depth and the mixing depth at Station P. Solid lines indicate the ranges of the critical depth (Equation 2, see text). Broken lines indicate the mean mixed-layer depth (± 1 SD). (Modified from Parsons *et al.* 1966.)

weakened due to surface cooling and the increased frequency of storms. Eventually, the seasonal thermocline is destroyed and the surface waters are again well mixed down to depths of 100 to 150 meters. Winter productivity levels are typically less than 50 mg C/m²d.

Loss Processes Affecting Oceanic Phytoplankton

The difference between seasonally variable algal productivity and seasonally consistent biomass presents somewhat of an enigma in the Gulf of Alaska. This discrepancy has been attributed to the intense grazing of algal cells by zooplankton (McAllister, Parsons, and Strickland 1960). This manner of phytoplankton population control is different from the situation in many other ocean areas and was first suggested by Heinrich (1975). The grazers that are thought to be the most influential in this control are two large, herbivorous calanoid copepods endemic to the subarctic Pacific: *Neocalanus plumchrus* and *N. cristatus*.

The last larval stage of these two species overwinters at depth, during which time the adults both develop and reproduce without any additional food supplies. The young arrive at the surface in the spring where they can feed on the phytoplankton at approximately the same time that the plant community begins its accelerated growth. In this scenario, any increase in the biomass due to growth is grazed by the resident zooplankton population. As a result, a constant phytoplankton population is maintained.

Recently, the hypothesis that the large herbivores controlled the phytoplankton population at Station P was quantitatively tested. This test entailed using a plant pigment budget to calculate both algal growth rates and herbivore grazing rates (Welschmeyer and Lorenzen 1985). Sediment traps were used to catch particles that sank from the surface water. These samples were then used for pigment analyses. Herbivore grazing rates can be partitioned, in a functional sense, into 1) grazing that is attributable to macrozooplankton and that produces consolidated fecal pellets or 2) grazing by microzooplankton that produces non-consolidated material. Microzooplankton grazing residue does not sink and therefore is sampled with water bottles.

In May and August 1983, a series of seven successful experiments designed to partition grazing losses between macro- and micrograzers was carried out (Lorenzen 1984a, b, unpubl. data). The results indicated that the average chlorophyll *a* specific growth rate for the phytoplankton community was 0.13/d. The phytoplankton standing crop did not change during the observation period, and therefore the growth rate could be partitioned among those loss processes that affected the phytoplankton. The three major algal loss rates were: 1) 0.076/d from microzooplankton grazing (56%), 2) 0.046/d from macrozooplankton grazing (35%), and 3) 0.010/d from cells that sank (7%). Clearly, the macrozooplankton were not the dominant grazers during this period. Over half the estimated phytoplankton loss was attributed to grazing by microzooplankton.

Even though the partitioning experiments established the role of the macro- and microzooplankton in phytoplankton loss, no previous analysis of phytoplankton grazing losses has addressed the role of megazooplankton such as salps, which are known to be episodically abundant in the

Gulf (Iseki 1981). These tunicates can remove phytoplankton smaller than 4 μm from surface waters (Harbison and McAllister 1979). The size distribution of Gulf phytoplankton may be strongly influenced by grazing conditions (Parsons 1972). Also, the results of some recent sediment-trap studies at Station P suggest that phytoplankton cell sinking is a much more important loss process than previously thought. For example, large amounts of opal (silica) were collected in deep traps throughout the year in the form of ungrazed phytoplankton diatom frustules (K. Takahashi, Woods Hole Oceanographic Institution, pers. comm.). Only a two-week delay separated the peaks in diatom biomass collected from traps at 1,000- and 3,800-m depths. This delay equals a sinking rate of 180 m/d. Solitary diatom cells sink much more slowly than this (Bienfang 1984), and these rapid rates suggest that diatoms might sink as aggregated particles. Ungrazed phytoplankton cells that sink from the surface therefore may account for a significant portion of the phytoplankton loss in the oceanic Gulf of Alaska.

Large-Scale Features of Phytoplankton Growth

A number of measurements that pertain to oceanic phytoplankton have been collected from American Mail Line (AML) ships that traverse the southern Gulf (Anderson and Munson 1972). These cruise tracks provided zonal coverage of both the central subarctic and the Alaskan Gyre waters from late winter through summer of the years 1968 to 1972 (between 50 and 55°N). The zonal distribution of several relevant parameters that were measured by the AML ships is shown in Figure 9-7. The sections that were examined extend beyond the Gulf (west of 176°W and east of 135°W).

Both the Kuroshio water (in the west) and the water closer to the North American continent (in the east) exhibit consistently warmer temperatures than the water in the Gulf (Fig. 9-7a). Within the Gulf itself, the Alaskan Gyre (west of 145°W) has a colder surface-water signature than the Central Subarctic Domain in the east—a condition that lasts well into the summer. This cooler water often signals higher surface concentrations of inorganic nutrients such as phosphate, nitrate, and silicate (Figs. 9-7d through f). Such cool, high-nutrient water is often a sign of deeper water upwelling, as would be expected from the cyclonic nature of the Alaskan Gyre. Meridional sections across the Gulf of Alaska also revealed increased isohaline 'doming' along 156°W as the Alaskan Gyre is encountered near 52°N (Favorite, Dodimead, and Nasu 1976).

Chlorophyll *a* levels in the central Alaskan Gyre are usually lower than those in the central subarctic water (Fig. 9-7c). In spite of the steady increase in insolation across the Gulf from March through May (Fig. 9-7b), chlorophyll *a* levels did not display an analogous increase (Fig. 9-7c). However, spring productivity did increase (Fig. 9-7g) in proportion to increases in the amount of daily light. The disparity between the increase in biomass and the increase in productivity indicates that the more detailed measurements made at Station P have widespread applicability across the Gulf.

In both the Central Subarctic Domain and the western Gulf, productivity values greater than 50 mg C/m²d were measured by late March, although in the central Alaskan

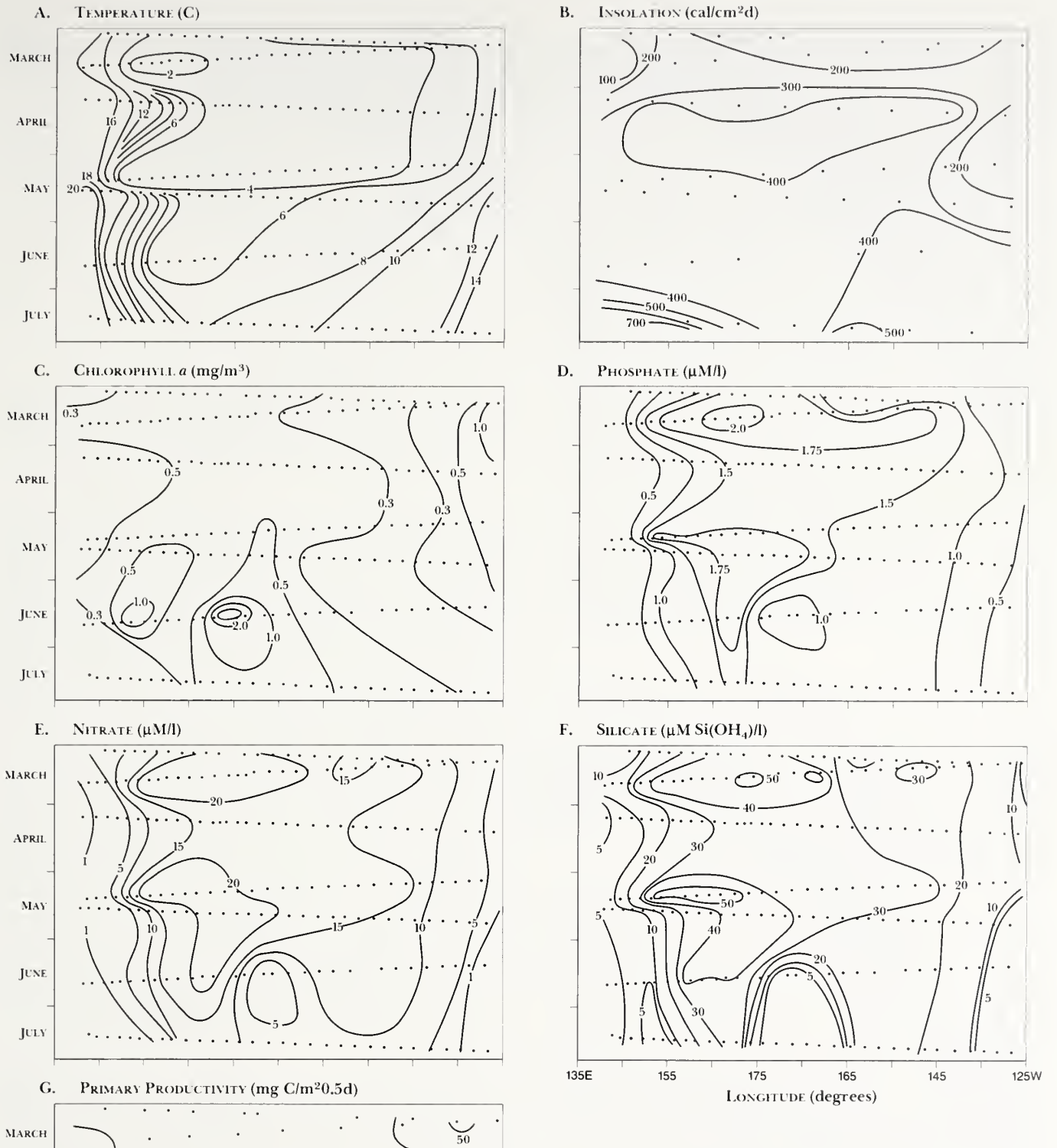


Figure 9-7. Time/space contours of seven parameters measured during the American Mail Line ship crossings of the Gulf of Alaska between 50 and 55° North. (Modified from Anderson and Munson 1972.)

Gyre this value was not exceeded until May. Also, the western Gulf of Alaska was by far the most productive area and the only location in which chlorophyll *a* levels greater than 2 mg/m³ were recorded (Larrance 1971a, b). This same chlorophyll *a* pattern was recorded during the 1968 sections from the AML ships.

These sections indicate that the spring increase in daily light is important for stimulating production in the oceanic areas of the Gulf. However, a stable upper-water layer is also an important criterion for enhanced phytoplankton growth. Parsons *et al.* (1966) considered data from throughout the eastern subarctic Pacific, then used the critical depth approach to predict seasonal increases in phytoplankton growth. Their analysis indicated that growth would begin during March south of Kodiak Island and during April in much of the Central Subarctic Domain. This is even earlier than the point at which seasonal growth increases are observed at Station P.

Detailed productivity data are not available to determine if enhanced productivity actually does occur in these areas at the predicted times. However, the times that were predicted for spring phytoplankton growth did coincide with measured increases in copepod abundance in Gulf waters (Parsons, Ch. 18, this volume). This indicates that changes in the depth to which vertical mixing of surface-waters occur may cause a significant impact on phytoplankton growth in the Gulf and probably correspond to those growth trends exhibited at Station P.

Nitrogen uptake data for August were collected at a station located at 50°N, 155°W (Hattori and Wada 1972). New (nitrate) production was 0.56 μM/m²d. The ratio of new uptake to total (nitrate and ammonium) uptake was ~0.36. Assuming that carbon and nitrogen are assimilated in the Redfield ratio (Redfield *et al.* 1963), then the total nitrogen productivity is equivalent to a carbon productivity of ~130 mg C/m²d. This carbon productivity is greater than the ¹⁴C values measured in this area in July (Fig. 9-7g).

The results of recent United States/Japan cooperative-sampling efforts include vertical chlorophyll *a* data that were collected across the Gulf at 55°N during July 1982 (Fig. 9-8). The chlorophyll *a* values in the samples are generally low (<1 μg/l), similar to other measurements taken in this area. An abrupt increase in chlorophyll *a* levels at the middle station in the section coincided with the boundary between the Alaskan Gyre in the west and the Central Subarctic Domain in the east. However, there may be no causal significance to this relationship because high chlorophyll *a* values found at the eastern end of this section did not correspond to any similar water mass boundary.

The data presented in Figure 9-8 show the chlorophyll *a* levels that were extracted from all the particulate material that was retained on glass-fiber filters. In contrast to this pattern of 'whole community' chlorophyll *a*, the distribution of chlorophyll *a* in selected particle-size ranges (or fractions) exhibited east-to-west differences across the sampling section. Specifically, in the western four stations in the Alaskan Gyre, there was less chlorophyll *a* associated with particles greater than 28 μm (8.1%) than there was for the four eastern stations in the Central Subarctic Domain (19.5%). The cause of the zonal differences in the phytoplankton-size distribution across the section is not clear.

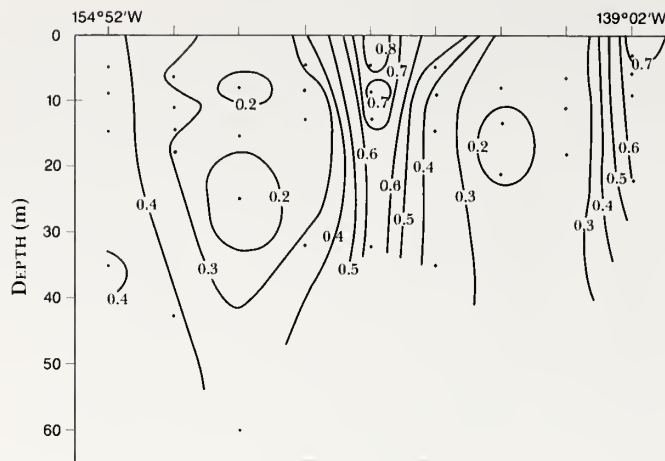


Figure 9-8. Extracted chlorophyll *a* values along 55°N in the Gulf of Alaska between the indicated longitudes (Faculty of Fisheries, Hokkaido University 1983; R.N. Sambrotto and J.J. Goering; University of Alaska, unpubl. data).

In the eastern portion of the section, the mixed layer of the Central Subarctic Domain was warmer (10–12°C) than the mixed layers in the west (8–9°C). More importantly, the net tows across this section collected many more zooplankton of the copepod genus *Calanus* (largely *C. pacificus*) in the eastern waters. Therefore, the observed differences in phytoplankton size distribution may reflect this east/west difference in grazing pressure. This interpretation is compatible with the observation that *C. pacificus* cannot efficiently remove large-size particles from seawater (Parsons, LeBrasseur, and Fulton 1967).

Parsons (1972) did not find any clear zonal differences in particle-size spectra in the measurements he made during the spring bloom period. During an east-to-west crossing of the southern Gulf, he found that nanoplankton (2–20 μm) accounted for most of the chlorophyll *a*. Parsons and LeBrasseur (1969) suggested that because small phytoplankton dominated the Gulf, the food chain leading to harvestable particles was longer. This also meant it was less efficient than a system that supported larger phytoplankton. In addition, Parsons (1972) found that the particulate carbon-to-chlorophyll ratio of ~236 was much larger than the previous ratios (15–60) reported by McAllister (1969) from Station P.

When Anderson *et al.* (1977) presented twenty years of phytoplankton data from the Gulf, they divided the eastern subarctic Pacific into geographic zones based largely on the physiographic domains introduced by Dodimead *et al.* (1963) (Fig. 9-9). They organized the data by zone and by data type in their presentation of broad-scale patterns. Seasonal chlorophyll *a* data that were integrated through the euphotic zone and organized in the above manner are presented in Figure 9-10.

As Figure 9-10 shows, the oceanic areas in the Gulf generally exhibited both low and relatively uniform chlorophyll *a* levels throughout the year. In contrast, the coastal zones exhibited a pronounced seasonal trend in phytoplankton biomass and attained much higher maximum values. Exceptions to the above trends were the relatively large oceanic chlorophyll *a* concentrations south of the Aleutian Islands

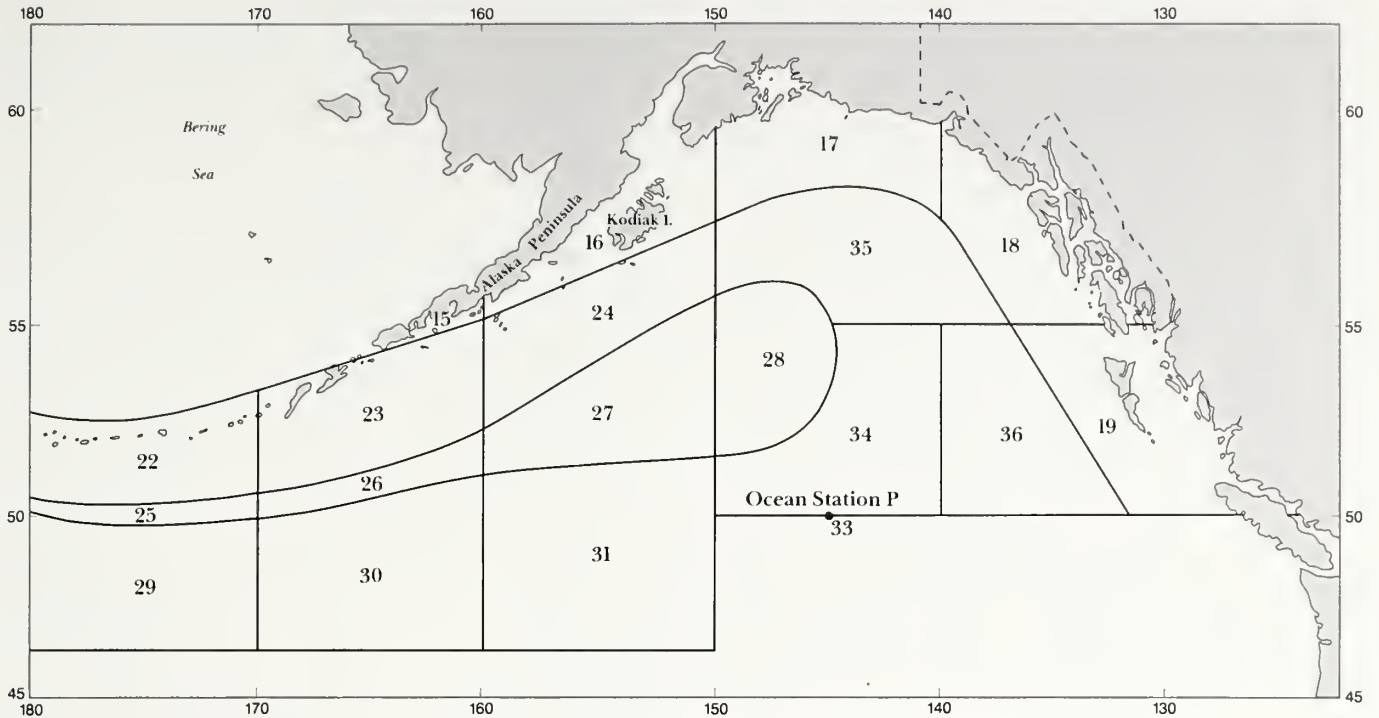


Figure 9-9. Geographic zones used by Anderson *et al.* (1977) to analyze both phytoplankton and productivity data in the northern North Pacific.

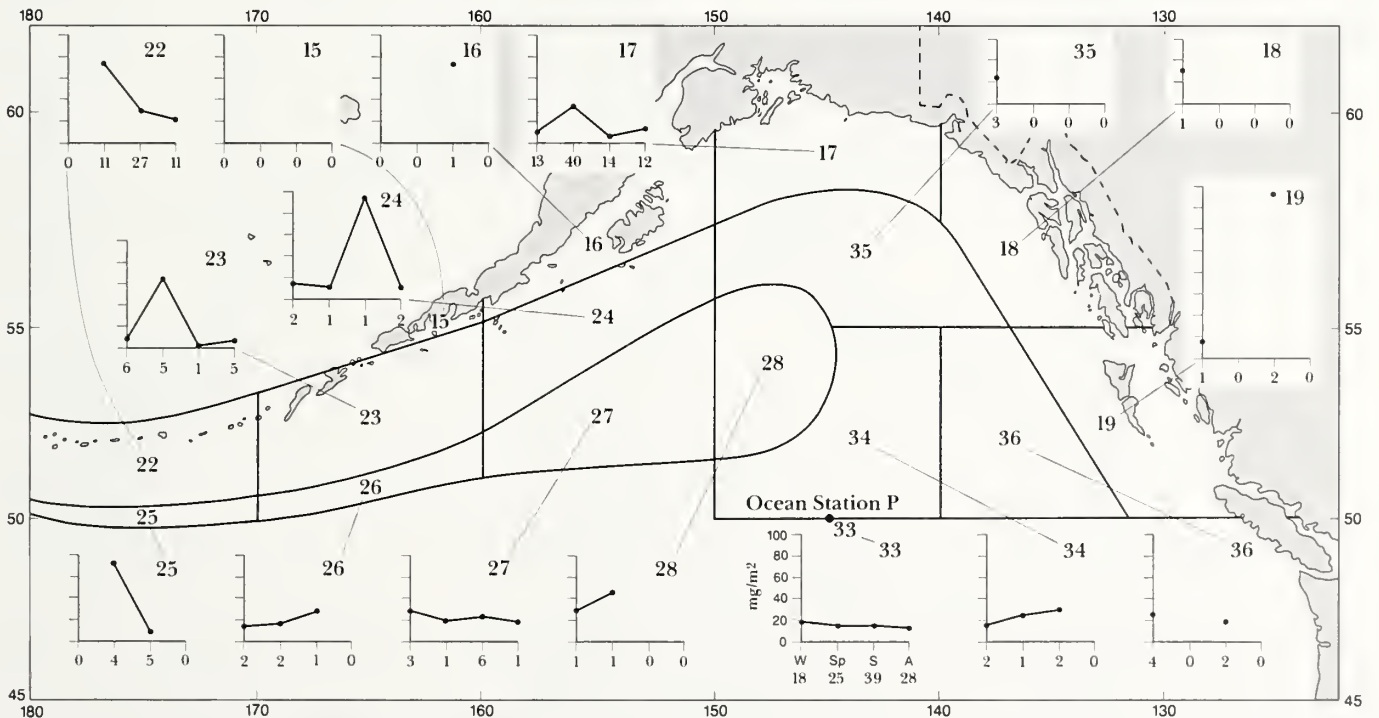


Figure 9-10. Distribution of depth-integrated chlorophyll *a* (seasonal means for the euphotic zone are in mg/m²) for the Gulf of Alaska during the years 1958 through 1974. (Modified from Anderson *et al.* 1977.) W = December to February; Sp = March to May; S = June to August; A = September to November. The number of measurements on which the mean is based is given below each season.

in Zone 25 and beyond the Kodiak shelf in Zone 24. However, the values in this latter zone are based on few data points and may not represent typical conditions.

Both the seasonal and geographic productivity data that are integrated through the euphotic zone confirm the patterns discussed previously for Station P (Fig. 9–II). For example, in those zones for which sufficient data are available, the oceanic areas exhibit productivity peaks during the summer, whereas the coastal areas show productivity increases that begin earlier in the year. Seasonal productivity changes in many parts of the Gulf cannot be resolved with existing data; however, extensive data for the central Gulf of Alaska coastal region are available and will be reviewed below.

Anderson *et al.* (1977) also reviewed nutrient data. In the oceanic zones, nitrate levels went from late winter/early spring maxima to lower (but still non-limiting) concentrations in the summer—conditions similar to those at Station P. Nitrate concentrations decreased more than phosphate concentrations. Silicate was completely stripped from the surface water during the spring in Zone 17, and was stripped from the surface during summer in Zones 23 and 36. Silicate concentrations in Zone 17 are low throughout the year, suggesting that vigorous diatom growth takes place in this area in all seasons.

Oceanic Phytoplankton Species Composition

A list of those phytoplankton species recorded for the eastern subarctic Pacific is presented in Table 9–2. Note that this list also includes collections from transition waters south of 50°North. Therefore, the list includes warm-water

species not often found in the Gulf such as *Ethmodiscus rex*, *Eucampia zodiacus*, *Hemiaulus sinensis*, *Planktoniella sol*, *Rhizosolenia styliformis*, and *Pseudoeunotia doliolus*. However, these can be carried along the outer edge of the Alaskan Gyre from lower latitudes, and *P. sol* has been found as far north as Zone 22.

In reviewing phytoplankton taxonomic composition data collected from 120 ships of opportunity, Anderson *et al.* (1977) were not able to delineate any clear geographic pattern. This contrasts with the findings of Venrick (1971), who was able to identify groups of diatoms that were associated with certain areas. For example, both Venrick (1971) and Anderson *et al.* (1977) found that *Rhizosolenia hebatata f. hiemalis*, and *Thalassionema nitzschioides* were restricted to waters north of the transition zone. However, unlike Venrick (1971), Anderson *et al.* (1977) found *Thalassiothrix longissima* and *Tropidoneis antarctica* distributed well north into the Gulf area. These differences may reflect seasonal and yearly variations in species distributions. Later work has suggested that the diatom *Denticulopsis seminae* is ubiquitous in the oceanic Gulf of Alaska (Booth 1981; Taylor and Waters 1982).

Both the photosynthesis/light response and the composition of phytoplankton communities in the western Gulf of Alaska were examined by Motoda and Kawamura (1963). The response of community photosynthesis to light was found to vary with community composition. For example, a community dominated by the diatom *Thalassiothrix longissima* did not exhibit photosynthesis light saturation. In contrast, communities with significant numbers of *Chaetoceros debilis* exhibited maximum photosynthesis

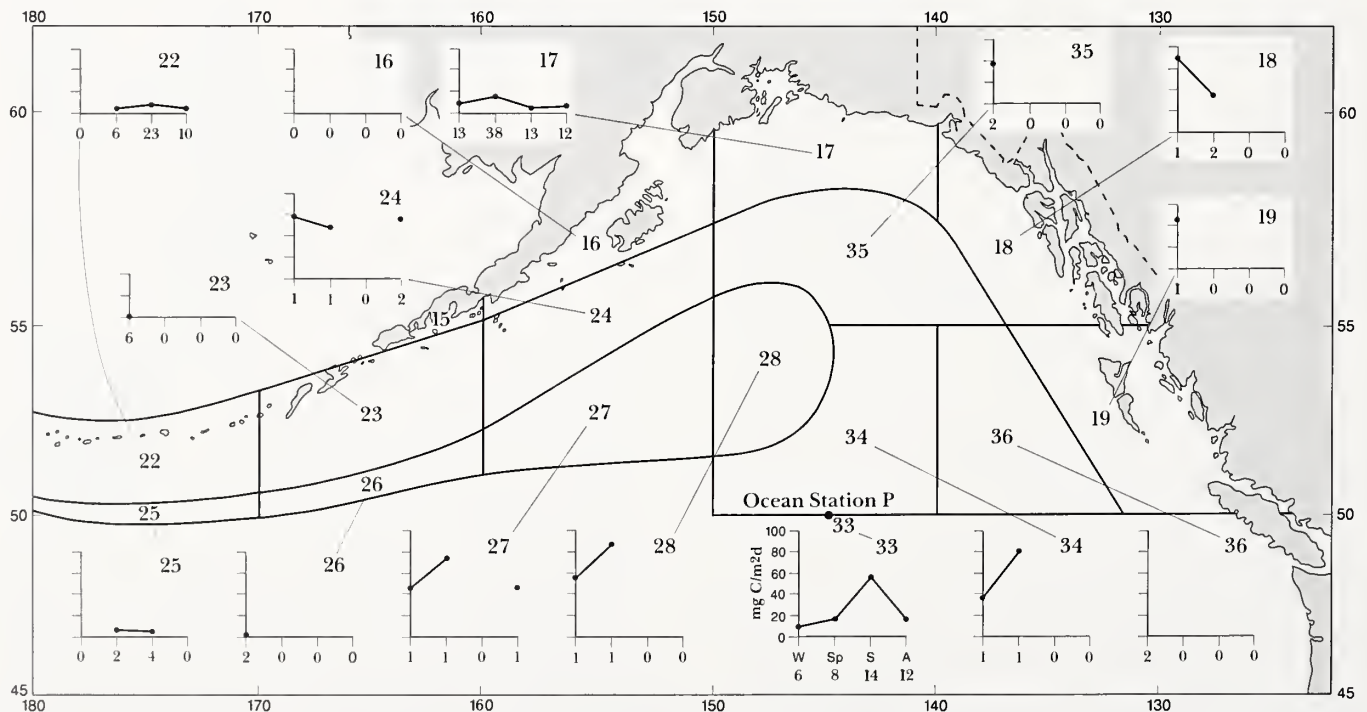


Figure 9–II. Distribution of depth-integrated carbon productivity (seasonal means for the euphotic zone are in mg C/m²d) for the Gulf of Alaska during the years 1958 through 1974. (Modified from Anderson *et al.* 1977.) W = December to February; Sp = March to May; S = June to August; A = September to November. The number of measurements on which the mean is based is given below each season.

Table 9-2.

Phytoplankton species list for the eastern subarctic Pacific north of 42°N and east of 180° West. (Modified from data compiled by Anderson *et al.* 1977.)

Diatoms		<i>Ditylum brightwellii</i> (West)		<i>T. angatii</i> (Gran.) Makarova	O
<i>Achnanthes longipes</i> Ag.	O ^a	Grun.	O	<i>T. nordenskiöldii</i> Cl.	O
<i>A. sp.</i>	N	<i>Ethmodiscus rex</i> (Wall.) Hendey	O	<i>T. rotula</i> Meun.	O
<i>Actinocyclus curvatulus</i> Janisch	O	<i>Eucampia zodiacus</i> Ehr.	O	<i>T. pacifica</i> Gran and Angst	O
<i>A. sp.</i>	O	<i>Gyrosigma sp.</i>	N	<i>T. subtilis</i> (Osten.) Gran	O
<i>Actinopterychus undulatus</i> (Bail.)		<i>Grammatophora marina</i>		<i>T. condensata</i> Cl.	O
Ralfs	O	(Lyng.) Kütz.	O	<i>T. lineata</i> Jousé	O
<i>Amphiprora sp.</i>	N	<i>Hemiaulus sinensis</i> Grev.	O	<i>T. antiqua</i> (Grun) A. Cl. var.	
<i>Asterionella japonica</i> Cl.	O	<i>H. membranaceus</i> Cl.	O	<i>septata</i> Prosh. Lavr.	O
<i>Asterolampra marylandica</i> Ehr.	O	<i>Hemidiscus cuneiformis</i> Wall.	O	<i>T. oestrupii</i> (Ostf.) Hasle	O
<i>A. flabellatus</i> (Brèb.) Grev.	O	<i>Lauderia borealis</i> Gran.	O	<i>T. eccentrica</i> (Ehr.) Cleve	O
<i>A. heptactis</i> (Brèb.) Ralfs	O	<i>Leptocylindrus danicus</i> Cl.	O	<i>T. polychorda</i> (Gran) Jørg.	O
<i>A. robustus</i> Castr.	O	<i>Licmophora abbreviata</i> Ag.	N	<i>Thalassiothrix longissima</i> Cl. and	
<i>Bacteriastrium delicatulum</i> Cl.	O	<i>Melosira moniliformis</i> (Müll.) Ag.	N	Gran	O
<i>Bacterosira fragilis</i> Gran.	N	<i>M. sulcata</i> (Ehr.) Kütz.	N	<i>Triceratium arcticum</i> Brightw.	N
<i>Biddulphia aurita</i> (Lyng.) Brèb.		<i>Navicula sp.</i>	O	<i>Tropidoneis antarctica</i> Grun. var.	
and God.	N	<i>Nitzschia seriata</i> Cl.	O	<i>polyplasta</i> Gran and Angst	O
<i>B. longicurvus</i> Grev.	O	<i>N. sicula</i> (Castr.) Hustedt	O		
<i>B. sp.</i>	O	<i>N. bilobata</i> Wm. Smith	O	Dinoflagellates	
<i>Cerataulina sp.</i>	O	<i>N. bicapitata</i> Cl.	O	<i>Ceratium fusus</i> (Ehr.) Dujardin	O
<i>C. bergonii</i> H. Pèr.	O	<i>N. heimii</i> Manguin	O	<i>C. longipes</i> (Bailey) Gran	O
<i>Chaetoceros atlanticus</i> Cl.	O	<i>N. turgiduloides</i> Hasle	O	<i>C. tripos</i> O. F. Müller	O
<i>C. convolutus</i> Castr.	O	<i>N. longissima</i> (Brèb.) Ralfs	O	<i>C. macroceros</i> (Ehr.) Vanhöffen	O
<i>C. concavicornis</i> Mang.	O	<i>N. pungens</i> Hasle	N	<i>C. pentagonum</i> Gourret	O
<i>C. peruvianus</i> Brightw.	O	<i>N. paradoxa</i> (Gmel.) Grun.	N	<i>C. lineatum</i> (Ehr.) Cl.	N
<i>C. debilis</i> Cl.	N	<i>N. pseudonana</i> Hasle ^b	O	<i>C. intermedium</i> (Jørg.) Jørg.	O
<i>C. decipiens</i> Cl.	N	<i>N. sp.</i>	O	<i>Dinophysis acuta</i> Ehr.	O
<i>C. didymus</i> Ehr.	N	<i>Planktoniella sol</i> (Wall.) Schütt	O	<i>Exuviella baltica</i> Lohmann	O
<i>C. lacinosus</i> Schütt	N	<i>Pleurosigma directum</i> Grun.	O	<i>Gymnodinium sp.</i>	O
<i>C. radicans</i> Schütt	N	<i>Podosira sp.</i>	O	<i>Gyrodinium sp.</i>	O
<i>C. affinis</i> Laud.	N	<i>Pseudoemotia doliolus</i>		<i>Minusculea bipes</i> Lebour	O
<i>C. brevis</i> Schütt	N	(Wall.) Grun.	O	<i>Peridinium depressum</i> Bailey	O
<i>C. mitra</i> (Bail.) Cl.	N	<i>Rhabdonema arcuatum</i> Kütz.	O	<i>P. cerasus</i> Paulsen	O
<i>C. pelagicus</i> Cl.	N	<i>Rhizosolenia alata</i> Brightw.	O	<i>P. conicum</i> (Gran) Ost. and	
<i>C. socialis</i> Laud.	N	<i>R. alata f. curvirostris</i> Gran	O	Schmidt	N
<i>C. subsecundus</i> (Grun.) Hust.	N	<i>R. alata f. inermis</i> (Castr.)		<i>P. pallidum</i> Ost.	N
<i>C. teres</i> Cl.	N	Hust.	O		
<i>Cocconeis sp.</i>	O	<i>R. hebetata f. hiemalis</i> Gran	O	Coccolithophorids	
<i>Corethron hystrix</i> Hen.	O	<i>R. hebetata f. semispina</i>		<i>Calyptrosphaera sp.</i>	O
<i>Coscinodiscus lineatus</i> Ehr.	O	(Hen.) Gran	O	<i>Coccolithus huxleyi</i> (Lohm.) Kpt. ^c	O
<i>C. curvatulus</i> Grun.	O	<i>R. stollerfathii</i> H. Pèr.	O	<i>C. pelagicus</i> (Wallick) Schiller	O
<i>C. centralis</i> Ehr.	O	<i>R. styliformis</i> Brightw.	O	<i>Cyclococcolithus leptoporus</i>	
<i>C. radiatus</i> Ehr.	O	<i>R. styliformis f. longispina</i>	O	(Murr. <i>et.</i> Blackm.) Schiller	O
<i>C. stellaris</i> Rop.	O	Hust.	O	<i>C. fragilis</i> (Lohm.) Gaarder	O
<i>C. oculis iridis</i> Ehr.	O	<i>R. fragilissima</i> Berg.	O	<i>Michaelsarsia sp.</i>	O
<i>C. tabularis</i> Grun.	O	<i>R. imbricata shrubsolei</i> (Cl.)		<i>Rhabdosphaera tignifer</i> Sch.	O
<i>C. marginatus</i> Ehr.	O	Schröd.	O	<i>Syracosphaera sp.</i>	O
<i>C. wailesii</i> Gran and Angst	O	<i>R. obtusa</i> Hensen	O		
<i>C. granii</i> Gough	N	<i>Roperia tessellata</i> (Roper) Grun.	O	Other groups	
<i>C. perforatus</i> Ehr.	O	<i>Skeletonema costatum</i> (Grev.) Cl.	O	<i>Pterosperma sp.</i>	O
<i>Cyclotella stelligera</i>	O	<i>Stephanopyxis nipponica</i> Gran		<i>Halosphaera vividis</i> Schmitz	O
Cl. and Grun.		and Yendo	O	μ m flagellates	O
<i>Cylindrotheca closterium</i> (Ehrb.)		<i>S. turris</i> (Grev. and Arn.) Ralfs	N	<i>Phaeocystis pouchetii</i> (Hariot)	
Reimanna and Lewin	O	<i>Striatella unipunctata</i> (Lyng.) Ag.	N	Lagerheim	N
<i>Cymbella sp.</i>	O	<i>Surirella sp.</i>	N	<i>Ebria tripartita</i> (Schum.)	
<i>Dactyliosolen mediterraneus</i>		<i>Synedra vaucheriae</i> Kutz. var.		Lemmerman	O
H. Pèr.	O	<i>capitellata</i> Grun.	O	<i>Dictyocha fibula</i> Ehr.	O
<i>Denticulopsis seminae</i> (Semina)		<i>Thalassionema nitzschioides</i> Grun.	O	<i>Distephanus speculum</i> (Ehr.)	
Simon. and Kanaya	O	<i>Thalassiosira decipiens</i> (Grun.)		Haeckel	O
		Jørg.	O	<i>D. octangulatus</i> Wailes	O

^a O = oceanic, N = neritic^b This taxon probably includes a small number of cells of *Nitzschia pseudonana* Hasle, but is mostly cells of *N. cylindroformis* Hasle (called *N. cylindrus* Hasle in Booth *et al.* 1982 and described as *N. cylindroformis* by Hasle and Booth 1984). The taxonomic complexities of this group are discussed in Hasle and Booth 1984 (B. Booth, University of Washington, pers. comm., 1986).^c *Coccolithus huxleyi* (Lohm.) Kpt. is now *Emiliania huxleyi* (Lohm.) Hay and Mohler.

around 500 lux. These results suggest that the spatial differences found in species distribution may influence phytoplankton growth in the Gulf as well.

One useful index of seasonal species changes at Station P—at least among the diatoms—is available from the sediment-trap data of K. Takahashi (Woods Hole Oceanographic Institution, pers. comm.). For example, *Rhizosolenia alata* and *Coscinodiscus marginatus* were numerically abundant during winter conditions, while *Chaetoceros concavicornis* was the peak species during spring. *Rhizosolenia styliiformis* exhibited a numerical maximum in the summer, while *Corethron hystrix* appeared episodically throughout the growing season. *Denticulopsis seminae* was the only pennate diatom that accounted for a significant percentage of the biomass.

The trap data suggest that certain silicoflagellates are useful indicators for productive periods. However, trap data probably will not be a useful sampling device for the microflagellates that usually constitute a large portion of the phytoplankton standing crop in the Gulf.

A more complete species compilation than that available from the trap data is presented in Table 9-2. Anderson *et al.* (1977) ranked species from this list according to the maximum number of cells per liter and the maximum amount of carbon per liter (Table 9-3). The maximum number of cells per liter for the top 15 species ranged from a high of 7×10^5 to a low of 2.4×10^3 . Carbon per liter was estimated from cell volume (as described in the Methods section) and ranged from highs of 7.7×10^4 mg C/l to a minimum of 1.62×10^3 mg C/l. Note that the coccolithophorid *Cyclcoccolithus* sp. moved up dramatically in the carbon-per-liter ranking—mainly due to the extensive calcium carbonate test of these cells. Also, the diatom *Corethron hystrix* may contribute significantly to the total pool of particulate organic carbon due to its large size.

Table 9-3.

Phytoplankton species from 121 eastern subarctic stations (neritic stations omitted) ranked according to A) maximum number of cells per liter and B) maximum nanograms of carbon per liter. (Modified from Anderson *et al.* 1977.)

A) SPECIES RANK (# cells/l)	B) SPECIES RANK (ng C/l)
1. <i>Nitzschia pseudonana</i>	<i>Nitzschia pseudonana</i>
2. <i>Denticulopsis seminae</i>	<i>Cyclcoccolithus</i> sp.
3. <i>Rhizosolenia alata</i> f. <i>inermis</i>	<i>Denticulopsis seminae</i>
4. <i>Nitzschia</i> sp. (<i>Pseudonitzschia</i> group)	<i>Rhizosolenia alata</i> f. <i>inermis</i>
5. <i>Corethron hystrix</i>	<i>Corethron hystrix</i>
6. <i>Cylindrotheca closterium</i>	<i>Nitzschia</i> sp. (<i>Pseudonitzschia</i> group)
7. <i>Cyclcoccolithus</i> sp.	<i>Cylindrotheca closterium</i>
8. <i>Coccolithus huxleyi</i> (= <i>Emiliania huxleyi</i>)	<i>Coccolithus huxleyi</i> (= <i>Emiliania huxleyi</i>)
9. <i>Thalassiosira nordenskiöldii</i>	<i>Coccolithus pelagicus</i>
10. <i>Thalassiosira lineata</i>	<i>Chaetoceros convolutus</i>
11. <i>Coccolithus pelagicus</i>	<i>Thalassiosira nordenskiöldii</i>
12. <i>Asteromphalus</i> spp.	<i>Nitzschia</i> sp. (<i>Fragilariopsis</i> group)
13. <i>Thalassiosira rotula</i>	<i>Thalassiosira rotula</i>
14. <i>Chaetoceros atlanticus</i>	<i>Asteromphalus</i> spp.
15. <i>Chaetoceros convolutus</i>	<i>Thalassiosira lineata</i>

However, as Anderson *et al.* (1977) point out, the listings in Tables 9-2 and 9-3 are not quantitative for phytoplankton that do not preserve well and are therefore not adequately sampled by most investigators. In a section across Zones 18, 35, and 28 (Fig. 9-9), Booth *et al.* (1982) collected detailed information on the smaller phytoplankton (<20 μ m cell size). This study characterized these smaller cells (<20 μ m) in much greater detail than previous studies. The Booth *et al.* (1982) data differed in several respects from those of Anderson *et al.* (1977), largely reflecting improved methodology and updated taxonomy. For example, the prymnesiophyte *Phaeocystis pouchetii* was not restricted to neritic locations as suggested by Table 9-2, and attained cell numbers of over 10^6 /l in those oceanic areas that were sampled. In addition, four species of choanoflagellates were identified and two different kinds of cryptomonads were found.

Coastal Gulf of Alaska

The geographic productivity pattern suggested by Koblentz-Mishke, Volkovinsky, and Kabanova (1970) indicated that yearly productivity in the Gulf increased from oceanic values of less than 100 g C/m² to values of 100 to 150 g C/m² in the shelf and nearshore regions. These regions are here referred to as the coastal Gulf of Alaska. The original productivity contours of Koblentz-Mishke *et al.* (1970) were largely speculative, but later measurements confirmed a general increase in productivity for the coastal areas (Larance 1971a, b; Goering, Shiels, and Patton 1973). The data sources on which the present discussion of coastal phytoplankton is based are listed in Table 9-4—analogueous to the listing of oceanic data sources in Table 9-1. Before reviewing these data, some comments on the marked differences between phytoplankton growth conditions in coastal and oceanic water are in order.

Major Influences on Coastal Phytoplankton Growth

There is appreciable advection along the coastal area from British Columbia to the Aleutian Islands. Two distinct currents dominate local flow characteristics along this area (Reed and Schumacher, Ch. 3, this volume). The first is the Alaska Current, which flows counterclockwise along the shelf break at velocities up to 1.5 m/s (Niebauer, Roberts, and Royer 1981). Both wind and baroclinic forcing allow some of this water to enter Shelikof Strait through its northern end (Schumacher and Reed 1980). The second current is the Alaska Coastal Current, which is a prominent feature of the entire Gulf within ~35 km of the coast. This current reaches a velocity of 0.5 m/s and transports in excess of 1×10^6 m³/s (Royer 1981). Part of this coastal current flows along the Alaska Peninsula and exits the south Aleutian shelf through Unimak Pass (Schumacher, Pearson, and Overland 1982).

These currents foster a much more energetic environment in the surface water of the shelf and near-shelf areas than is found in the oceanic region. Also, unlike oceanic areas where excess plant nutrients are found year-round, nutrient-depleted surface layers develop during summer in the shallow, nearshore areas. Therefore, spring bloom con-

Table 9-4.

Biological and oceanographic data collected in the coastal area of the Gulf of Alaska. The data type codes used are the same as in Table 9-1. Specialized measurements of interest are also noted.

YEAR/MONTH	DATA TYPE	SOURCE
Eastern Aleutian Passes		
1970 - June, September	7, pCO ₂	Kelley <i>et al.</i> 1971
1978 - July	1,7	Koike <i>et al.</i> 1982
Shelikof Strait/Kodiak Island Shelf		
1967 - June	6,7,8	Wright 1970
Cook Inlet		
1968 - February, March, May-October	5-8	Hood <i>et al.</i> 1968 Kinney <i>et al.</i> 1970
1974 - January-December	5	Schandelmeier 1975
1976 - April, May, July, August	1,2,3,5,7,9	Larrance <i>et al.</i> 1977
1978 - March, May-August	1-3,5,7 (sediment traps)	Larrance and Chester 1979 Chester and Larrance 1981
Resurrection Bay		
1972-1975	3,7,8	Heggie <i>et al.</i> 1977
1983 - summer	1,3,5	Bienfang 1984
Prince William Sound		
1971 - May-December	1-7	Goering, Shiels, and Patton 1973; Goering, Patton, and Shiels 1973; Hood and Patton 1973
1972 - March-April	1-3,5-7	Horner <i>et al.</i> 1973
1976 - April, May, July, August	1,2,3,5,7,9	Larrance <i>et al.</i> 1977
Northeast Gulf of Alaska Shelf		
1976 - April, May, July, August	1,2,3,5,7,9	Larrance <i>et al.</i> 1977
Tenekee Inlet		
1975 - July-August	5	Zimmerman and McMahon 1976
Auke Bay		
1966 - 1968 various months	1,5,7,9	Bruce 1969
1968 - April-June	1,4,7	Schell 1974
1969 - June-August	1,7,9	Iverson, Curl, O'Connors, Kirk, and Zakar 1974
Smeaton Bay		
1980 - October-December	1-3,5,7,8 1,2,3,6-8	VTN Sciences 1982 Burrell 1984
1981 - February-October	1-3,5,7,8 1,2,3,6-8	VTN Sciences 1982 Burrell 1984
Boca de Quadra		
1979 - December	1-3,5,7-9	VTN Sciences 1982
1980 - April-July, September, December	1,2,3,6-9	Burrell 1984; VTN Sciences 1982
1981 - January, April-June, August-October	1,2,3,6-8	Burrell 1984
1982 - April, December	1,2,3,6-8	Burrell 1984
1983 - March-April	Sediment traps	Burrell 1984
Hecate Strait		
1979 - June, July	1,5,7	Perry <i>et al.</i> 1983
1980 - June, August		
Multi-Site Studies		
1978-1979	5 ^a	Hall 1982 ^b

^a Most identifications from sediment isolates.

^b Sampled 23 sites in several areas (see Fig. 9-23).

ditions in many of the coastal areas are short-lived. A recent review of phytoplankton production on several shelves indicated that differences in yearly production levels were directly related to both the strength and the consistency of those physical mechanisms that supplied nutrients during the growing season (Sambrotto, Goering, and McRoy 1984).

There are several mechanisms in the coastal Gulf waters that can supply nutrients to the euphotic zone throughout

the summer. For example, a vigorous current such as the Alaska Coastal Current prevents nutrient depletion during summer by enhancing the vertical diffusion of nutrients (Winant and Olson 1976). Also, while coastal upwelling is not a dominant feature along the Gulf shelf, it does occur in the summer (Royer 1985). In addition, the intrusion of the Alaska Coastal Current into lower Cook Inlet brings summer-long upwelling in that area (Muench, Mofjeld, and

Charnell 1978). Additional upwelling areas have been identified along the Gulf coast and will be identified in the next section, which surveys the entire coastal environment.

The spatial variability or patchiness in the distribution of chlorophyll *a* often coincides with specific physical hydrographic features found in the coastal environment (*e.g.*, Seliger, McKinley, Biggley, Rivkin, and Aspden 1981). The association between phytoplankton abundance and along-shelf frontal features is well established for high-latitude shelves with low to moderate current regimes such as the eastern Bering Sea (Iverson, Coachman, Cooney, English, Goering, Hunt, Macaulay, McRoy, Reeburgh, and Whitedge 1979). Tidally mixed frontal systems, in particular, enhance the nutrient supply to the surface waters and are areas where there is active phytoplankton growth throughout the summer (Pingree, Pugh, Holligan, and Forrester 1975). Fronts such as these influence phytoplankton growth in coastal British Columbia (Perry, Dilke, and Parsons 1983).

One important environmental factor that strongly influences phytoplankton growth along the Gulf coast is the turbidity that comes from suspended terrestrial material. The geographic pattern of late-fall carbon productivity for the central northern Gulf reflects this influence (Larrance, Tennant, Chester, and Ruffio 1977). These data are presented by Parsons (Ch. 18, this volume: Fig. 18-3). The lowest productivities measured by Larrance *et al.* (1977) were located south and west of the mouth of the Copper River—in the path of a substantial amount of suspended material delivered to the area by this river. The light available for photosynthesis was so attenuated by this material that it resulted in a 50% decrease in the depth of the euphotic zone. This, in turn, greatly decreased the vertically integrated productivity.

The only sampling area west of the Copper River that was highly productive was the relatively clear Orca Bay in Prince William Sound. There, an apparently isolated bloom of *Skellonema costatum* was encountered. Cases where nearshore productivity is inhibited by turbid water may be common in the Gulf, judging from the extent to which coastal areas are influenced by silt-laden water (Hampton, Carlson, Lee, and Feely, Ch. 5, this volume).

Grazing pressure in coastal areas may differ significantly from that found in oceanic areas. In the southeast Bering Sea, phytoplankton losses due to macrozooplankton grazing are significantly fewer in the coastal areas than they are farther offshore (Cooney and Coyle 1982). This is probably the case in nearshore regions in the Gulf, although this pattern is certainly not applicable to all coastal Gulf regions. For example, coastal advection carries oceanic zooplankton into Prince William Sound, which is deep enough for these populations to overwinter (Cooney, Ch. 10, this volume). Therefore, grazing pressure in such areas may approach that found in oceanic regions of the Gulf.

Survey of Coastal Phytoplankton-Related Measurements

Both chlorophyll *a* and productivity levels in Adak Bay and in the adjacent coastal/inner-Alaskan Stream water were consistently greater than those levels for oceanic

waters of the Gulf (Larrance 1971a, b). Summer daily productivity in the coastal waters here typically exceeded 0.4 g C/m²d, with integrated euphotic zone chlorophyll *a* values of over 20 mg/m². Values for both parameters were greater still inside Adak Bay.

In the oceanic region south of Adak Island, productivity rarely exceeded 0.3 g C/m²d, and the integrated chlorophyll *a* levels were never greater than 20 mg/m². Larrance (1971a, b) also noted that there were elevated nutrient levels in the coastal surface water compared with the nutrient levels for the surface layer of deeper waters. These nutrients may be an indication of coastal upwelling in this region.

Water movement through the Aleutian passes appears to produce local upwelling. This may be the case in Unimak Pass, where nutrient-rich water produces localized high productivity (Kelley *et al.* 1971). On the shelf between Kodiak Island and Unimak Pass, wind stress usually promotes upwelling during the summer (Ingraham, Bakun, and Favorite 1976). During August, the relatively cold surface water found both in and around Unimak Pass and in the Shumagin Islands suggests that substantial upwelling occurs throughout this entire area (Fig. 9-12). Kelley *et al.* (1971) found a strong correlation between surface-water pCO₂ and nitrate, suggesting that these two upwelled nutrients are consumed at least in part during plant growth. In this area, a supply of cold, deep water elevates the nitrate levels, the pCO₂, and the diatom growth well into July (Koike, Furuya, Otake, Nakai, Nemoto, and Hattori 1982).

During those summer conditions when upwelling does not occur near the coast, surface nutrient levels may decrease to a point where they begin to limit phytoplankton growth. In such cases, the vertical mixing caused by the Alaska Coastal Current could still provide enough nutrients to sustain growth. However, no clear examples of this inter-

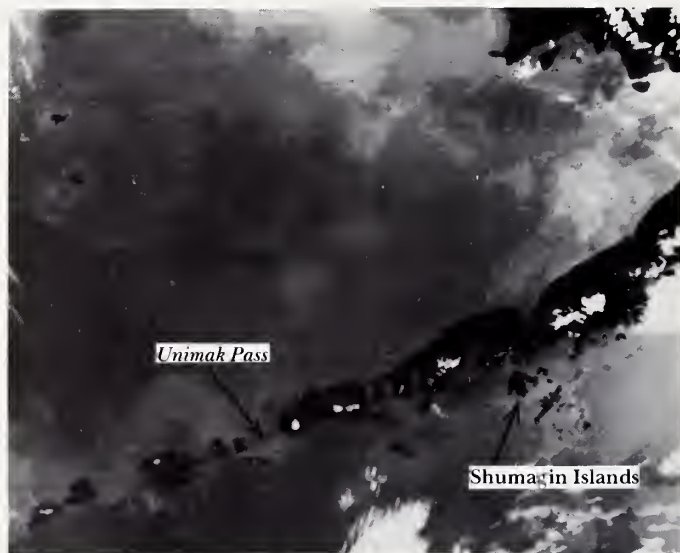


Figure 9-12. Satellite image of the western Gulf during the summer. Shades of gray correspond to surface-water temperatures that range from cold (light gray) to warm (dark gray). The upwelling of cold subsurface water is apparent from the lighter-shaded surface water in and around Unimak Pass and the Shumagin Islands.

action are available from the limited data available for the Gulf.

On the northern shelf of the Alaska Peninsula, there is a coastal current that is associated with an intense subsurface chlorophyll *a* layer (Fig. 9-13). The rise in the depth of the nitrate isopleths in Figure 9-13a was probably caused by an intensified vertical shear at this depth. The water stratum just above the isopleths is commonly associated with a relative maximum in zooplankton abundance (Herman 1983). Also, these layers may serve as important feeding environments for larval pollock (Nishiyama, Hirano, and Haryu 1982). This sequence of relationships provides a mechanism by which the biological processes of the coastal area could respond to variations in both the transport and the speed of the coastal current (Sambrotto 1985).

In late fall 1975, Larrance *et al.* (1977) made an extensive collection of productivity and related data in the central Gulf's coastal and nearshore areas (see Fig. 18-3, this vol-

ume). This figure illustrates the inhibiting effect that turbidity has on productivity in nearshore waters. It also indicates that productivity rates greater than 0.4 g C/m²d were present throughout both the outer-shelf and the oceanic areas that were sampled at that time. In July of 1976, the extreme southwestern station in this survey supported an integrated carbon productivity value of 2.4 g C/m²d. This indicates that both the central Gulf shelf and slope regions are much more productive than the oceanic and nearshore areas.

Detailed seasonal data in Cook Inlet were presented by Larrance and Chester (1979) and by Chester and Larrance (1981). A section that extended across the lower portion of the Inlet was repeatedly sampled from April through August (Fig. 9-14). The results illustrate the dependence of coastal phytoplankton productivity on hydrographic conditions. Figure 9-15 depicts typical end-of-winter conditions along the section from Kamishak Bay (Station 1) to Kachemak Bay (Station 7). Judging from the lack of structure in the density field, the upper mixed layer was relatively deep (Fig. 9-15a). The standing crop of phytoplankton at this time was low (Fig. 9-15b). Also, the depth uniformity of the nitrate concentration indicates that no substantial phytoplankton growth had occurred (Fig. 9-15c).

Conditions in the sampling area changed a great deal during spring, however; and by 10 June, surface-water stratification was evident in both Kamishak and Kachemak Bays (Fig. 9-16a). The stratification was associated with surface accumulations of chlorophyll *a* (Fig. 9-16b), indicating that a typical, physically mediated, high-latitude spring bloom sequence takes place in these waters. By June, phytoplankton nitrate consumption had significantly reduced the nitrate levels across the sampling section and had exhausted

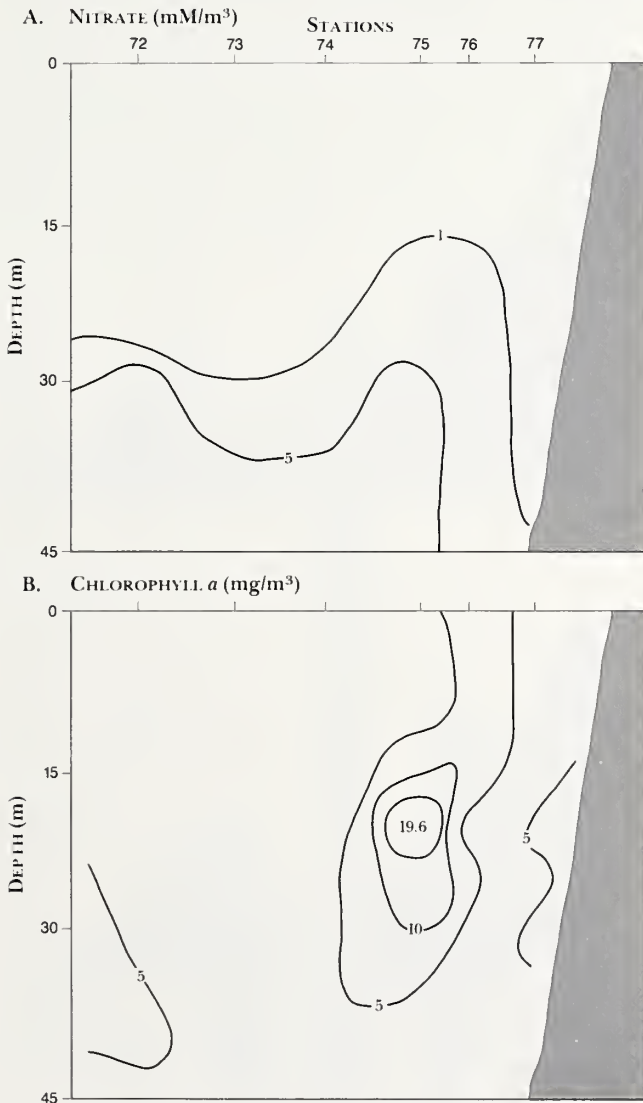


Figure 9-13. Nitrate and chlorophyll *a* sections normal to the North Aleutian Shelf (56°47'N, 164°19'W to 57°9'N, 162°17.9'W). (Compiled from data in Niebauer, McRoy, and Goering 1980.)

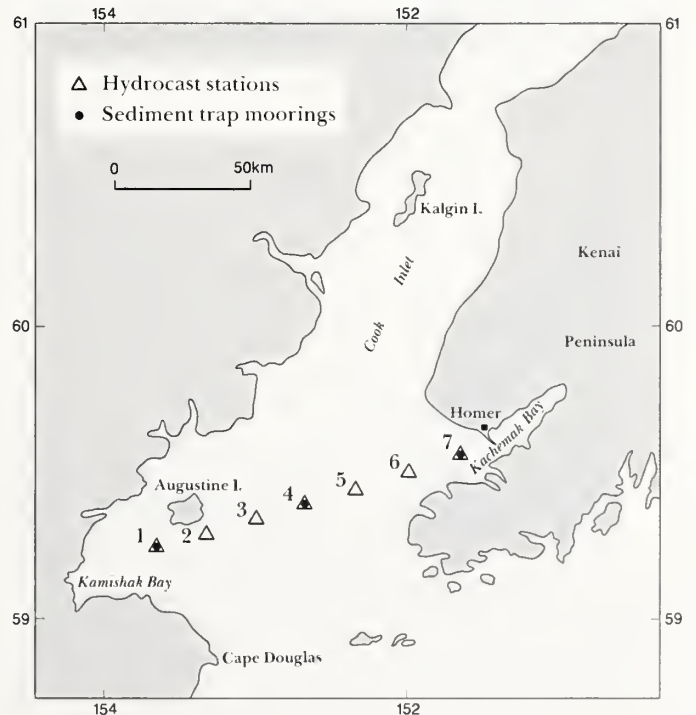


Figure 9-14. Lower Cook Inlet station locations sampled during April through August by Larrance and Chester (1979).

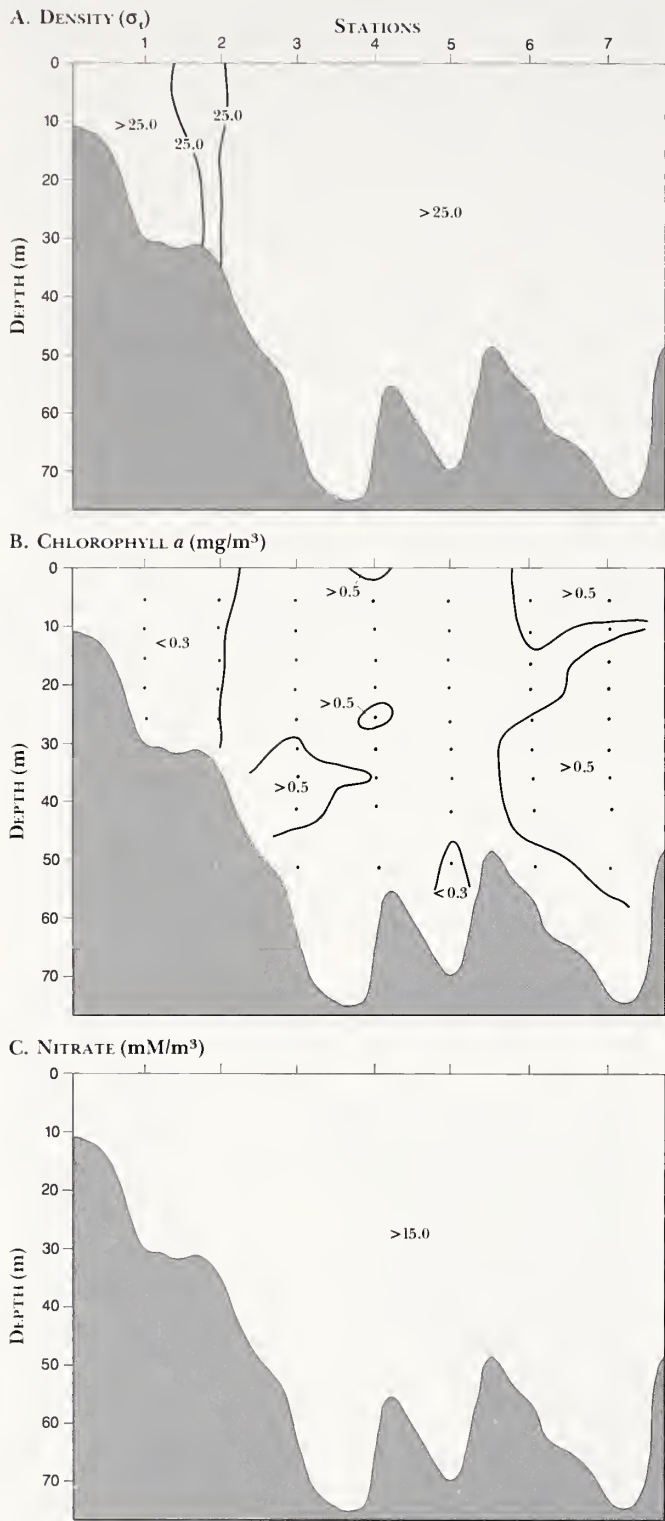


Figure 9-15. Late March 1978 sections across lower Cook Inlet from Kamishak Bay (Station 1) to Kachemak Bay (Station 7). (Modified from Larrance and Chester 1979.)

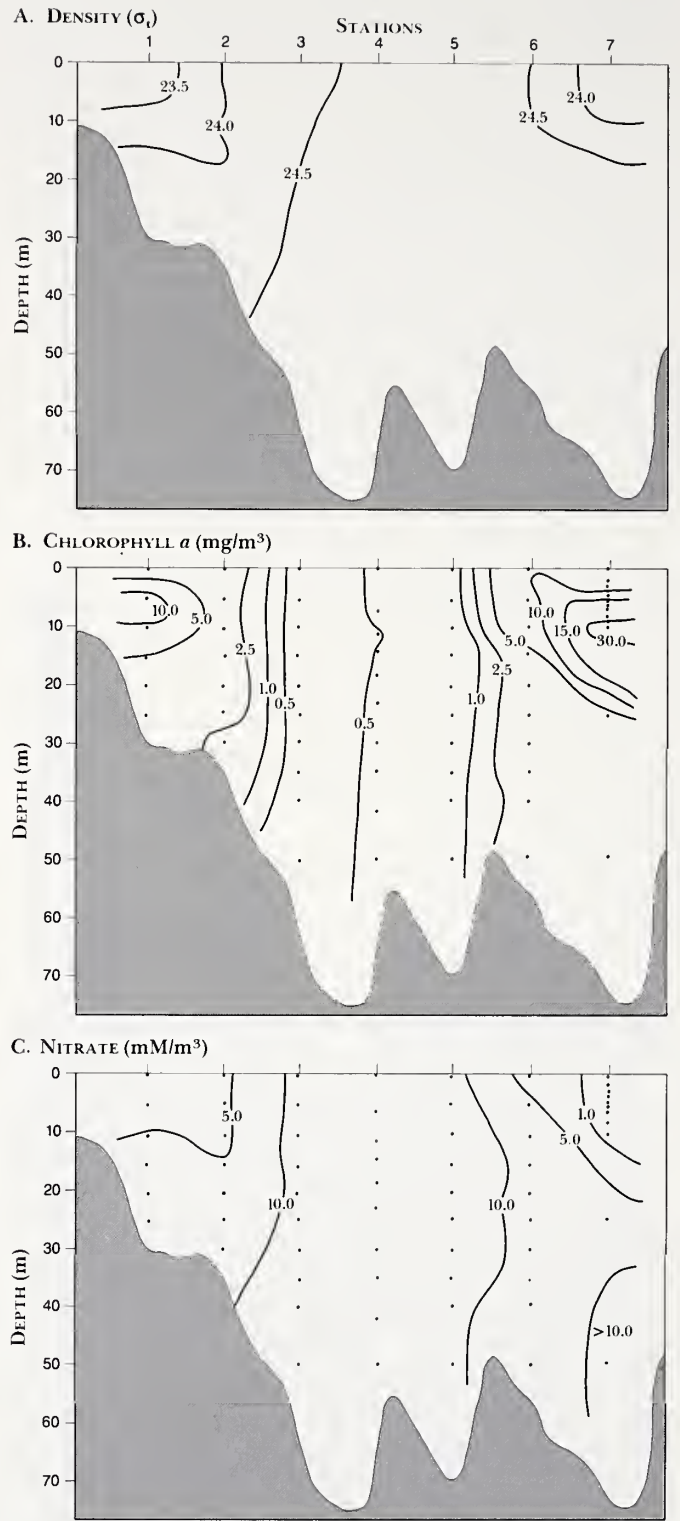


Figure 9-16. June 1978 sections across lower Cook Inlet from Kamishak Bay (Station 1) to Kachemak Bay (Station 7). (Modified from Larrance and Chester 1979.)

the nitrate content of the surface waters in Kachemak Bay. In contrast, nitrate concentrations remained relatively high in outer Kachemak Bay (Fig. 9-16c). Chlorophyll *a* concentrations across this section were at their maximum in early July, coincident with minimum nitrate levels. Bacterial activity in Kachemak Bay closely followed this production cycle, although heterotrophic activity may lag phytoplankton production slightly (Griffiths, Caldwell, and Morita 1982).

Even in early July, nitrate was not exhausted from the upper water in the middle of lower Cook Inlet. Deeper water that upwelled may be responsible for maintaining these nitrate levels and the extremely productive area in outer Kachemak Bay. Productivity in this area was high throughout the summer (Fig. 9-17). Production values exceeding 7 g C/m²d were measured here, and time-integrated productivity values suggest that yearly production may exceed 300 g C/m². These data indicate that lower Cook Inlet is among the most productive high-latitude shelf areas in the world.

Sediment trap data collected in outer Cook Inlet demonstrate the important role that copepod fecal pellets play in the sinking flux of surface organic particles (Table 9-5) (Larrance and Chester 1979). Fecal pellets accounted for 83% of the loss of surface chlorophyll *a*. Large numbers of oceanic grazers may be brought to this area by the Alaska Coastal Current (T. Cooney, University of Alaska, pers. comm.). This

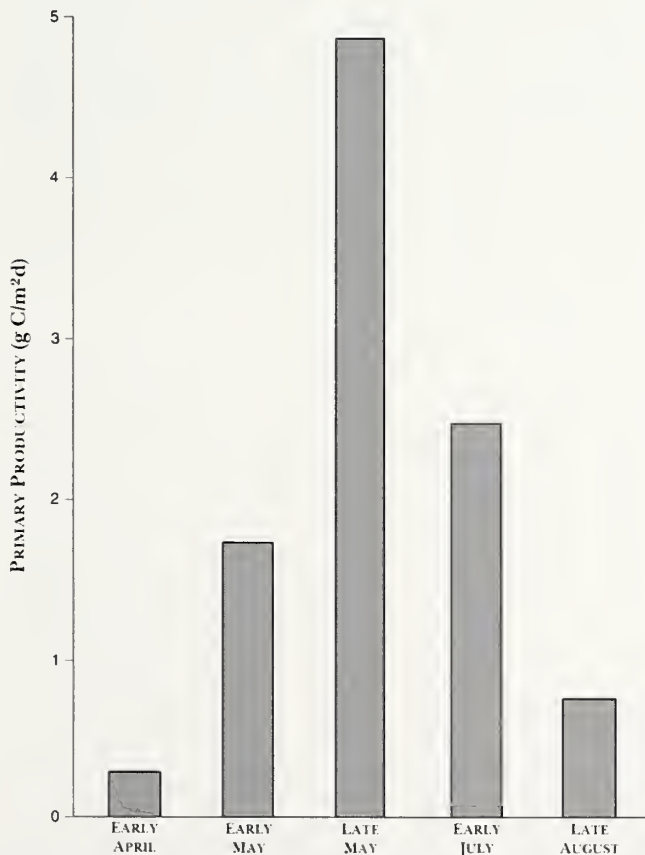


Figure 9-17. Average seasonal primary productivity in outer Kachemak Bay (Station 7, Fig. 9-14) during 1976. (Modified from Larrance *et al.* 1977.)

Table 9-5.

Daily particulate flux (numbers/m²) settling near the bottom in lower Cook Inlet, 1978 (from Larrance and Chester 1979). See Figure 9-14 for locations of sediment traps.

	FECAL		TINTINNIDS (× 10 ⁶)	DINOFLLAGELLATES	MOLTS
	PELLETS	DIATOMS			
Kachemak					
May	0.360	13.41	0.114	0.023	0.027
Jun	0.932	15.82	0.408	0.024	0.016
Jul	-	-	-	-	-
Aug	3.110	9.40	2.355	0.240	0.046
Central					
May	0.247	154.07	0.148	0.018	0.001
Jun	2.010	14.23	0.489	0.073	0.006
Jul	0.079	7.27	0.041	0.010	0.001
Aug	0.119	196.22	0.118	0.012	0.004
Kamishak					
May	0.092	20.05	0.199	0.133	0.000
Jun	-	-	-	-	-
Jul	0.750	9.29	0.367	0.208	0.016
Aug	1.830	6.75	1.158	0.025	0.034

means that—unlike some nearshore areas—phytoplankton grazing losses in lower Cook Inlet are significant.

Ungrazed diatoms that sink also account for significant losses of surface-produced carbon in this area. In Cook Inlet, detrital phytoplankton are associated with fine-sized sediment material that exhibits a high percentage of organic carbon content (Atlas, Venkatesan, Kaplan, Feeley, Griffiths, and Morita 1983). Analysis of this material indicated that petroleum hydrocarbons from local oil-extraction activities were not contaminating nearby food webs.

Production studies began in the early 1970s in Resurrection Bay on the Kenai Peninsula (Heggie, Boisseau, and Burrell 1977). Even though these measurements are scattered, they indicate that yearly production here may exceed 200 g C/m². A facility was established in Seward, Alaska for pumping deep, nutrient-rich water from the fjord into ponds in order to study artificial upwelling (Nevé, Clasby, Goering, and Hood 1976). This facility was used to study both the growth and the sinking dynamics of coastal phytoplankton (Bienfang 1984). In Resurrection Bay, most of the phytoplankton biomass, as well as the photosynthesis that took place during the summer, was associated with cell sizes of less than 5 μm. Conversely, in the upwelling test ponds, more than 50% of the phytoplankton were larger than 20 μm. No significant difference was found between the sinking rates of the two groups (sinking rates varied from 0.07 to 0.63 m/d). Almost the entire downward flux of organic carbon and nitrogen was associated with the larger particles, however.

Detailed seasonal data on phytoplankton growth also exist for selected areas of Prince William Sound. In Port Valdez and Valdez Arm, both chlorophyll *a* concentrations and carbon productivity were measured bimonthly from May 1971 to April 1972 by Goering, Shiels, and Patton (1973). They found a typical spring-bloom sequence in which both the areal photosynthesis and the standing crop increased dramatically in April, depleting the upper water of nitrate.

Productivity then decreased during the remainder of the summer in the dozen areas for which time series are available. They did, however, find fall increases in areal photosynthesis for several areas (Fig. 9–18). The average yearly production for all the areas covered in the study was $\sim 185 \text{ g C/m}^2$.

Goering, Shiels, and Patton (1973) also made ^{15}N measurements of both nitrate and ammonium uptake (Table 9–6). During April—before the surface-water nutrients were depleted—nitrate was the dominant form of nitrogen used for growth, and the percentage of nitrate uptake—to-total nitrogen uptake (nitrate and ammonium) was over 65% on an areal basis. Their July measurements were made well after the nutrients were depleted, and carbon productivity had decreased more than an order of magnitude compared with the April sampling. In July, the nitrogenous-nutrition pattern was completely reversed from that in April, and nitrate supplied only 1% of the phytoplankton nitrogen demands. These data illustrate the tendency for nitrate to play a more important role as a phytoplankton nitrogen source in eutrophic (more productive) situations.

During the summer, it is common to find such nutrient-depleted conditions in the surface mixed layer of the coastal areas. For example, the strong physical stratification that develops in Auke Bay also results in nitrogen limitation and a sharp decrease in the phytoplankton standing crop compared with the spring values (Bruce 1969). Storms with accompanying winds that are strong enough to both deepen the surface mixed layer and to resupply the upper euphotic zone with nutrients during the summer were associated with renewed phytoplankton growth (Iverson, Curl, O'Connors, Kirk, and Zakar 1974).

Iverson, Curl, and Sanger (1974) incorporated this wind mixing into their numerical model of Auke Bay phytoplankton dynamics—a model that predicted phytoplankton responses to a deeper mixed layer. In Auke Bay, the Mendenhall Glacier runoff apparently does not significantly enrich the nutrient levels—as occurs in some other glacially fed coastal areas (Apollonio 1973). Also, a study of how organic nitrogen was used by the Auke Bay phytoplankton indicated that although the dissolved free amino acids become relatively abundant during phytoplankton growth, an uptake of ^{15}N -labeled amino acids accounted for only a small fraction of the phytoplankton nitrogen requirements (Schell 1974).

Several groups have conducted detailed studies of seasonal phytoplankton production in Alaskan fjords, specifically in Boca de Quadra fjord and in Smeaton Bay–Wilson Arm near the Alaskan/Canadian border (Burrell 1984; VTN Sciences 1982). Seasonal sampling in Boca de Quadra fjord in 1980 indicated that the annual production there was $\sim 145 \text{ g C/m}^2$, and that much of this production took place during spring and fall bloom periods (Burrell 1984). The surface waters of both these fjords were nutrient depleted throughout the summer, causing peaks in both productivity and biomass to occur in subsurface layers (Fig. 9–19).

Often in such physically stratified waters, the productivity maximum occurs in shallower areas than the biomass (chlorophyll *a*) maxima. April carbon and nitrogen compositional data for the particulate material in Boca de Quadra fjord is presented in Table 9–7. Station BQ–15 is outside the mouth of the fjord and BQ–3A is the farthest station inside the fjord. At the outer station (BQ–15), the lowest C-to-N ratios in the particulate material were found at the

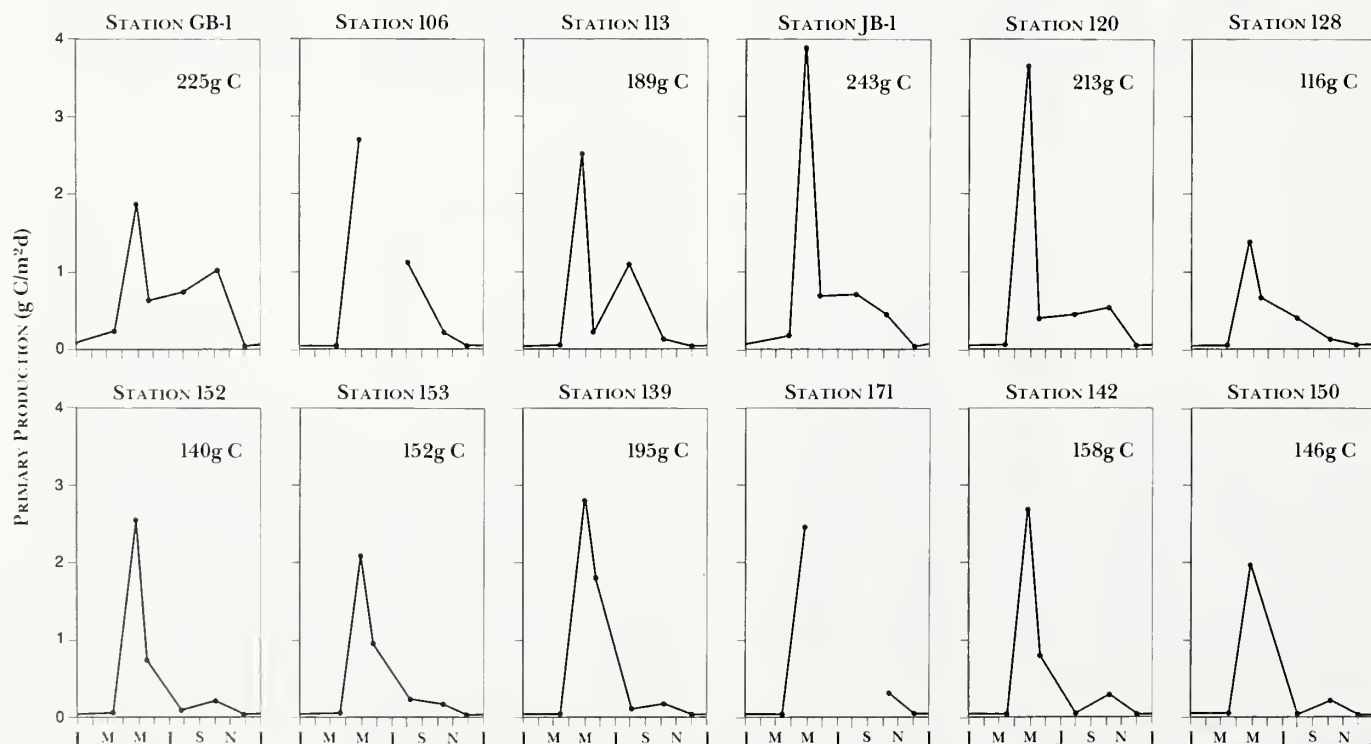


Figure 9–18. Daily and annual rates of primary production in 12 locations around Port Valdez, Valdez Arm, and contiguous bays. (Modified from Goering, Shiels, and Patton 1973.)

Table 9-6. Nitrogen-15 and carbon-14 uptake rates by phytoplankton during spring and summer at Jackson Point, Port Valdez. (Modified from Goering, Shiels, and Patton 1973.)

DEPTH (m)	NO ₃ ⁻ UPTAKE (μM NO ₃ ⁻ - N/l·h)	NH ₄ ⁺ UPTAKE (μM NH ₄ ⁺ - N/l·h)	PERCENT NO ₃ ⁻ UPTAKE ^a	CARBON UPTAKE (μM HCO ₃ ⁻ - C/l·h)	C:N UPTAKE RATIO
31 July 1971					
0	0.0003	0.0091	2.8	0.0508	5.4
5.0	0.0006	0.0397	1.5	0.0350	0.9
10.0	0.0002	0.0230	0.9	0.0250	1.1
15.0	0.0001	0.0108	0.9	0.0100	0.9
20.0	0.0001	0.0025	2.0	0.0058	2.3
25 April 1972					
0	0.0184	0.0019	90.6	0.8525	42.0
2.0	0.0038	0.0023	62.8	1.5775	258.6
3.5	0.0102	0.0022	81.9	1.6917	136.5
5.0	0.0103	0.0026	79.6	1.3858	107.4
10.5	0.0009	0.0057	13.3	0.1467	22.4

$$^a \%NO_3^- \text{ uptake} = \frac{NO_3^- \text{ uptake}}{NO_3^- \text{ uptake} + NH_4^+ \text{ uptake}} \times 100$$

surface, unlike the more inshore stations at which minima in the C-to-N ratio occurred in subsurface strata. These subsurface minima in the C-to-N ratios coincided with subsurface chlorophyll *a* maxima, and may indicate that the phytoplankton there were growing in a nitrogen-replete environment.

East of the Queen Charlotte Islands in Hecate Strait, the summer phytoplankton biomass was greatest along a coastal front (Perry *et al.* 1983). This physical feature marks the transition between the vertically mixed nearshore water and the deeper, stratified water. The characteristics of these tidally mixed fronts apparently prevent the depletion of local nutrients. These fronts are often associated with a summer increase in phytoplankton populations in several other temperate shelf areas as well. Most likely, these fronts are present along much of the Gulf coast and, as in Hecate

Strait, they locally enhance phytoplankton growth during the summer.

Just south of Hecate Strait, Denman, Mackas, Freeland, Austin, and Hill (1981) identified zones of both high productivity and high biomass along the west coast of Vancouver Island. These zones were attributed to the combined effects of the along-shore current and to complex bathymetry that produced upwelling conditions. The Alaskan Stream may have the same effects in other areas of the Gulf. For example, the interaction of the Alaskan Stream and the shelf break may bring nutrient-rich slope water into the euphotic zone.

Coastal Phytoplankton Species Composition

In the fall of 1975, Larrance *et al.* (1977) conducted a taxonomic analysis of the phytoplankton communities found in the coastal and near-oceanic areas of the central Gulf. These data indicated that the geographic distribution of the silicoflagellate *Dictyocha fibula* was mutually exclusive of the distribution of the diatom *Fragilariopsis* sp. (The genus *Fragilariopsis* has since been combined with *Nitzschia*.) The silicoflagellate was found only in areas west of the Copper River delta, and the diatom was restricted to areas east of the

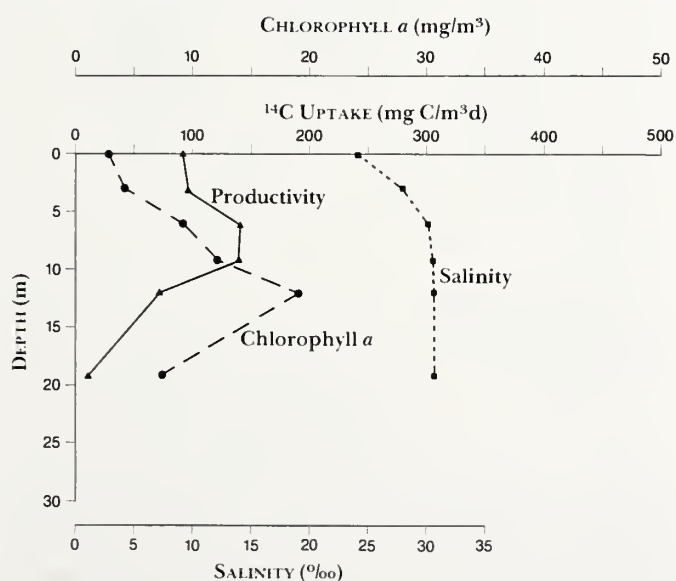


Figure 9-19. Vertical profiles through the euphotic zone for ¹⁴C uptake, chlorophyll *a*, and salinity at the head of Wilson Arm off Smeaton Bay near Ketchikan, Alaska during April 1982. (Modified from Burrell 1984.)

Table 9-7. Carbon-to-nitrogen ratios found in particulate matter through the euphotic zone in Boca de Quadra fjord in April 1983 (from Burrell 1984).

LIGHT LEVEL (%)	STATION					
	BQ-15	BQ-11B	BQ-9	MA-2	BQ-5	BQ-3A
100	5.6	5.9	7.7	7.0	7.6	6.5
50	5.9	5.0	6.7	5.6	5.2	6.3
25	6.0	5.8	5.7	7.1	5.6	9.3
11	6.3	7.9	5.2	7.7	4.5	5.7
6	5.3	6.0	4.6	5.8	6.2	-
1	9.1	11.7	4.9	5.9	4.0	-

delta at that time. However, microflagellates were ubiquitous throughout the sampling area (Fig. 9–20). There is some indication that microflagellate densities on the shelf were about an order of magnitude larger than their densities at the more oceanic stations.

In addition, Larrance *et al.* (1977) observed differences between the phytoplankton communities found at the oceanic stations and those found in Prince William Sound. The offshore areas were dominated by microflagellates, while the Sound assemblage was dominated by diatoms. Diatoms also dominated the phytoplankton composition throughout the year off Nikiski (Schandelmeier 1975). A list of those phytoplankton species that were found in significant numbers in lower Cook Inlet during the spring and summer of 1976 is presented in Table 9–8 (Larrance *et al.* 1977). This list differs from the oceanic–species list (Table 9–2) in several respects. In particular, neritic species such as *Melosira sulcata*, which are totally absent from oceanic areas, were found in coastal waters. Based on temporal data in Table 9–8, the seasonal changes in phytoplankton community composition are presented graphically in Figure 9–21. A build-up of *Thalassiosira* spp. in April preceded the appearance of *Chaetoceros* spp., and both of these genera coexisted during the very productive period during May. Microflagellates dominated the outer Inlet in late August as they did throughout the oceanic waters during this time. The neritic *Melosira sulcata* usually dominated the upper parts of Cook Inlet.

The seasonal succession of phytoplankton species is closely associated with the changing hydrography of the coastal areas (Levasseur, Therriault, and Legendre 1984). This tendency is evident in the species changes recorded by Larrance *et al.* (1977) in lower Cook Inlet (Fig. 9–21). For example, the appearance of the *Thalassiosira*–*Chaetoceros* community in May coincided with the establishment of a stable upper–water column at this time. These observations are similar to those of Iverson, Curl, O’Connors, Kirk, and Zakar (1974) made in Auke Bay. The diatom bloom which formed upon the initial stratification of the water column in Auke Bay was composed mainly of *Thalassiosira aestivalis*, a

Table 9–8.

Phytoplankton species present in abundances greater than 1,000 cells/l in lower Cook Inlet from April through August 1976. (Modified from Larrance *et al.* 1977.)

	APRIL 7–12	MAY 6–9	MAY 25–28	JULY 10–15	AUGUST 25–31
Chrysophytes					
<i>Dictyocha fibula</i>				x	
<i>Ebria tripartita</i>				x	
Diatoms					
<i>Actinopterychus undulatus</i>				x	
<i>Bacteriastrium delicatulum</i>					x
<i>Cerataulina bergonii</i>				x	x
<i>Chaetoceros affinis</i>			x	x	
<i>Chaetoceros compressus</i>				x	x
<i>Chaetoceros concavicornis</i>	x	x	x	x	
<i>Chaetoceros constrictus</i>				x	x
<i>Chaetoceros convolutus</i>				x	
<i>Chaetoceros debilis</i>		x	x	x	x
<i>Chaetoceros decipiens</i>		x	x	x	
<i>Chaetoceros didymus</i>				x	
<i>Chaetoceros radicans</i>			x	x	
<i>Chaetoceros subsecundus</i>				x	
<i>Chaetoceros socialis</i>		x	x		x
<i>Chaetoceros</i> spp.			x	x	x
<i>Corethron hystrix</i>			x	x	
<i>Cylindrotheca closterium</i>	x		x		
<i>Denticulopsis semina</i>			x	x	
<i>Fragilariopsis</i> spp.	x	x	x	x	
<i>Leptocylindrus danicus</i>				x	
<i>Melosira sulcata</i>	x	x	x	x	x
<i>Navicula distans</i>					x
<i>Navicula</i> spp.				x	x
<i>Nitzschia delicatissima</i>	x	x	x	x	x
<i>Nitzschia longissima</i>	x	x	x	x	x
<i>Nitzschia</i> spp.				x	x
<i>Rhizosolenia delicatula</i>				x	
<i>Rhizosolenia fragilissima</i>				x	
<i>Rhizosolenia stouterfothii</i>				x	
<i>Schroederella delicatula</i>		x		x	
<i>Skeletonema costatum</i>			x		
<i>Stephanopyxis nipponica</i>				x	
<i>Thalassionema nitzschioides</i>	x	x	x	x	x
<i>Thalassiosira aestivalis</i>	x	x	x	x	x
<i>Thalassiosira decipiens</i>	x	x	x		
<i>Thalassiosira gravida</i>	x		x		
<i>Thalassiosira nordenskiöldii</i>	x	x	x		
<i>Thalassiosira pacifica</i>	x		x	x	
<i>Thalassiosira polychorda</i>		x	x		
<i>Thalassiosira rotula</i>	x	x	x		
<i>Thalassiosira</i> spp.	x	x	x	x	
<i>Tropidoneis antarctica</i>					x
Dinoflagellates					
<i>Exuviella</i> spp.	x	x	x		
<i>Gymnodinium lohmanni</i>	x				
<i>Oxytoxum</i> spp.			x	x	
<i>Peridinium mimusculum</i>			x		
<i>Peridinium</i> spp.		x	x	x	
Miscellaneous					
green algae		x	x	x	x
microflagellates	x	x	x	x	x

common early bloom species. However, the later productivity peaks associated with wind mixing were often composed of *Skeletonema costatum*.

Goering, Shiels, and Patton (1973) found that the flagellate *Phaeocystis pouchetii* was numerically dominant during April in Valdez Arm. However, during the less productive July conditions, the phytoplankton community was domi-

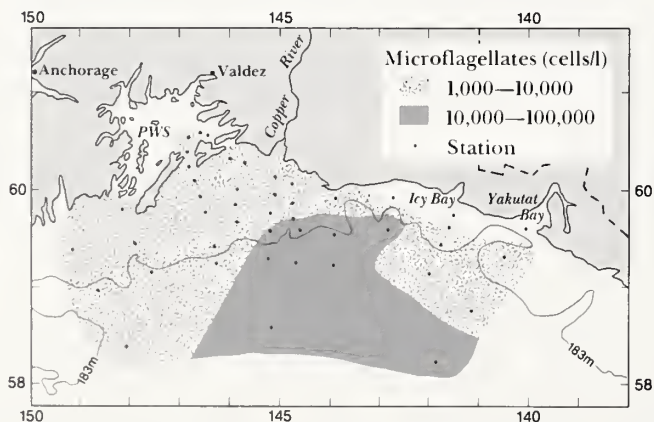


Figure 9–20. Distribution of microflagellates at the 10-m depth in the central Gulf of Alaska from October through November 1975. (Modified from Larrance *et al.* 1977.)

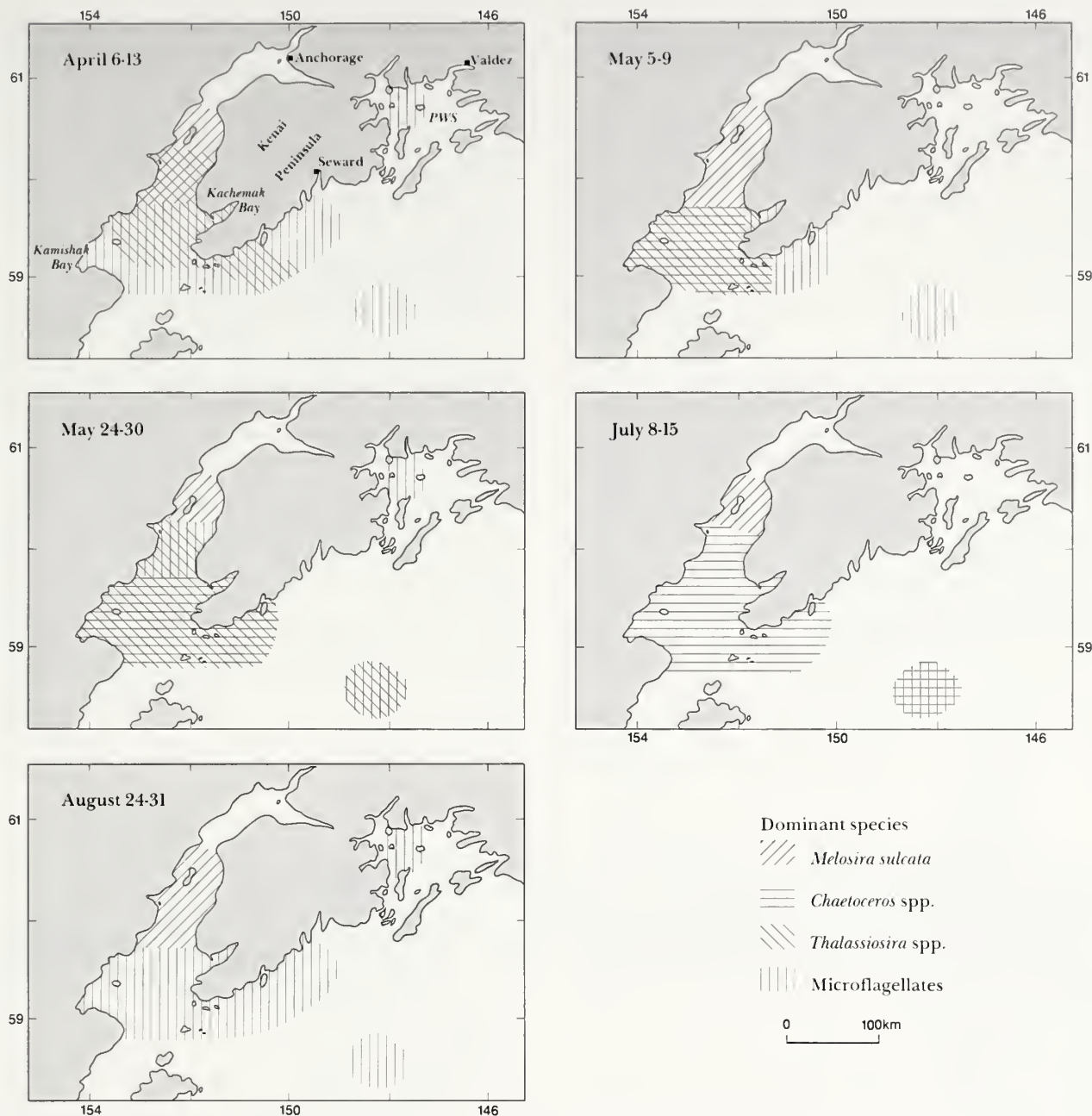


Figure 9-21. Distribution of dominant phytoplankton groups in lower Cook Inlet and adjacent waters from April through August 1976. (Modified from Larrance *et al.* 1977.)

nated by the dinoflagellate *Ceratium longipes*. During this time, the nitrate and carbon productivities changed dramatically as well (Table 9-5). Therefore, the composition of the phytoplankton community may play an important role in determining local production rates.

Generalizations regarding the exact sequence of species during the growing season are difficult to make because of the heterogeneous nature of the phytoplankton growth conditions that are encountered in the coastal Gulf. For example, the high volume of siltation found in the area west of the Copper River mouth is similar to the suspended-particulate loading found in Cook Inlet (Kinney, Groves, and Button 1970). The shading caused by this suspended material is

probably responsible for the slower-than-expected utilization of surface nitrate in the upper Inlet during spring. This shading effect may also slow the successional sequence of the phytoplankton species found here. An additional complication in successional studies is that species composition can vary with depth as well as time. For example, cell counts from Galena Bay indicated that *Phaeocystis pouchetii* could be found in numbers of over 1,000 cells/ml at depths where the light level was 1%, and at the same time they were almost absent from the surface waters above (Table 9-9).

Size fractionation studies of the phytoplankton biomass have been done in Smeaton Bay near Ketchikan (Southeast Alaska) (VTN Sciences 1982). These studies indicated that

Table 9–9. Phytoplankton counts (cells/ml) of samples collected from the 100% and 1% light depths in Galena Bay during late April (from Horner *et al.* 1973).

SPECIES	CELL COUNTS
100% light depth	
Diatoms	205
Small flagellates	9
<i>Phaeocystis pouchetii</i>	2
1% light depth	
Diatoms	1006
Small flagellates	30
<i>Phaeocystis pouchetii</i>	1148

the ultraplankton (< 5 μm) usually dominated the standing crop of chlorophyll *a*. Only during the spring diatom bloom did the larger (> 5 μm) phytoplankton dominate the community. However, during the bloom, the larger phytoplankton constituted up to 95% of the total chlorophyll *a*.

Successional changes in the phytoplankton were well documented by tracking the species changes at four stations in the Smeaton Bay area (Fig. 9–22). During each time series, the large, chain-forming diatom *Thalassiosira nordenskioldii* reached its peak abundance and numerically dominated the

phytoplankton community during the April spring bloom. Since this was also the maximum productivity period of this species, it alone may be responsible for more than 25% of the total yearly production here. The most seaward station (SB7) exhibited a reduced diatom bloom in spring. However, during the summer, diatoms contributed a larger proportion of the total phytoplankton numbers at this station than at the more protected stations.

Dinoflagellate Growth in Coastal Gulf Waters

Certain dinoflagellates produce toxins that can be transmitted to people if they eat contaminated filter-feeding organisms such as clams. Periods of intense summer dinoflagellate growth (often called 'red tides' because of the color that dense populations impart to nearshore waters) can produce local anoxic conditions that damage fish populations (Malone 1978). Alaska has the potential for a substantial bivalve mollusk fishery (Orth, Smelcher, Feder, and Williams 1975). Therefore, red tides near such fisheries are significant both in terms of human health and in terms of economics (Fortune 1975).

Dinoflagellates have been found among the phytoplankton in both southeast Gulf coast waters (Chang 1971) and in northern Gulf coast waters (Schantz and Magnussen

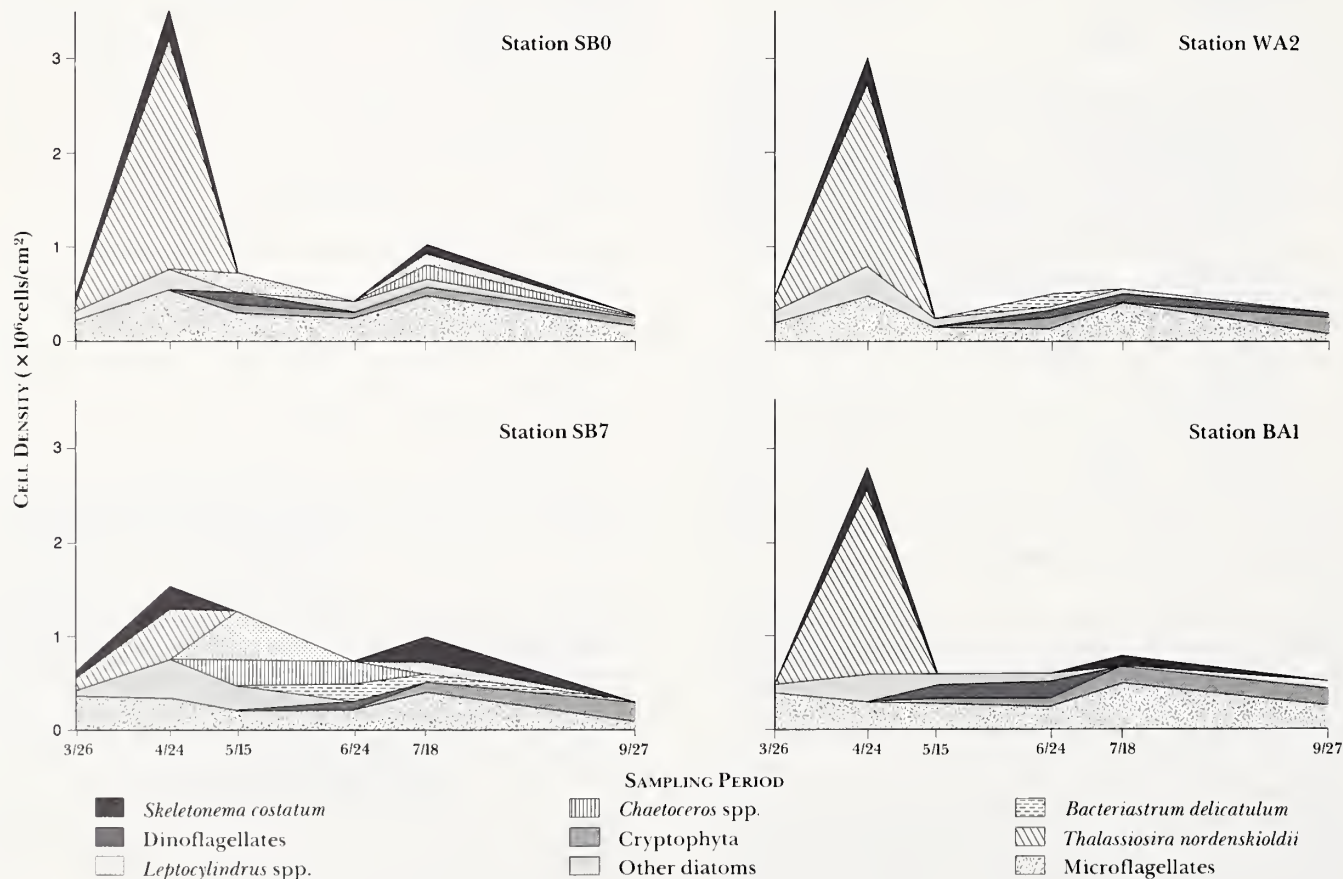


Figure 9–22. Seasonal changes in composition of the phytoplankton community at four stations in the Smeaton Bay area near Ketchikan, Alaska. (Modified from VTN Sciences 1982.) Station SBO is at the juncture of Wilson and Bakewell Arms, Station SB7 is in Behm Canal at the mouth of Smeaton Bay, and Stations WA2 and BAI are approximately at the midpoints of Wilson and Bakewell Arms, respectively.

1964). The Wilson Arm/Smeaton Bay taxonomic data (Fig. 9–22) indicated that dinoflagellates appear in the coastal phytoplankton community at the end of the spring diatom bloom and persist throughout much of the summer. This is typical of the way they occur in the seasonal species sequence of coastal waters in other areas as well (Karentz and Smayda 1984).

Dinoflagellate resting cysts have been isolated from sediments throughout Alaskan coastal waters (Fig. 9–23). Hall (1982) identified the dinoflagellates as members of the genus *Protogonyaulax* and demonstrated their capacity for toxicity. Although Figure 9–23 is not a quantitative record of dinoflagellate distribution for Alaskan waters, it suggests that dinoflagellates are a common component of the phytoplankton assemblage in the coastal Gulf. Dinoflagellates have also been found in surface waters during episodes of paralytic shellfish poisoning that occurred both in False Pass (Meyers and Hilliard 1955) and in Tenakee Inlet (Zimmerman and McMahon 1976). However, only in areas near Ketchikan was there an actual correlation made between shellfish toxicity and an abundance of dinoflagellates (Neal 1967). A definitive link between an abundance of dinoflagellates and filter-feeder toxicity may be missing for several reasons: 1) invertebrates may remain toxic for some time after the short-lived dinoflagellates have disappeared, 2) not all dinoflagellate species are toxic, and 3) invertebrates may become toxic after ingesting dinoflagellate cysts from the sediments.

Summary of Regional Productivity Estimates and Conclusions

Estimates for annual phytoplankton production and ranges for seasonal chlorophyll *a* levels for several areas of the Gulf are shown in Table 9–10. Seasonal production measurements in the nearshore areas of the Gulf are scattered. The values presented for the protected embayments near Port Valdez, Auke Bay, and for Boca de Quadra fjord are fairly similar. Typically, most of the production comes from relatively brief blooms in the spring, followed by a secondary production peak in the fall. In Auke Bay, these blooms are augmented by wind-mixing-induced productivity pulses throughout the summer. Less detailed data from Resurrection Bay suggest that yearly production in this fjord could exceed 200 g C/m^2 .

Coastal areas are unusual with respect to most other regions in the Gulf in that the surface waters remain in a nutrient-depleted condition throughout most of the summer. The maximum surface-water chlorophyll *a* values may be exceeded several-fold in subsurface layers that exist during much of the summer.

Studies of primary production in selected Gulf shelf areas indicate that these regions are very productive. In lower Cook Inlet, upwelling that is associated with the Alaska Coastal Current appears to play an important role in maintaining the large daily production ($> 1 \text{ g C/m}^2$) throughout the summer. Water movement through the Aleutian passes also produces local upwelling, and the relatively high productivity values recorded near Adak may reflect this process.

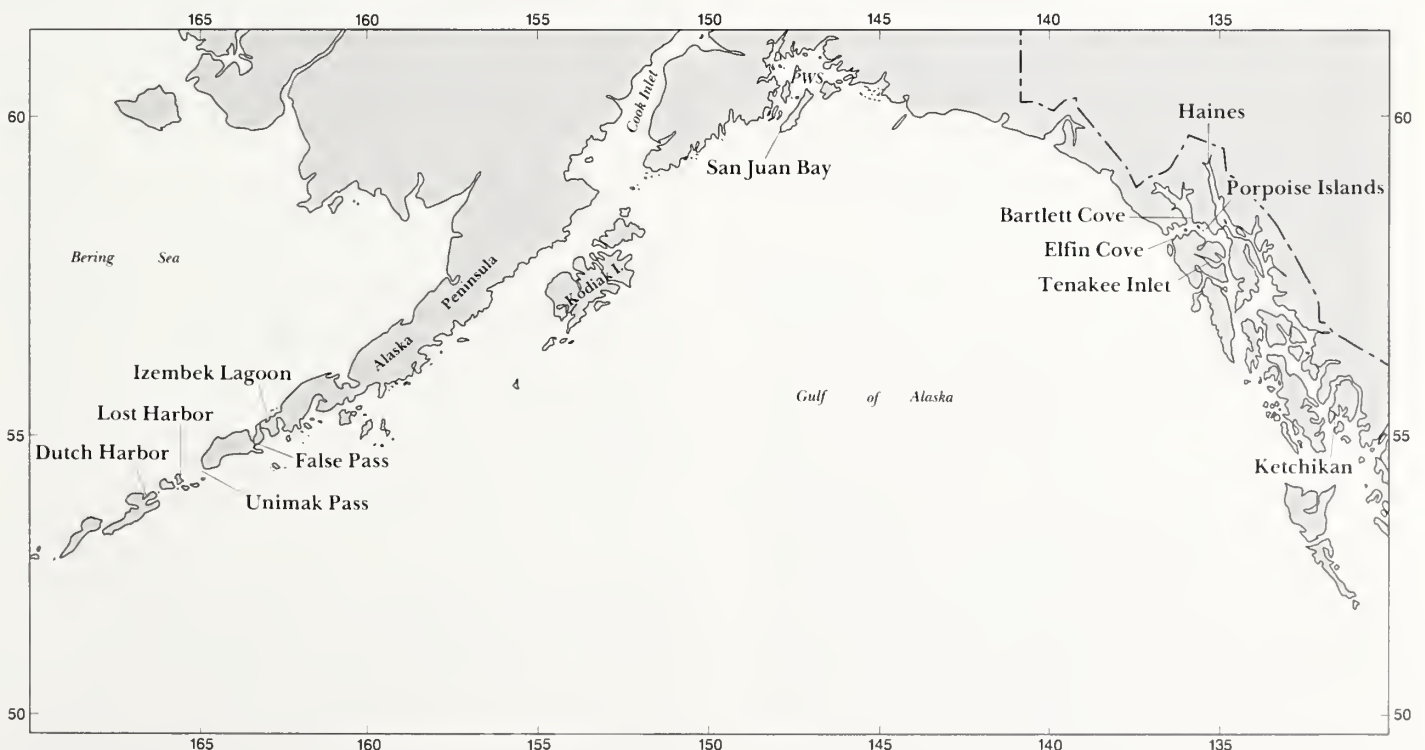


Figure 9–23. Locations where dinoflagellate resting cysts (*Protogonyaulax* sp.) have been isolated in Gulf coastal waters, and where they have been shown to produce paralytic shellfish toxins. (Modified from Hall 1982.)

Table 9–10.
Summary of estimated annual phytoplankton production and chlorophyll ranges from various locations in the Gulf of Alaska.

LOCATION	ANNUAL PRODUCTION (g C/m ²) BASED ON:			SURFACE WATER CHLOROPHYLL <i>a</i> (mg/m ³)
	¹⁴ C	MASS BALANCE OF: NITRATE PHOSPHATE		
Nearshore				
Port Valdez and Valdez Arm ^a	185	–	–	1 to 8*
Auke Bay ^b	200	–	–	1 to 10*
Boca de Quadra ^c	145	–	–	1 to 7*
Shelf				
Adak Bay/Shelf ^d	330	–	–	0.1 to 6*
Lower Cook Inlet ^e	300	–	–	0.1 to 10*
Kenai Shelf	300 ^f	–	–	0.1 to 3 ^g
Oceanic				
Ocean Station P	48 ^h	>100 ⁱ	–	0.2 to 0.5 (rarely 2) ^g
Western Gulf of Alaska ^d (along 176°W)	72–85	–	100	0.2 to 2

^a Goering, Shiels, and Patton 1973.

^b Iverson, Curl, O'Connors, Kirk, and Zakar 1974.

^c Burrell 1984.

^d Larrance 1971a.

^e Larrance and Chester 1979.

^f Larrance *et al.* 1977.

^g Anderson *et al.* 1977.

^h McAllister 1969.

ⁱ See text.

* Larger values measured in subsurface layers.

The reasons for the intense production on the Kenai shelf in the central Gulf are less clear. Environmental features such as the Alaskan Stream coupled with intense grazing pressure on resident phytoplankton may play an important role in the productivity for this area. In any case, our review indicates that previous estimates of phytoplankton production in shelf areas of the Gulf of Alaska must be revised upwards to ~300 g C/m²y.

For the oceanic areas, there is a striking discrepancy between the results of using ¹⁴C incubation techniques and the results of using nutrient mass-balance methods for estimating yearly production. The nitrate mass-balance at Station P was based on the average seasonal nitrate data shown in Figure 9–3. From early March until September, the nitrate content of the upper 100 m decreased ~480 mM/m². If this nitrate (or new) production is multiplied by the average carbon-to-nitrogen composition of phytoplankton (6.6 by atoms) (Redfield *et al.* 1963), it yields an estimated annual carbon production of 38 g C/m². However, nitrate production is only a portion of the total production, and the measurements of Hattori and Wada (1972) indicate that nitrate supplies less than 40% of the phytoplankton nitrogen requirements. Based on the findings of Hattori and Wada, the 38 g C/m² estimate of annual carbon production was increased to 95 g C/m².

Even a production estimate of 95 g C/m²y is conservative because it is based only on the observed local nitrate change without taking into account the summer-long vertical

nitrate supply from deeper waters. Based on Acara's (1964) estimate of upwelling at Station P (~17 m/y), 150 mM NO₃⁻/m² would be supplied vertically over the course of the growing season. Phytoplankton consumption of this extra nitrate would result in ~30 g of additional carbon production. A similar approach to estimating carbon production (based on phosphate) was taken by Larrance (1971a) in the western Gulf. He also suggested that the ¹⁴C incubation estimates for phytoplankton production in the Central Subarctic Domain are low.

The explanation for these significant (over 100% at Station P) discrepancies is not clear. The poor temporal resolution of changes in productivity that are characteristic of the discrete-incubation methods may be a factor, but the sampling at Station P at least, should be fairly reliable. Platt (1984) suggested that microzooplankton grazing that occurs during ¹⁴C incubations could cause underestimates of carbon production. The importance of microzooplankton grazing in the control of phytoplankton standing crop in the Gulf suggests that the conditions necessary to cause such an underestimate are present.

Because there are few detailed data for the Alaskan Gyre, a detailed comparison between productivity in this oceanic area and the productivity in the Central Subarctic Domain is not possible. However, although the phytoplankton growth in both of these areas is never nutrient limited, the more intense upwelling found in the Alaskan Gyre should influence phytoplankton growth there. Specifically, the delay in the onset of elevated productivity in the Alaskan Gyre (suggested by the data of Anderson and Munson 1972) may reflect this greater degree of upwelling.

In terms of overall productivity, the shortened growing season makes the Alaskan Gyre less productive than the Central Subarctic Domain on a yearly basis. However, overall nutrient-consumption calculations indicate that production levels in both the Central Subarctic Domain and the western Alaskan Gyre are greater than previous estimates (*e.g.*, Sanger 1972).

The Gulf of Alaska supports vast fisheries resources (OCSEAP Staff, Ch. 14, this volume; Rogers, Ch. 15, this volume). Predictive fisheries models have been developed that address those interactions that affect phytoplankton growth in the Gulf (Laevastu 1978). However, we still lack the biological information necessary in order to do the same detailed trophodynamic modeling that has been done for other important fishing areas (*e.g.*, Sherman, Smith, Morse, Berman, Green, and Ejsymont 1984). Any advances we can make in quantifying those loss processes that affect phytoplankton in the oceanic Gulf will be helpful in this regard.

Major environmental fluctuations have been recorded for the subarctic Pacific (Fulton and LeBrasseur 1985). These fluctuations appear to be associated with large-scale atmospheric changes (Hamilton and Emery 1985). Such fluctuations most likely influence not only the character, but the quantity of biological production in the Gulf—as they have been shown to do in other North Pacific areas (*e.g.*, Peterson and Miller 1975). Better information (perhaps through remote sensing) on the annual variability in phytoplankton growth is needed in order to address the biological impact of these environmental fluctuations.

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ABSTRACT

This chapter reviews the distribution, seasonal abundance, species composition, and production of zooplankton in the Gulf of Alaska. Emphasis is placed on research conducted since 1970.

Approximately 30 species account for the majority of the biomass and numerical abundance, with copepods being the most common taxa collected when using plankton nets and trawls with mesh sizes ranging between 0.200 and 0.500 millimeters.

Zooplankton standing stock (wet weight) varies seasonally. Summer and fall highs range from 1,600 g/m² for the deep inside waters (Prince William Sound; 700 m) to 30 g/m² in the upper 150 m at Ocean Station P. Winter values decline to 1.5 g/m² in the open ocean, with higher biomass occurring over the shelf and in the inside waters; 40 g/m² in the Strait of Georgia, British Columbia, and 1,320 g/m² in Prince William Sound.

Oceanic zooplankton populations may produce up to 30 g C/m²y (upper 150 m) assuming that all the phytoplankton production is grazed, and that 30% of what is ingested appears as growth. The annual growth of populations over the shelf and in the inside waters is probably higher, with production estimates ranging from 27 to 50 g C/m²y. Since the annual primary production over the shelf (where measured) does not exceed 300 g C/m²y, the zooplankton growth is not likely to be greater than 20% of this value, 60 g C/m²y.

The Alaska Coastal Current (ACC) and the Alaska Current/Alaskan Stream provide physical mechanisms that mix oceanic and shelf populations, and then distribute this assemblage around the periphery of the Gulf. The result is a homogeneous subarctic community occurring over 2,200 km of coastline from northern British Columbia to the tip of the Alaska Peninsula. The abundance of several oceanic zooplankters in shelf and coastal collections demonstrates the influence that the bordering ocean has on shallower-water processes such as synthesis and transfer of organic matter. However, this influence has yet to be fully evaluated.

Introduction

Oceanographic studies in the North Pacific Ocean date from observations made during the *Challenger* Expedition (1872–1876), from three cruises of the American vessel, *Albatross* (1888–1905), and from a portion of the Carnegie Expedition (1929). As early as 1889, the Harriman Alaska Expedition crossed the northern Gulf of Alaska and examined some of the physical and geological features of the coastal zone between Yakutat Bay and Kodiak Island, including much of interior Prince William Sound. This latter effort was furthered by studies conducted during the Canadian Arctic Expedition (1913–1924). These early ven-

tures were, in part, responsible for collecting and describing the common flora and fauna of the open ocean and coastal regions of Alaska.

The International Pacific Halibut Commission (formerly the International Fisheries Commission) collected plankton samples in the northern Gulf of Alaska from 1926 to 1934 in order to support studies of the distribution and abundance of fish eggs and larvae (Thompson and Van Cleve 1936). Samples from the *Northern Holiday* expedition and the International Fisheries Commission also form a basis for descriptions of euphausiid distributions in the North Pacific (Brinton 1962). In 1955, Japan, Canada, and the United States began an international study of the North Pacific Ocean

titled NORPAC. Nineteen research vessels and 14 institutions studied the physics, biology, and fisheries of this region. The most ambitious zooplankton research for multi-year time series at Ocean Station 'P' (OSP) and from broader reaches of the northeastern Pacific was reported by LeBrasseur (1965a, 1965b) and Fulton and LeBrasseur (1985). Seasonal and annual variability for copepods, euphausiids, amphipods, decapods, chaetognaths, pteropods, and small cephalopods was described from a collection of ~ 5,000 vertical tows (taken with a NORPAC net with 0.3-mm mesh size). Only a small percentage of the 5,000 samples was obtained from shelf and coastal regions. In addition, several Soviet investigators described the ecological importance of the large upper-layer oceanic copepods in seasonal studies of the North Pacific Ocean (Vinogradov 1968; Heinrich 1968; Vinogradov and Arashkevich 1969).

The purpose of this chapter is to review both the published manuscripts and the unpublished reports that describe the distribution, abundance, and species composition of zooplankton communities occurring in the oceanic and shelf/coastal regions of the Gulf of Alaska. Particular attention is given to investigations sponsored by BLM/NOAA under the Alaska Outer Continental Shelf (OCS) studies (1974–1979). The intent is to summarize and discuss the present knowledge of zooplankton in this northern temperate ocean and to identify areas where future research needs to be done. Although the study area has been defined as that portion of the northeastern Pacific Ocean north of 52°N and extending west to 176°W, it is necessary to draw on information (mostly Canadian) published for a few more southerly locations to supplement the available information.

The Database

This review is limited to information that describes the distribution, abundance, and standing stock of zooplankters that were collected using nets and trawls with mesh sizes ranging between 0.200 and 0.500 millimeters. Consequently, crustacean microzooplankton and marine protozoans are excluded from this chapter.

In a number of the OCS-sponsored studies, the standing stock of net-caught zooplankton is reported as settled volume. In the interest of consistency within this chapter, settled volumes in ml/m³ or ml/m² were converted to g/m³ or g/m² after Weibe, Boyd, and Cox (1975). This conversion assumes that 70% of the settled volume in milliliters is equivalent to the wet weight in grams. Since at least two different mesh sizes (0.333 or 0.211 mm) and several nets (1-m, 0.5-m, neuston, 60-cm bongo, and 2-m Tucker trawl) were used, strict comparisons between standing stocks reported by various investigators are probably not appropriate in view of errors associated with active avoidance or losses through the mesh. Also, it is likely that nets fished with 0.211-mm mesh contained higher amounts of phytoplankton than did 0.333-mm nets. However, there is neither a way to tell if this is true, nor a method to remove this bias from settled volume measurements.

In those few cases where formalin dry-weight values were reported, wet weights were estimated by first using a 15% conversion factor (Ikeda and Motoda 1978) and then doubling the resultant values to account for preservation losses (Paffenhöfer 1980). Zooplankton carbon was considered to be 45% of the reported or estimated dry weight since the samples were dominated primarily by copepods (euphausiids were probably not well sampled in most studies). These problems with the database are acknowledged so the reader may be aware of the limitations inherent in the underlying observations and their subsequent interpretation.

Community Composition

In all, 284 species and six generic composites have been reported for zooplankton and micronekton collected from the oceanic, shelf, and coastal waters of the northern Gulf of Alaska (Fig. 10-1; Appendix I, II). Four taxa constitute the most diverse groups: Cnidaria, Copepoda, Amphipoda, and Osteichthys (Table 10-1). In general, the Gulf of Alaska community reflects a similarity with the zooplankton and micronekton communities reported previously for the Bering Sea (Cooney 1981) and (though not shown) for British Columbia (Arai and Brinckmann-Voss 1980; Gardner and Szabo 1982). The Copepoda and Amphipoda are apparently much less diverse in the northern Gulf than in the Bering Sea (Cooney 1981). Since the collection techniques have generally been similar in these two regions (vertical tows, mostly upper 150–200 m), and the database roughly the same size, it seems possible that the Bering Sea may host a mixture of both subarctic and arctic species. This mixture may account for the difference in Copepoda and Amphipoda diversity. (Motoda and Minoda 1974).

Table 10-1.
Numbers of species and generic composites reported for the Gulf of Alaska and southern Bering Sea.

TAXON	GULF OF ALASKA ^a	BERING SEA ^b
Cnidaria	42	41
Ctenophora	3	1
Polychaeta	9	17
Mollusca	9	8
Cladocera	5	2
Ostracoda	4	7
Copepoda	76	111
Cumacea	3	8
Mysidacea	10	20
Isopoda	3	
Amphipoda	29	67
Euphausiacea	8	7
Decapoda	14	13
Chaetognatha	5	6
Larvacea	4	2
Thaliacea	2	0
Osteichthys	64	27
Total	290	337

^aAppendix I

^bCooney 1981

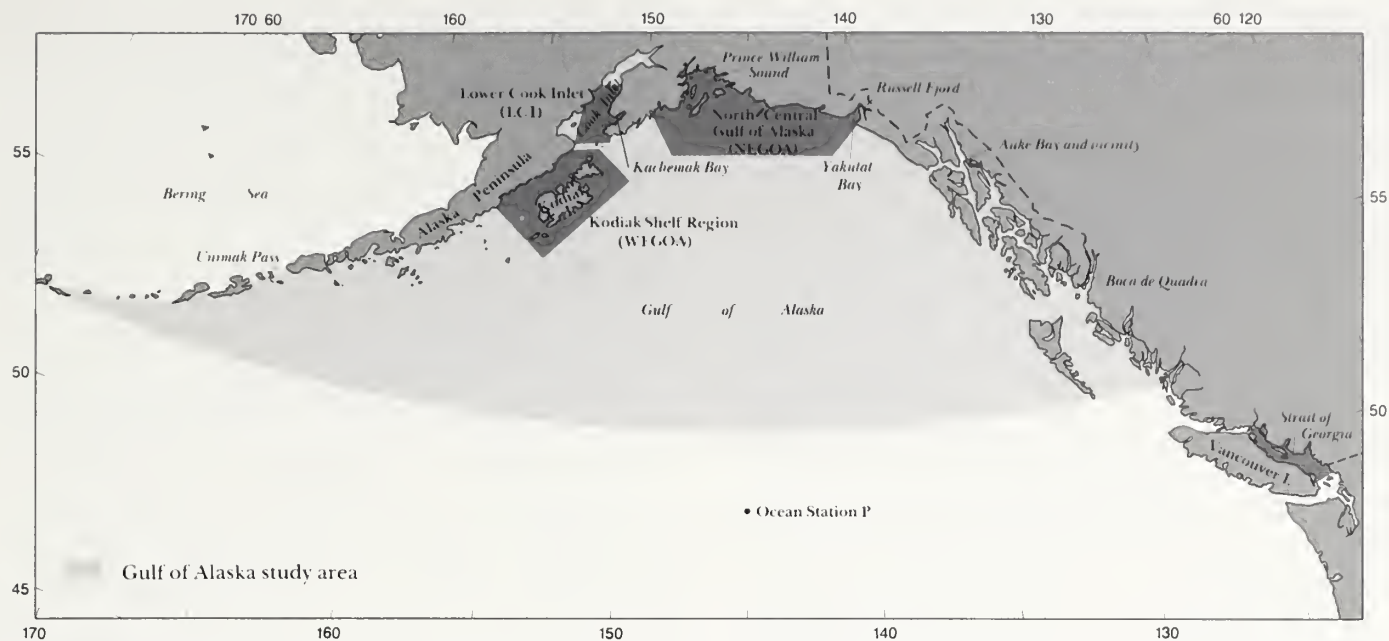


Figure 10-1 Locations of data sets used to describe the distribution, abundance, and production of zooplankton covered in this chapter. Large study areas are depicted by dark shading.

Zooplankton communities in the Gulf of Alaska are numerically dominated by relatively few species; approximately 30 species constitute the numerically common taxa, with copepods being the most numerous (Table 10-2). Cooney (1975) reports 14 species and 2 generic composites as common in the northern Gulf of Alaska (NEGOA). All but one of these categories appear on the list of common species from OSP and the western Gulf of Alaska (WEGOA). Fourteen of 25 taxa from OSP are common to both the other locations, while 18 taxa are common to at least one of the other locations. There are no taxa (common or otherwise) listed for OSP that do not occur at the other locations. Damkaer (1977) reports 19 species and four generic composites from lower Cook Inlet (LCI) (including Kachemak Bay). Nine taxonomic categories listed for this inshore area are also commonly found at OSP.

These listings demonstrate a continuity in the subarctic oceanic zooplankton community that spans roughly a thousand nautical miles—from OSP to Kodiak Island. Unlike the southeastern Bering Sea (Cooney 1981), a mixed assemblage of oceanic and neritic species inhabits the entire shelf and coastal zone including sounds, fjords, and protected inside waters.

Life History Considerations

Scientists have long recognized that the oceanic production cycle in the subarctic Pacific differs from the cycle in most other temperate latitude oceans. In spite of sufficient year-round nutrients and illumination in the surface waters, subarctic Pacific waters lack a well-defined spring phytoplankton bloom. This lack is attributed to the evolution of a specialized grazing community. Heinrich (1957,

1962) and Beklemishev (1957) suggested that seasonally non-varying stocks of oceanic phytoplankton in the northern North Pacific Ocean result from intense grazing by herbivorous copepods.

Unlike *Calanus finmarchicus* in the North Atlantic, the large calanoid copepods in the Pacific subarctic, *Neocalanus cristatus* and *N. plumchrus*, reproduce at depth in late winter when primary production is still light-limited. This places their annual broods in the photic zone ahead of the seasonal phytoplankton growth period. The energy for their egg production comes from lipid reserves stored at the sea surface during the previous year's phytoplankton production cycle. This ability to anticipate and reproduce before seasonal phytoplankton growth, rather than in response to it, assures an extremely close coupling between plant and animal stocks. This coupling eliminates the classic lag period observed in other high-latitude oceans. Because of the intensity of the grazing afforded by this reproductive strategy, the seasonal biomass increase at OSP occurs at the secondary (zooplankton) rather than primary (phytoplankton) level (Parsons 1965; Fulton 1983).

A third large calanoid, *Eucalanus bungii*, augments oceanic grazing by producing surface broods later in the spring and summer when much of the *Neocalanus* biomass is descending to its overwintering and reproductive depths far below the surface. Together, these three copepods contribute as much as 75% to the net zooplankton biomass (>0.333-mm mesh) in the upper 2,000 m of the open ocean (Miller, Frost, Batchelder, Clemons, and Conway 1984). The medium-sized copepod, *Metridia pacifica*, is also an important contributor to the oceanic biomass, particularly in the surface waters after the interzonal species have migrated to depth. Cooney (1975) reports a species of similar size, *Calanus pacificus*, as the most abundant near-surface oceanic

Table 10-2.
Numerically common zooplankton and micronekton from oceanic and shelf regions of the Gulf of Alaska.

TAXON	LOCATION			
	OSP ^a	NEGOA ^b	WEGOAC ^c	LCI ^d
Cnidaria				
Hydrozoa				
<i>Aglantha digitale</i>	x	x		
Chaetognatha				
<i>Sagitta elegans</i>	x	x	x	x
<i>Eukrohnia hamata</i>	x	x	x	
Arthropoda				
Copepoda				
<i>Aetideus</i> sp.	x			
<i>Acartia clausi</i>	x	x		
<i>A. longiremis</i>	x	x	x	x
<i>A. tumida</i>	x	x		
<i>Calanus marshallae</i>	x	x		
<i>C. pacificus</i>	x	x	x	x
<i>C. glacialis</i>	x			
<i>Neocalanus cristatus</i>	x	x	x	x
<i>N. plumchrus</i>	x	x	x	
<i>Eucalanus bungii</i>	x	x	x	
<i>Centropages arcuicornis</i>	x			
<i>Clausocalanus abdominalis</i>	x	x		
<i>Epilabidocera longipedata</i>	x			
<i>Mesocalanus tenuicornis</i>	x			
<i>Microcalanus</i> spp.	x	x		
<i>Metridia pacifica</i> (= <i>M. lucens</i>)	x	x	x	x
<i>Eurytemora</i> spp.	x			
<i>Oithona similis</i>	x	x	x	x
<i>O. spirostris</i>	x			
<i>Pseudocalanus</i> spp.	x	x	x	x
<i>Scolecithricella minor</i>	x			
<i>Tortanus discaudatus</i>	x	x		
<i>Cyclopina</i> sp.	x			
<i>Oncaea borealis</i>	x			
<i>Tegastes</i> sp.	x			
<i>Tisbe gracilis</i>	x			
Amphipoda				
<i>Parathemisto libellula</i>	x			
<i>P. pacifica</i>	x	x	x	
<i>Cyphocaris challengerii</i>	x			
<i>Hyperoche medusarum</i>	x			
<i>Hyperia</i> sp.	x			
<i>Euprimno</i> sp.	x			
Ostracoda				
<i>Conchoecia</i> spp.	x	x		
Cladocera				
<i>Podon</i> spp.	x	x		
<i>Evadne</i> spp.	x			
Euphausiacea				
<i>Euphausia pacifica</i>	x	x	x	
<i>Thysanoessa inermis</i>	x			
<i>T. longipes</i>	x	x	x	x
<i>T. spinifera</i>	x	x		
<i>T. raschii</i>	x			
Annelida				
Polychaeta				
<i>Tomopteris</i> spp.	x			
Mollusca				
Pteropoda				
<i>Limacina helicina</i>	x	x		
<i>Clione limacina</i>	x			
Cephalopoda				
<i>Gonatus</i> spp.	x			
Chordata				
Larvacea				
<i>Oikopleura</i> spp.	x	x	x	x
<i>Fritillaria borealis</i>	x			
Total	25	16	33	23

^aOcean Weather Station P (LeBrasseur 1965b).

^bNortheastern Gulf of Alaska (Cooney 1975).

^cWestern Gulf of Alaska (Kendall, Dunn, Wolotira, Bowerman, Day, Matarese, and Munk 1980; Vogel and McMurray 1986).

^dLower Cook Inlet (Damkaer 1977).

calanoid during late summer and early fall in the northern Gulf of Alaska.

The life histories of the shelf and coastal neritic species exhibit a more classic response to the annual primary production cycle. The abundant small copepods, *Pseudocalanus* spp., *Acartia* spp., and *Centropages abdominalis*, build their late spring and summer populations following the spring phytoplankton bloom. All produce from one to several generations, depending upon food availability and temperature. *Calanus marshallae*, a medium-sized neritic copepod, is also most numerous during the summer months after overwintering adults have fed and reproduced. To date, there is no evidence that this latter species produces more than one generation each year in either the Gulf of Alaska or the southern Bering Sea (Smith and Vidal 1984; Vogel and McMurray 1982).

Ctenophores and small cnidarians make up a relatively unimportant portion of the seasonally varying zooplankton stocks in the northern and western Gulf of Alaska, unlike their numbers in the more southerly waters bordering the British Columbia coastline and in the protected straits and sounds (Cooney 1975; Vogel and McMurray 1982). However, midsummer blooms of larvaceans are not uncommon, as is also the case in waters further south (Harrison, Fulton, Taylor, and Parsons 1983).

Seasonality in Abundance and Biomass

The Oceanic/Slope Community

Kendall, Dunn, Wolotira, Bowerman, Dey, Matarese, and Munk (1980) report seasonal variations in total zooplankton biomass as mean settled volumes for nearshore, shelf, and slope locations in the western Gulf of Alaska near Kodiak Island (Fig. 10-2). The seasonal variations for a 150-m water column in the slope regime range from a low of 9.5 g/m² in the winter to a high of 65.1 g/m² in the summer. Cooney (unpubl. NEGOA data) measured a seasonal high of 19.9 g/m² in May, falling to 3.3 g/m² in late winter for the northern portion of the Gulf of Alaska (Table 10-3). Further to the west, Larrance (1971) reported a summer high volume of 29.4 g/m², and a winter low of 7.4 g/m². This seasonality compares with a high of 30.2 g/m² and low of 1.5 g/m² based on observations at OSP (McAllister 1969; LeBrasseur 1965b). Thus, over broad areas of the open Gulf of Alaska, seasonal variations in standing stock of near-surface zooplankton are roughly comparable, with the largest seasonal variability occurring at OSP, and the smallest variability occurring at locations to the north and west.

A considerable portion of the seasonal biomass variation that occurs in the slope and oceanic regions probably reflects the life histories of three interzonal copepods: *Neocalanus cristatus*, *N. plumchrus*, and *Eucalanus bungii*. These large species are present at some stage of development in the upper 150 m for at least 10 months of each year (Miller *et al.* 1984). Unlike populations that occur in the deeper inside waters of British Columbia (Fulton 1973) and Alaska (Cooney, Urquhart, and Barnard 1981), the oceanic species demonstrate far less synchrony in their reproduction. Therefore, a variety of copepodid stages occur together, both at depth and in the surface waters.

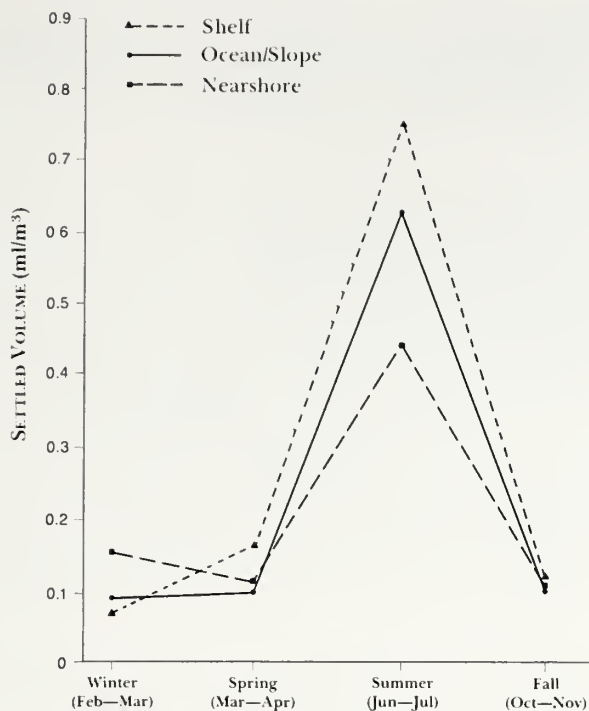


Figure 10-2 Seasonal variability in zooplankton biomass near Kodiak Island, Alaska, based on samples collected with 60-cm bongo nets with 0.333-mm mesh. (Modified from Kendall *et al.* 1980.)

Although the oceanic biomass of net zooplankton is dominated by the large interzonal copepods, several other taxa contribute to the seasonality. The smaller copepods, *Calanus pacificus* and *Metridia pacifica*, occur abundantly and at different times of the year. *C. pacificus* exhibits a strong seasonal signal with its highest amplitude occurring in the fall. *M. pacifica* populations are less variable with time, but have been reported as being the most numerous in late winter and spring (LeBrasseur 1965b). The even-smaller species, *Pseudocalanus* spp., *Scolecithricella ovata*, *Pseudocalanus parvus*, and *Oithona* spp., are all most apparent during times when

Table 10-3. Zooplankton standing stocks (in mg/m³) for the Gulf of Alaska.

LOCATION	WINTER	SPRING	SUMMER	FALL
OSP ^a				
NEGOA ^b	10.0	88.0	190.0	80.0
1. Shelf	41.2	140.8	168.1	70.2
2. Oceanic	22.8	132.8	33.3	25.6
WEGOAc				
1. Shelf	42.0	112.0	525.0	77.0
2. Oceanic	63.0	70.0	434.0	70.0
LCId	-	5,010.0	1,440.0	-
Prince William Sound ^d	-	1,890.0	2,060.0	2,290.0
Russell Fjord ^e	-	110.0	470.0	250.0
Strait of Georgia ^f	-	100.0	-	800.0

^aOcean Weather Station *PaPa* (Fulton 1983).
^bNortheastern Gulf of Alaska (R.T. Cooney, University of Alaska, unpubl. data).
^cWestern Gulf of Alaska (Kendall *et al.* 1980) (settled volumes converted).
^dLower Cook Inlet (Damkaer 1977) (settled volumes converted).
^eReeburgh, Muench, and Cooney 1976.
^fHarrison *et al.* 1983.

the larger species are less abundant in the near-surface waters. The chaetognath, *Sagitta elegans*, is most common in the summer and fall months, as are the pteropods, *Limacina helicina* and *Clione limacina*.

Kendall *et al.* (1980) report chaetognaths occurring in densities of about 6 organisms/m³ in the summer, fall, and winter months in slope waters near Kodiak Island. Likewise, the ostracods, *Conchoecia* spp., are present in concentrations of 1 to 2 organisms/m³ with the highest values occurring in the summer. The most common amphipod, *Parathemisto pacifica*, is most numerous in the summer and fall months. Adult euphausiids, *Euphausia pacifica* and *Thysanoessa longipes*, reach peak densities in the winter. *Oikopleura* spp. occur most abundantly in the open ocean in the summer. In oceanic surface waters bordering the shelf, the zooplankton community composition reflects a distinct neritic cast in the summer and early fall as the shallower water assemblage grows and spreads seaward (Table 10-4).

The Shelf Community

Cooney (unpubl. data) measured 30.6 g/m² in July and 6.2 g/m² in February (150-m water column) for the northeastern portion of the Gulf. This compares with summer values of 78.8 g/m² and winter values of 6.3 g/m² measured by Kendall *et al.* (1980) further to the west over the shelf near Kodiak Island. Since these studies were conducted in different years and with different nets, there is no way to determine whether the summer differences represent interannual, location, or merely sampling variability.

Table 10-4. Seasonal variations in abundance by rank order for WEGO offshore locations (Vogel and McMurray 1986).

RANK ORDER	MONTH	
	MARCH 1978	JUNE 1978
1	<i>Neocalanus plumchrus</i>	<i>Pseudocalanus</i> spp.
2	<i>Pseudocalanus</i> spp.	<i>Metridia</i> spp.
3	<i>Metridia</i> spp.	<i>Neocalanus plumchrus</i>
4	<i>Neocalanus cristatus</i>	<i>Acartia longiremis</i>
5	<i>Limacina helicina</i>	<i>Eucalanus bungii</i>
6	<i>Scolecithricella minor</i>	<i>Acartia tumida</i>
7	<i>Oikopleura</i> spp.	<i>Centropages abdominalis</i>
8	<i>Sagitta</i> spp.	<i>Calanus marshallae</i>
9	<i>Oithona</i> spp.	<i>Oikopleura</i> spp.
10	Cnidarians (unidentified)	<i>Parathemisto pacifica</i>
	OCTOBER 1978	FEBRUARY 1979
1	<i>Acartia longiremis</i>	<i>Pseudocalanus</i> spp.
2	<i>Metridia</i> spp.	<i>Metridia</i> spp.
3	<i>Pseudocalanus</i> spp.	<i>Scolecithricella minor</i>
4	<i>Oithona</i> spp.	<i>Neocalanus plumchrus</i>
5	<i>Calanus marshallae</i>	<i>Conchoecia</i> spp.
6	<i>Parathemisto pacifica</i>	<i>Calanus marshallae</i>
7	<i>Limacina helicina</i>	<i>Limacina helicina</i>
8	<i>Sagitta</i> spp.	<i>Sagitta</i> spp.
9	<i>Oikopleura</i> spp.	<i>Oithona</i> spp.
10	<i>Parathemisto pacifica</i>	Cnidarians (unidentified)

Zooplankton and micronekton communities on the shelf are composed of a mixture of oceanic and neritic species (Table 10–5). Expressed in the rank order of their abundance, the copepods *Pseudocalanus* spp., *Metridia* spp., *Acartia longiremis*, *A. tumida*, *Calanus marshallae*, *Neocalanus plumchrus*, *N. cristatus*, *Eucalanus bungii*, *Scolecithricella minor*, *Oithona* spp., and *Centropages abdominalis* all occur in the top ten rankings at least once each season. Unidentified cnidarians, medusae, and euphausiids, the cladocerans *Podon* spp. and *Evadne* spp., the chaetognaths *Sagitta* spp., the pteropod *Limacina helicina*, and larvaceans *Oikopleura* spp. complete the list of dominant zooplankton and micronekton found on the shelf.

Seasonally, the zooplankton community shifts from its oceanic domination in late winter through early spring, to a greater neritic influence in mid- to late-summer and fall. *Neocalanus* spp. drop out of the ten most abundant taxa in July and August, being replaced by the cladocerans, *Podon* spp. and *Evadne* spp. *Centropages abdominalis* and *Acartia long-*

iremis become more prominent as the season progresses from winter through summer. *Sagitta* spp. are most numerous in the fall, winter, and early spring, as are adult *Thysanoessa inermis* (Kendall *et al.* 1980).

Protected Inside Waters, Fjords, and Sounds

Few studies have focused on zooplankton and micronekton populations in protected inside waters bordering the Gulf of Alaska (Damkaer 1977; Wing and Reid 1972; VTN 1983). A description of the pelagic ecosystem in the Strait of Georgia (Harrison *et al.* 1983) is considered first because of its thoroughness and seasonal coverage. Three distinct communities were described in this deep (<400 m) basin: an epipelagic community, a mid-water community, and a deep-water community (Table 10–6).

The epipelagic community extends from the surface to the base of the mixed layer, and is generally composed of small copepods. These organisms are supplemented in the

Table 10–5.
Seasonal variations in abundance by rank order for WEGOA inshore locations (Vogel and McMurray 1986).

RANK ORDER	MONTH		
	<u>MARCH 1978</u>	<u>APRIL 1978</u>	<u>MAY 1978</u>
1	<i>Calanus</i> ^a copepodites I–III	<i>Pseudocalanus</i> spp.	<i>Pseudocalanus</i> spp.
2	<i>Pseudocalanus</i> spp.	<i>Calanus</i> copepodites I–III	<i>Acartia longiremis</i>
3	<i>Metridia</i> spp.	<i>Neocalanus plumchrus</i>	<i>Calanus marshallae</i>
4	<i>Acartia longiremis</i>	<i>Acartia tumida</i>	<i>Acartia tumida</i>
5	<i>Acartia tumida</i>	<i>Metridia</i> spp.	<i>Metridia</i> spp.
6	<i>Oikopleura</i> spp.	<i>Neocalanus cristatus</i>	<i>Centropages abdominalis</i>
7	<i>Neocalanus plumchrus</i>	<i>Oikopleura</i> spp.	<i>Calanus</i> copepodites I–III
8	<i>Neocalanus cristatus</i>	<i>Scolecithricella minor</i>	<i>Oithona</i> spp.
9	Cnidarians (unidentified)	<i>Acartia longiremis</i>	<i>Limacina helicina</i>
10	<i>Scolecithricella minor</i>	<i>Limacina helicina</i>	Medusae (unidentified)
	<u>JUNE 1978</u>	<u>JULY 1978</u>	<u>AUGUST 1978</u>
1	<i>Pseudocalanus</i> spp.	<i>Pseudocalanus</i> spp.	<i>Acartia longiremis</i>
2	<i>Acartia tumida</i>	<i>Acartia longiremis</i>	<i>Pseudocalanus</i> spp.
3	<i>Acartia longiremis</i>	<i>Calanus marshallae</i>	<i>Podon</i> spp.
4	<i>Calanus marshallae</i>	<i>Centropages abdominalis</i>	<i>Centropages abdominalis</i>
5	<i>Metridia</i> spp.	<i>Metridia</i> spp.	<i>Oikopleura</i> spp.
6	<i>Neocalanus plumchrus</i>	<i>Podon</i> spp.	<i>Calanus marshallae</i>
7	Cnidarians (unidentified)	<i>Oikopleura</i> spp.	<i>Oithona</i> spp.
8	<i>Centropages abdominalis</i>	<i>Parathemisto pacifica</i>	<i>Metridia</i> spp.
9	<i>Eucalanus bungii</i>	<i>Eucalanus bungii</i>	<i>Limacina helicina</i>
10	<i>Scolecithricella minor</i>	<i>Oithona</i> spp.	<i>Parathemisto pacifica</i>
	<u>NOVEMBER 1978</u>		
1	<i>Acartia longiremis</i>		
2	<i>Metridia</i> spp.		
3	<i>Pseudocalanus</i> spp.		
4	<i>Oithona</i> spp.		
5	<i>Calanus marshallae</i>		
6	<i>Sagitta</i> spp.		
7	<i>Parathemisto pacifica</i>		
8	<i>Limacina helicina</i>		
9	<i>Calanus pacificus</i>		
10	<i>Eucalanus bungii</i>		

^aIncludes *Neocalanus* spp. copepodites.

Table 10-6.
Zooplankton communities in the Strait of Georgia, B.C. (Harrison *et al.* 1983).

DEPTH ZONE	WINTER	SPRING	SEASON	SUMMER	FALL
Epipelagic (0-100 m)	<i>Pseudocalanus</i> spp. <i>Paracalanus parvus</i> <i>Oithona helgolandica</i> <i>Corycaeus</i> sp.	<i>Neocalanus plumchrus</i> <i>Calanus marshallae</i> <i>C. pacificus</i> <i>Metridia pacifica</i> <i>Sagitta elegans</i>			<i>Pleurobrachia</i> spp. <i>Phialidium</i> sp. <i>Oikopleura</i> sp.
Midwater (100-250 m)	<i>Euphausia pacifica</i> ^a <i>Pasiphaea pacifica</i> ^a <i>Cyphocaris challengeri</i> ^a <i>Tomopteris septentrionalis</i>	<i>Aglantha digitale</i> ^a <i>Aegina citrea</i>			
Deepwater (>250 m)				<i>Neocalanus plumchrus</i> <i>Calanus marshallae</i> <i>C. pacificus</i> <i>Pseudocalanus</i> spp.	

^aDiel migration into the epipelagic zone at night.

spring by large numbers of the early stage copepodids of *Neocalanus plumchrus* that are recruited to the surface waters along with adult *Calanus marshallae* and *C. pacificus*. Both small and large species respond to the spring phytoplankton bloom by rapidly increasing their population biomass. By mid spring, *N. plumchrus* reaches its biomass high at 30 g/m² (upper 20 m), during which time *Pseudocalanus* spp. show a high of 4 g/m². *Calanus marshallae* follows with highs of 10 g/m² in the late spring. *Euphausia pacifica* reaches its seasonal peak of 14 g/m² as a diel migrator into the surface waters in late fall and winter. Spring is also the time when the cnidarian *Phialidium* sp. and the ctenophore *Pleurobrachia* sp. begin a rapid increase in number and biomass.

The jelly-like zooplankton, including *Oikopleura* sp., reach seasonal highs in the summer and fall months, along with *Sagitta* sp. and amphipods. Later in the fall, small blooms of *C. marshallae*, *C. pacificus*, *Metridia pacifica*, and *Pseudocalanus* spp. occur in response to renewed phytoplankton growth. During the late fall and winter, the epipelagic community is composed mainly of the small copepods *Pseudocalanus* spp., *Paracalanus parvus*, *Oithona helgolandica*, and *Corycaeus* sp., supplemented by *Euphausia pacifica* during the hours of darkness. At this time, the overwintering populations of *N. plumchrus* have migrated below 250 m in the Strait.

The midwater community between 100 and 250 m is dominated primarily by the euphausiid *Euphausia pacifica* (during the day), the glass shrimp *Pasiphaea pacifica*, the amphipod *Cyphocaris challengeri*, the polychaete *Tomopteris septentrionalis*, and hydromedusae that include *Aglantha digitale* and *Aegina citrea*. Most of these species also migrate into the epipelagic zone during darkness.

The deep-water or mesopelagic community below 250 m is dominated by the overwintering herbivorous copepods, *Neocalanus plumchrus*, *Calanus marshallae*, *C. pacificus*, and

Pseudocalanus spp. *N. plumchrus* enters a diapause in late fall in the copepodid stage V (CV), and later molts to become an adult. Spawning occurs at depth from January through April. The other species migrate to the surface either as CV or adult stages. Once at the surface, they first feed and then reproduce. Zooplankton tows made from 400 m to the surface yielded 0.8 g/m³, or 320 g/m² in October and November. Most of this biomass is made up of the deep overwintering copepods. Seasonal lows from zooplankton tows (also 400 m to the surface) occur in April and May when the biomass is reduced to 40 g/m². These lows occur mostly in the surface waters.

Considerably less is known about the zooplankton and micronekton communities of Alaska's inside waters. Wing and Reid (1972) reported zooplankton data for samples collected between 1962 and 1964 in surface waters of Auke Bay and vicinity. Unfortunately, this report provides no synthesis of seasonal patterns or any interpretation of results. Damkaer (1977) reports settled volumes for Prince William Sound and for a series of locations in lower Cook Inlet. Samples taken in the fall in Prince William Sound had settled volumes of ~770 g/m² for a water column 730 m deep. Much of this biomass was associated with *Neocalanus plumchrus* that was overwintering at depths below 300 meters. A diel migration of copepods, amphipods, euphausiids, and pteropods contributed to an increase in the night biomass in the upper 100 meters.

Cooney, Urquhart, Nevé, Hilsinger, Clasby, and Barnard (1978) and Cooney *et al.* (1981) describe the zooplankton community in the upper 25 m during the spring and early summer months in Prince William Sound. The mixture of neritic and oceanic species that was numerically dominated by copepods suggests that this large enclosed basin is influenced by circulation processes originating outside the Sound. *Pseudocalanus* spp., *Acartia longiremis*, and *Oithona similis* were consistently the most numerous zooplankters. The

only seasonal observations in Prince William Sound demonstrate a succession in numerical dominance for large zooplankton beginning with *N. plumchrus*, *Calanus marshallae*, and *Sagitta elegans* in late spring, shifting to *C. marshallae*, *Metridia okhotensis* and *M. pacifica*, and *Thysanoessa raschii* in mid-summer, followed by *Sagitta elegans* and *M. pacifica* in the fall and winter (Cooney, Redburn, and Shiels 1973).

In lower Cook Inlet, including Kachemak Bay, zooplankton populations vary seasonally, with the biomass in the upper 25 m reaching lows of 1.8 to 10.5 g/m² in the early spring and highs of 267.8 to 542.2 g/m² in the late spring and summer months (Damkaer 1977). These spring and summer stock estimates seem somewhat high for a shallow environment, and may be influenced by measurable amounts of phytoplankton (mesh size, 0.211 mm). Similarly, an upper 150-m summer measurement of 242.2 g/m² (reported for a location in the oceanic Gulf of Alaska upstream from Kodiak Island), is roughly four times the oceanic seasonal high measured in a nearby area by Kendall *et al.* (1980). Reducing the spring and summer standing stock estimates in lower Cook Inlet by this difference provides what appears to be more reasonable estimates of between 67 and 135.6 g/m² for seasonal highs. Conversely, the higher values reported by Damkaer (1977) may include large quantities of small zooplankton and meroplankton missed by the larger-mesh nets.

The zooplankton community in Kachemak Bay and lower Cook Inlet is also composed of a mixture of oceanic and neritic species. During the months of April through August, barnacle nauplii and crab zoea contribute large numbers to the meroplankton. During the spring and summer months, the small copepods, *Pseudocalanus* spp., *Acartia longiremis*, and *Oithona similis*, numerically dominate the community (Damkaer 1977).

Annual Production

Few attempts have been made to measure secondary productivity in any of the major hydrographic regions of the Gulf of Alaska. McAllister (1969) estimated the annual secondary production at 13 g C/m²y for OSP based on the rate at which phytoplankton was grazed by oceanic herbivores and assuming that sinking losses were negligible. If it can be assumed that, as a first approximation, zooplankters (including microzooplankton) ingest all of the annual production (as hypothesized by Heinrich 1957, 1962; Beklemishev 1957), and further that 30% of this material is used for growth (Copping and Lorenzen 1980), then some additional estimates of secondary production can be calculated from other measures of oceanic annual primary production. Koblents-Mishke (1965), in a summary of data from the Pacific Ocean, estimated the annual primary production for the mid-subarctic region to be between 55 and 91 g C/m²y, with between 35 and 55 g C/m²y occurring in the transition zone. Although these estimates were admittedly subject to error because of the methodology, they nonetheless generally agree with those estimates reported by other investigators (Larrance 1971; Anderson 1964; and McAllister 1969). Under the assumption that the annual contribution is

Table 10-7.
Zooplankton annual production estimates for the oceanic Gulf of Alaska and Strait of Georgia.

AUTHOR	METHOD	ANNUAL PRODUCTION g C/m ²
McAllister 1969	Phytoplankton grazing losses	13.0
Parsons <i>et al.</i> 1969	<i>Neocalanus plumchrus</i> growth; 81 mg C/m ² /d	9.72 ^a
This paper; using Koblents-Mishke 1965	30% phytoplankton production	10.5-27.3 ^b
Larrance 1971	30% phytoplankton production	24-30 ^b

^aCalculated for a 120-d growth period

^bAssumes all the primary production is grazed and 30% of what is ingested appears as growth

entirely grazed by zooplankton, estimates of secondary production range from a low of 10.5 g C/m²y to a high of 30 g C/m²y (Table 10-7).

Measures of zooplankton production for shelf and inside-water environments are practically non-existent. Parsons, LeBrasseur, Fulton, and Kennedy (1969) report production of 81 mg C/m²d for *Neocalanus plumchrus* in the Fraser River plume. If this rate were sustained for the four months that *N. plumchrus* is in the surface waters, then production on the order of 9.72 g C/m² would be realized. However, since the measured annual increase in zooplankton standing stock was 18.9 g C/m²y (not including losses to mortality) for the deeper portion of the Strait of Georgia, the *N. plumchrus* contribution represents a substantial, but unknown fraction of the total annual secondary production.

Cooney and Coyle (1982) report zooplankton grazing rates of 76 mg C/g dry weight of grazers per day in the middle-shelf domain of the southeastern Bering Sea (comparable community, and similar temperatures in April and May). If this value is applied to spring, summer, and fall zooplankton stocks occurring over the shelf near Kodiak Island, and if 30% of the material ingested can be assumed to go to growth, then the annual zooplankton production would be ~ 32 g C/m²y (Table 10-8). This value is somewhat less than

Table 10-8.
Seasonal zooplankton production rates for shelf populations in the WEGOA area (Kendall *et al.* 1980).

SEASON	STANDING STOCK ^a mg/m ²	INGESTION ^b mg C/m ² d	PRODUCTION ^c mg C/m ² 90d
Spring			
Mar-May	2,520	192	5,171
Summer			
Jun-Aug	11,813	898	24,239
Fall			
Sep-Nov	1,733	132	3,555
		Total	33.0 g C/m ² y

^aDry wt calculated as 15% wet wt (150 m water column).

^bUsing Cooney and Coyle (1982); 76 mg C/g dry wt 'grazer'/d.

^cUsing 30% gross growth efficiency and a period of 90 days.

Table 10-9.
Seasonal zooplankton production rates for Russell Fjord, Alaska
(Reeburgh *et al.* 1976).

SEASON	STANDING STOCK ^a mg/m ²	INGESTION ^b mg C/m ² d	PRODUCTION ^c mg C/m ² 90d
Spring			
Mar–May	3,380	257	6,939
Summer			
Jun–Aug	14,040	1,067	28,809
Fall			
Sep–Nov	7,460	467	15,309
		Total	51.1 g C/m ² y

^aMeasured dry wt; zooplankters > 0.571 mm.

^bUsing Cooney and Coyle (1982); 76 mg C/g dry wt 'grazer'/d.

the 51.1 g C/m²y that was obtained by using the same method on standing stock data reported by Reeburgh, Muench, and Cooney (1976) for Russell Fjord, Alaska (Table 10-9).

Finally, since most of the estimates of primary production for the fjords and inside waters range between 100 and 300 g C/m²y, it seems unlikely that the annual secondary production will exceed 10 to 20% of these values. Thus, the zooplankton production, though largely unknown, is probably greater than 10 g C/m²y and less than 60 g C/m²y in these protected coastal environments.

Oceanographic/Ecological Significance

Practically nothing is known about broad-scale abundance distributions of zooplankton in the open Gulf of Alaska. Parsons, Giovando, and LeBrasseur (1966) report generally higher copepod stocks around the northern, eastern, and southern periphery of the oceanic gyre. They made this determination using averages for areas composed of 2° latitude and 10° longitude, and based on collections made during 1962 and 1963. This places the highest surface concentrations of copepods in portions of the subarctic and Alaska Current systems.

Wickett (1967) concluded that, given this general pattern of distribution, concentrations of zooplankton along the California coast and in the eastern Bering Sea could be correlated with interannual variations in Ekman transport computed at seven locations in the northeast Pacific and Gulf of Alaska. In years following an above-average southerly component of surface flow, zooplankton volumes were higher than average off California. Conversely, under these same conditions, Bering Sea zooplankton populations were diminished. Wickett suggested that during those years when the southerly component of Ekman transport was strongly developed, more oceanic zooplankters were deflected southward into the California Current and fewer were deflected into the Alaska Current/Alaskan Stream. Since the transit time to these adjacent areas is roughly one year, the effects of transport variations in the Gulf lagged by this amount of time.

Frost (1983) found that there was considerable interannual variation in the standing stock at OSP. These differences showed a weak positive correlation with surface

salinities measured at the same location, as had previously been noted by Wickett (1967). However, since plant growth is apparently not limited by nutrients, it seems unlikely that zooplankton production is enhanced either by increased upwelling or by wind mixing as suggested by the relationship with salinity.

While the large-scale distributions of oceanic zooplankters are only vaguely known, both seasonal and vertical variations in abundance and biomass of oceanic species have been described in detail for OSP and other locations in the subarctic Pacific (Fulton 1978, 1983; Heinrich 1968; LeBrasseur 1965b; Marlowe and Miller 1974; Miller *et al.* 1984; Sekiguchi 1975; and Vinogradov and Arshkevich 1969). The most obvious feature is the approximately twenty-fold increase in surface layer biomass (upper 150 m) associated with the annual growth of the net plankton community. This community is dominated by the interzonal copepods, *Neocalanus cristatus*, *N. plumchrus*, and *Eucalanus bungii*. The rise in biomass to a spring peak in June tapers off during the fall and closely tracks the seasonal variation in light. This phenomenon, coupled with the fact that the oceanic phytoplankton standing stock remains relatively constant throughout the year (most values < 0.4 mg Chl *alm*³), suggests that zooplankton grazing must play a significant role in balancing the primary productivity.

That hypothesis has recently been critically examined at OSP (Frost, Landry, and Hassett 1983; Miller *et al.* 1984). It is now known that the reproductive strategies of the major grazers are much more complex than originally thought, and that *N. plumchrus* and *N. cristatus* exhibit behavioral and morphological adaptations that allow them to very efficiently exploit the phytoplankton stocks. Most recently, Miller (C. Miller, Oregon State University, pers. comm., 1985) has demonstrated that two distinct forms of *N. plumchrus* are present at OSP. These forms differ in color, size, and breeding cycle—one is reddish, smaller than 4 mm as adults, and reproduces in mid-summer, while the other (the typical *Neocalanus plumchrus*) is orange, larger than 4 mm, and reproduces in the fall. It is unknown how this discovery will affect the present understanding of how the zooplankton community functions in the open northeast Pacific Ocean.

In addition to Miller's discovery, it is now also known that the large herbivorous copepods are partitioned vertically in the water column during their upper-layer development. Both forms of *Neocalanus plumchrus* occur above the seasonal thermocline (upper 30 m), whereas *N. cristatus* and *Eucalanus bungii* are generally restricted to depths below the thermocline.

Cooney (1986) demonstrates the seasonal presence of the oceanic inter-zonal copepods over the shelf of the northern Gulf of Alaska. This presence is associated both with the time these species reside in the wind-influenced surface layer of the bordering ocean and with the duration of the shelf convergence season that lasts from October to April each year (Royer 1981). These and other oceanic zooplankters are dominant members of the shelf and coastal communities, a fact that adds support to the notion that the bordering ocean may be the source for substantial amounts of organic matter that is advected shoreward in the seasonally persistent onshore Ekman flow (Cooney 1984). The Gulf

of Alaska shelf is unlike the middle shelf domain of the southeastern Bering Sea, which is isolated from oceanic influence by a strong mid-shelf frontal system. The considerably narrower shelf of the Gulf of Alaska has a much more advective environment due to influences by both the Alaska Current over and along the shelf break, and by the Alaska Coastal Current (ACC) that occupies the first 40 km from the beach seaward. The ACC originates in northern British Columbia, and continues north and west around the periphery of coastal Alaska as far as Unimak Pass on the Alaska Peninsula (Royer 1983). Interaction between these two currents (where the shelf is < 50 km wide) presumably provides a mechanism to mix and transport the coastal and oceanic faunas over and along the shelf. This mechanism, combined with the wind-induced onshore Ekman flow, assures that near-surface (upper 200 m) zooplankters of oceanic origin become a seasonal part of the shelf/coastal zooplankton communities.

The degree to which the shelf is enriched by oceanic biomass can be estimated by measuring both the standing stocks and the rate of onshore surface flow. Cooney (1984) proposes that over an eight-month period from March to November of each year, $\sim 10 \times 10^6$ mt of zooplankton biomass are advected shoreward from the upper 50 m of the bordering ocean. This biomass then moves into the outer edge of the ACC along 1,000 km of coastline in the northern Gulf of Alaska. This advected zooplankton biomass compares to the $\sim 2 \times 10^6$ mt estimated as the production yielded by zooplankters resident in the ACC. If this calculated contribution is at all accurate, the bordering ocean supplies an immense and significant amount of biomass to both shelf and coastal food webs each year.

Mesoscale processes such as fronts and eddies concentrate forage species for higher trophic levels, and may also be extremely important in the process of organic matter transfer. Cooney (1984) suggests one such mechanism that may be associated with vertical circulation patterns in the outer margin of the ACC. Interactions between either upwelling or downwelling in the front separating the ACC from the shelf waters, coupled with the distributions of oceanically derived zooplankters, point to periods when forage biomass is concentrated in the frontal region of the ACC. This theoretical concentration may partially explain the apparent obligate use of the ACC by millions of outmigrating juvenile salmon each year (Rogers, Ch. 15, this volume).

The continuous counterclockwise flow of both the ACC and the Alaska Current/Alaskan Stream around the Gulf of Alaska implies a constant relationship between the upstream source regions and the downstream distributions for both oceanic and shelf/coastal zooplankton populations. Using a conservative estimate of 20 km/d for flow in the ACC (Royer 1981), and given the standing stock information for NEGOA shelf zooplankton (Table 10-3), it is possible to estimate the biomass of the zooplankton that is transported downstream each year. Under these conditions, approximately 1.5×10^6 mt of zooplankton are moved past fixed locations annually in a current 20 km wide and 100 m deep. In this context it is not surprising that the community composition of populations in the northern and western por-

tions of the Gulf of Alaska is similar to the fauna occurring at OSP. The system is at least partially closed as a gyre, and the cross-shelf Ekman flow and meander in the Alaska Current/Alaskan Stream both provide further means for mixing the oceanic and coastal communities. Even the zooplankton assemblages in Alaska's protected inside waters reflect an oceanic influence. The non-reversing nature of the flow further suggests that while population fluctuations that originate in British Columbian and southeastern Alaska waters may retain their continuity until they are observed off Kodiak, the converse of that is not likely—except for populations that retain their continuity while being circulated completely around the gyre.

Zooplankton in the Gulf of Alaska serve as forage for higher trophic levels including fishes, marine birds, and mammals (Vogel and McMurray 1986; Appendix III). In addition to these consumers, larval fishes may depend on the early life-history stages of zooplankton, particularly the Copepoda, for their first feeding (Dagg, Clarke, Nishiyama, and Smith 1984). It has long been assumed, but rarely observed in nature, that most fish larvae enter a critical phase at the time when their yolk sac is nearly absorbed and they must begin external feeding (May 1974). At this time, the presence of sufficient quantities of appropriate kinds of food is thought to be extremely important. Copepod nauplii have been described as one of these critical food items (Kamba 1977; Clarke 1978; Nishiyama and Hirano 1983; Lawrence 1974; and Paul 1983). In this regard, *Pseudocalanus* is probably one of the most ecologically important genera affecting fish production in the Gulf of Alaska, particularly in the shelf and coastal zones. *Pseudocalanus* spp. continuously produce nauplii while food is available and conditions are favorable (McLaren 1978), thus providing food for first-feeding larvae from April through November of each year. The tiny cyclopoids, *Oithona* spp., may also be important in the diets of first-feeding larvae, both because of their small size (even as late stage copepodids) and their great abundance (Miller *et al.* 1984).

Kendall *et al.* (1980) found that the greatest abundance of fish larvae occurred in both offshore and inshore regions near Kodiak during the summer when zooplankton stocks were also at their seasonal highs. Calanoid copepods, harpacticoid copepods, euphausiids, decapod larvae, fish larvae, mysids, and pelagic amphipods are all known as food sources for a variety of species, ranging from both juvenile and adult pelagic and demersal fishes to sea birds and several whale species.

Vogel and McMurray (1986) discuss relationships between fish, bird, and mammal consumer populations and the forage stocks in the WEGOA region. In the Kodiak area, the distribution of juvenile and adult walleye pollock was related to the distribution of both copepods and the euphausiids, *Euphausia pacifica* and *Thysanoessa spinifera*. These two species are also forage for juvenile pollock (Rogers, Rabin, Rogers, Garrison, and Wangerin 1979). A similar relationship was found for the larval Atka mackerel along the slope regime in this same area. In contrast, the distribution of herring in the inshore waters, including bays and channels, was most strongly related to the abundance of copepods and cladocerans. The most abundant pelagic fish

collected over the shelf near Kodiak, the capelin (Harris and Hartt 1977; Kendall *et al.* 1980), was distributed spatially according to zooplankton abundance, but was seasonally out of phase with the zooplankton biomass. Distributions of Pacific sand lance were weakly related to both copepod distribution and seasonal abundance.

The occurrence and distributions of some marine birds were positively related to the distribution of their food. Shearwaters frequented areas of high euphausiid, copepod, and capelin densities. Since the capelin feed on copepods and euphausiids, and the birds on euphausiids and capelin, the concomitance is expected. Distribution of tufted puffins and black-legged kittiwakes was strongly correlated to areas with larval capelin, but their distribution was weakly correlated to distributions of euphausiids and copepods (Rogers *et al.* 1979).

Five species of filter-feeding whales are found in the Kodiak area: minke, humpback, sei, fin, and blue whales (Science Applications, Inc. 1980; Calkins, Ch. 17, this volume). Humpbacks occur most abundantly over the shelf in the vicinity of the major bathymetric trenches where oceanic copepod and euphausiid populations are high. Both humpback and sei whales forage on copepods, euphausiids, and planktivorous fishes such as capelin and herring (Nemoto 1957, 1970; Nishiwaki 1972).

Conclusions

1. The composition of zooplankton communities in the Gulf of Alaska displays a homogeneity of species across oceanic, shelf, and coastal and inside waters. This composition reflects both the influence of the open ocean on the shallower, protected environments and the highly advective nature of the overall system. The Gulf of Alaska appears closed, and coastal and shelf-break currents distribute populations over ~2,200 km of coastline from northern British Columbia to Unimak Pass, Alaska.

2. Copepods are the dominant taxa reported in samples taken from all marine environments in the Gulf of Alaska. In the oceanic domain, more than 70% of the biomass (nets of 0.333 mm mesh and larger) is associated with three species, *Neocalanus cristatus*, *N. plumchrus*, and *Eucalanus bungii*. A complex life history pattern, including ontogenetic migrations and reproduction at depth, places a mixture of these large copepods in the upper 150 m for at least 10 months of each year.

3. Recent studies tend to confirm the hypothesis that grazing by oceanic herbivores controls both the stock and the production of phytoplankton in the open ocean. Oceanic zooplankton standing stocks vary seasonally by as much as a factor of 20 (between 1.5 and 30.0 g/m²; upper 150 m), with somewhat higher winter values occurring along the northern and western continental margin. It is unlikely that the annual production of oceanic zooplankton exceeds the 30.0 g C/m²y figure.

4. Shelf and coastal zooplankton stocks vary in abundance and species composition according to the season. Winter and early spring populations are augmented by oceanic species that are moved into the shallower waters by

the seasonally persistent onshore Ekman transport. The numerical importance of the open ocean community is diminished during the summer and fall months when the shelf and coastal communities are dominated by a more neritic assemblage. At this time, the copepods *Pseudocalanus* spp., *Acartia longiremis*, *A. tumida*, *Calanus marshallae*, *Metridia* spp., and *Centropages abdominalis* are common. The marine cladocerans, *Podon* and *Evadne*, and the larvaceans, *Oikopleura* spp., are also evident during the summer.

5. Shelf and coastal zooplankton stocks exhibit growth cycles that respond to phytoplankton production. Winter and early spring stocks are lowest (3–10 g/m²), followed by substantial increases (30–78 g/m²) in the summer and fall. In the deeper inshore waters of the Strait of Georgia, seasonal variations in a 400-m water column range from a low of 40 g/m² in the spring to a high of 320 g/m² in the fall. Annual zooplankton production probably does not exceed 30 to 60 g C/m²y in shelf and coastal areas.

6. Zooplankton serve as forage for fishes, shellfishes, marine birds, and mammals. Copepod nauplii are critical in the diets of most larval fishes. In this respect, the prolific small copepods, *Pseudocalanus* spp. and *Oithona* spp., are probably extremely important in the life cycles of most pelagic and demersal fishes. The larger copepods and euphausiids represent critical food items, particularly for marine birds, whales, and juvenile and adult pelagic fishes.

7. Our present understanding of both the zooplankton community structure and its function is flawed by our inadequate understanding of the production of key species in both shelf and inside water environments. General seasonal cycles have been described for biomass, but very few attempts have been made to determine those factors that enhance or constrain population growth rates and how those factors might vary interannually. Sizable annual variations in the returns of pink salmon (a species that feeds almost entirely on zooplankton and micronekton as juveniles) suggest that the coastal, shelf, and oceanic environments are all 'noisier' than our data sets portray. In addition, although the availability of food may not be the only factor affecting survival, it is probably extremely important. In this regard, information on mesoscale patchiness (1–10 km) is also lacking, although there is little doubt about its primary importance.

Future Studies

The zooplankton community plays a unique role in controlling the production cycle in the open portion of the Gulf of Alaska. Further, zooplankton are of significant trophic importance. Considering these facts, it seems appropriate to expand the more site-specific studies of zooplankton distribution and abundance into broader, hydrographically defined domains such as currents, convergences, and divergences. Studies at this level of complexity will certainly benefit from a close working tie with physical oceanographers who use a variety of techniques, including mass balance, satellite-tracked surface buoys, and multiple current meter deployments, to describe the Gulf's responses to seasonal wind and freshwater forcing patterns.

Recent advances in high-frequency quantitative acoustic sampling let investigators make hundreds of thousands of biomass measurements as routinely as they now take temperature and salinity readings both along cruise tracks that cross the currents and in upwelling regions which define the gyre in the northeast Pacific Ocean. While it is true that surveys of this kind still rely on net tows for identification of the zooplankton, the actual amount of direct sampling can be reduced to manageable limits. Euphausiids, which are likely to be as important in trophic exchange processes as copepods, are poorly sampled by conventional means. These organisms are particularly suited for acoustic censusing, and knowledge of their mesoscale distribution and abundance will benefit from the use of quantitative sonic methods.

Vast manpower and monetary resources have been expended on studies to determine how the oceanography of the northeast Pacific Ocean affects the production of commercially important fish and shellfish. These studies have generally lacked interdisciplinary coordination, and because of this, have been unfocused in terms of ecosystem function. Completion of the OCSEAP-sponsored research and its synthesis in this book will provide one of the first attempts—in a single volume—to assemble what is understood about the Gulf of Alaska. It is essential that this compilation not represent an end in itself, but rather become a point of departure for more focused oceanographic studies of the interrelationships between the living and non-living components of this system. In the spirit of the new initiatives to describe ocean productivity that are stated by the Division of Ocean Sciences, NSF, this is surely one area ripe for both continued and expanded research.

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It is my desire to dedicate this review of zooplankton in the Gulf of Alaska to my dear friend and mentor, the late Dr. T. Saunders English, Professor of Oceanography, University of Washington, Seattle, Washington. His dedication to oceanography, his inspiration as a colleague, and his boundless enthusiasm for life infected all who were privileged to know him. It seems fitting that many of his friends and associates were in some way involved in the preparation of this monograph on the Gulf of Alaska. Tom would have liked that.

Appendix I.

Zooplankton and ichthyoplankton, reported in samples taken from the northern Gulf of Alaska (LeBrasseur 1965b; Cooney *et al.* 1973; Cooney 1975; Damkaer 1977; Kendall *et al.* 1980; Cooney *et al.* 1981; Vogel and McMurray 1986; VTN 1983; Wing and Reid 1972).

Cnidaria

Rathkea octopunctata
Bougainvillia superciliaris (= *B. multitentaculata*)
Euphysa japonica
Hybocodon prolifer
Calycopsis sp.
Sarsia tubulosa
S. princeps
S. rosaria
Leuckartiara octona
L. nobilis
L. breviconis (= *Neoturris breviconis*)
Perigonimus vesicarius
Halimodusa typus
Stomotoca atra
Polyorchis penicillatus
Obelia borealis
Phialidium gregarium
Aequorea aequorea (= *A. victoria*)
Melicertum octocostatum
Halistaura cellularia
Tiaropsidium sp.
Staurophora mertensi
Eutonina indicans
Gonionemus vertens
Proboscoidactyla flavicirrata
Aglantha digitale
Pantachogon haeckeli
Aegina citrea
Cunina globosa
Lensia conoidea
Muggiacea atlantica
Dimophyes arctica
Vogtia serrata
Agalma elegans
Chumiphyes multidentata
Nanomia sp.
Periphylla periphylla
Nectopyramis diomedea
Aurelia aurita
Cyanea capillata
Praya reticulata
Crysaora melanaster

Ctenophora

Bolinopsidae infundibulum
Beroe sp.
Pleurobrachia pileus

Polychaeta

Pelagobia longicirrata
Tomopteris septentrionalis
T. pacifica

T. planktonis
T. renata
Plotohelmis tenuis
Autolytus sp.
Typhloscolex mulleri
Poebius meseres

Mollusca

Limacina helicina (= *Spiratella pacifica*)
Euclio pyramidata
Clione limacina
Gasteropteron pacificum
Rossia pacifica
Eledone sp.
Chiroteuthis veranyi
Galiteuthis armata
Octopus sp.

Cladocera

Daphnia schodleri
Evadne nordmanni
E. tergestina
Podon leuckarti
P. polyphemoides

Ostracoda

Philomedes sp.
P. trituberculatus
Conchoecia alata minor
C. elegans

Copepoda

Neocalanus cristatus (= *Calanus cristatus*)
N. plumchrus (= *C. plumchrus*)
Calanus marshallae
C. pacificus
Mesocalanus tenuicornis (= *Calanus tenuicornis*)
Eucalanus bungii
Clausocalanus arcuicornis
Microcalanus spp.
Pseudocalanus spp.
Spinocalanus brevicaudatus
Aetideus divergens
A. pacificus
Chiridius gracilis
C. poppei
Bradyidius saanichi
Gaetanus intermedius
Gaidius tenuispinus
G. simplex
G. variabilis
Pseudochirella sp.
Pareuchaeta elongata
P. sarsi
Lophothrix frontalis
Amalothrix inornata
Racovitzanus antarcticus
Scaphocalanus magnus
S. brevicornis
Scotectithricella minor
S. ovata

Undinella sp.
Metridia curticauda
M. okhotensis
M. pacifica (= *M. lucens*)
M. princeps
Pleuromamma scutullata
P. robusta
Centropages abdominalis
Paracalanus parvus
Limnocalanus macrurus
Diaptomus sp.
Eurytemora americana
E. pacifica (= *E. herdmani*)
Lucicutia flavicornis
L. ovalis
Disseta scopularis
Heterorhabdus tanneri
H. compactus
H. robustoides
Heterostylites major
Haloptilus pseudoxycephalus
Candacia columbiae
Pachyptilis pacificus
Epilabidocera longipedata
Acartia clausi
A. longiremis
A. tumida
Tortanus discaudatus
Microsetella rosea
Harpacticus sp.
Tegastes sp.
Tisbe sp.
Lubbockia wilsonae
Pseudolubbockia dilatata
Oncea conifera
O. borealis
O. parila
O. notopus
O. prolata
Corycaeus anglicus
Oithona helgolandica (= *O. similis*)
O. spirostris
Monstrilla helgolandica
M. longiremis
M. wandlii
M. canadiensis
Cymbasoma rigidum

Isopoda

Gnorimosphaeroma oregonensis
Idothea wosnesenskii
Neosphaeroma oregonensis

Cumacea

Cumella sp.
Diastylis dawsoni
Vaunthompsonia sp.

Mysidacea

Acanthomysis nephrophthalma
A. pseudomacropsis

Holmesiella anomala
Neomysis rayii
N. kadiakensis
N. nakazawai
Pseudomma truncatum
Meterythrope robusta
Gnathophausia gigas
Mysis oculata

Amphipoda

Andaniexis subabyssi
Calliopius laeviusucla
C. behringi
Cyphocaris challengerii
C. anonyx
Eusiriella multicalceola
Koroga megalops
Hyperia medusarum hystrix
Hyperoche medusarum
Monoculodes zernovi
Orchomene sp.
Parathemisto gracilipes
P. pacifica
P. libellula
Phronima sedentaria
Primno macropa
Proscina birsteini
Scina stebbingi
S. borealis
S. rattrayi
Streetsia sp.
Tryphaena malmii
Lanceola pacifica
Westwoodilla rectangulata
Vibila australis
Paraphronima crassipes
Caprella sp.
Paracallisoma alberti
Rhachotropis natator

Euphausiacea

Euphausia pacifica
Thysanoessa inermis
T. inspinata
T. longipes
T. raschii
T. spinifera
Tessarabrachion oculata
Stylocheiron sp.

Decapoda

Pasiphaea pacifica
Hymenadora frontalis
Pandalus borealis
P. danae
P. jordani
P. platyceros
P. montagui tridens
P. stenolepis
Pandeleopsis dispar
Eualus pusiola

Crangon alaskensis
Sergestes similis
Chionoecetes spp.
Paralithodes sp.

Chaetognatha

Eukrohnia hamata
E. fowleri
E. bathypelagica
Sagitta elegans
S. scrippsae

Larvacea

Oikopleura dioica
O. labradoriensis
O. vanhoeffeni
Fritillaria borealis

Thaliacea

Salpa fusiformis
S. maxima

Osteichthyes

Clupea harengus pallasii
Mallotus villosus
Thaleichthys pacificus
Bathylagus milleri
B. pacificus
Lampanyctus regalis
Leuroglossus schmidti
Stenobranchius sp.
S. leucopsarus
S. nannochir
Protomyctophum crockeri
P. thompsoni
Gadus macrocephalus
Theragra chalcogramma
Sebastes sp.
Hexagrammos sp.
H. decagrammus
H. lagocephalus
H. octogrammus
H. stelleri
Ophiodon elongatus
Pleurogrammus monopterygius
Anoplopoma fimbria
Arctidius spp.
Clinocottus sp.
Dasycottus setiger
Gymnocanthus sp.
Hemilepidotus spp.
H. hemilepidotus
Icelinus borealis
Malacocottus zomurus
Myoxocephalus spp.
Radulinus asperellus
Triglops sp.
Liparis florum
Lifucensis spp.

Trichodon trichodon
Aptocyclus ventricosus
Bathymaster sp.
Anoplarchus insignis
Ronquilius jordani
Chirolophis polyactcephalus
Lumpenella longirostris
Lumpenus sagitta
L. maculatus
Stichaeus punctatus
Lycnectes aleutensis
Pholis sp.
P. laeta
Zaprora silenus
Ammodytes hexapterus
Atheresthes stomias
Glyptocephalus zachirus
Hippoglossoides elassodon
Isopsetta isolepis
Lepidopsetta bilineata
Microstomus pacificus
Platichthys stellatus
Psettichthys melanostictus
Hippoglossus stenolepis
Cyclothone sp.
Chauliodus macouni
Lycodapus mandibularis
Gasterosteus aculeatus

Appendix II.

Zooplankton collected in Boca de Quadra fjord during 1982 (VTN 1984).

Cnidaria

Hydrozoans
 Anthomedusae
Leuckartiara sp.
Rathkea octopunctata
Sarsia rosaria
Bougainvillea sp.
 Leptomedusae
Obelia sp.
Phialidium gregarium
Aequorea aequorea
 Limnomedusae
Proboscicactyla flavicirrata
 Trachymedusae
Aglantha digitale
 Siphonophora
Nanomia bijuga
Lensia conoidea
Muggiacea atlantica
Dimophyes arctica
 Scyphozoans
Aurelia aurita
Cyanea capillata

Ctenophora

Pleurobrachia pileus

Annelida

Polychaete larvae
Tomopteris septentrionalis
Rhynchonerella angelini

Mollusca

Gastropod larvae
Limacina helicina
Clione sp.
 Bivalve larvae
 Cephalopod larvae

Cladocera

Evadne nordmanni
Podon leuckarti

Ostracoda

Conchoecia spp.

Copepoda

Calanoida

Calanus marshallae
C. pacificus
C. plumchrus
C. cristatus
Eucalanus bungii
Paracalanus parvus
Microcalanus pusillus
Pseudocalanus minutus
Aetideus armatus
Gaetanus simplex
Pareuchaeta elongata
Metridia okhotsensis
Metridia pacifica
Centropages abdominalis
Eurytemora sp.
E. pacifica
E. americana
Candacia columbiae
Epilabidocera longipedata
Acartia clausi
A. longiremis
Tortanus discaudatus

Harpacticoida

Microsetella rosea
Harpacticus sp.

Cyclopoida

Oncaea borealis
Corycaeus anglicus
Oithona helgolandica
O. spinirostris

Cirripeda

Balanus sp. larvae

Mysidacea

Unidentified mysid

Isopoda*Gnorimosphaeroma oregonensis***Amphipoda***Cyphocaris challengeri**Orchomene* sp.*Parathemisto pacifica**Primno macropa**Scina borealis***Euphausiacea**

Euphausiid larvae

*Euphausia pacifica**Thysanoessa raschii**T. longipes**T. inermis**T. spinifera***Chaetognatha***Sagitta elegans***Tunicata***Oikopleura* spp.*Fritillaria borealis*

Ascidian larvae

Appendix III.

Planktivorous organisms
off Kodiak Island classified by
known food sources (Vogel and
McMurray 1986).

Calanoid Copepods

juvenile salmonids
capelin
herring
Pacific sand lance
juvenile whitespotted greenling
juvenile pollock
juvenile rock sole
juvenile yellowfin sole
gray whale
sei whale
fin whale
right whale

Fish Larvae

juvenile salmonids
Pacific sand lance
juvenile whitespotted greenling

Harpacticoid Copepods

juvenile salmonids
capelin

Pacific sand lance
juvenile whitespotted greenling
juvenile masked greenling
juvenile pollock
Pacific cod

Mysids

sand sole
pollock

Pelagic Amphipods

juvenile chum salmon
herring

Euphausiids

pollock
Pacific Ocean perch
yellow Irish lord
yellowfin sole
rex sole
flathead sole
juvenile arrowtooth flounder
short-tailed shearwater
tufted puffin
black-legged kittiwake
minke whale
fin whale
blue whale
humpback whale

Decapod Larvae

Pacific Ocean perch
herring
smelt
juvenile pink salmon
pandalid shrimp

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Biogeography and Ecology of Intertidal and Shallow Subtidal Communities

11

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ABSTRACT

Recent studies of the natural shore communities of the Gulf of Alaska provide a descriptive foundation for future work on the primary factors that determine both geographical and local distribution and abundance patterns for algal and invertebrate populations. However, there is still a lack of experimental evaluation to determine the role that physical disturbances, gradients in physical regimes, and biological interactions play in determining these patterns.

Our analysis of both the biotic composition and the zoogeographic affinities of those invertebrates of the major phyla revealed no major biogeographical discontinuities between Yakutat and the eastern Aleutian Islands. However, we found that the intertidal flora and fauna of the western Aleutians (Amchitka and Shemya Islands) differed markedly from the flora and fauna of the eastern Gulf. The distribution of species among trophic levels was similar between these two regions, but the western Aleutians had more Asiatic and fewer North American species, and had a greater proportion of endemic species of Mollusca, Crustacea, and Echinodermata than were found in the eastern Gulf.

Physical disturbance was only of overriding importance in controlling community structure at three of the 29 study sites. Gradients in the regimes for salinity, turbidity, and exposure altered both the community composition and the relative abundances of intertidal species, such as *Semibalanus balanoides* and *Balanus glandula*, which have a tolerance for a broad range of values for these factors. *Pisaster ochraceus* and *Evasterias troschelli* do not appear to play key roles in the organization of intertidal communities in Alaska because *Mytilus californianus* is rare there and *M. edulis* is vulnerable to the activities of other predators and perhaps to physical disturbance as well.

When most intertidal species are lifted even slightly above their upper vertical limits by land-level changes, they either die or emigrate. This supports the contention that the upper limits of most intertidal organisms are physiologically determined. The exceptions are *Balanus glandula*, *Semibalanus cariosus*, and *Chthamalus dalli* which can survive uplift of nearly 1 m above their upper limits. It normally takes at least three years for communities to redevelop to their former condition after an uplift.

Introduction

The Gulf of Alaska is bordered by an extensive and intricate coastline that provides a variety of habitats for intertidal organisms. For this chapter, we include the western Aleutian Islands in our discussion of intertidal communities in the Gulf so we can include research on the effects that sea otters (*Enhydra lutris*) have on intertidal and shallow subtidal communities, as well as research on the response of intertidal communities to land-level changes.

We have included an historical review of those studies done on the biogeography and the ecology of intertidal biota, with emphasis on recent work. We describe in detail the biogeographical relationships between intertidal algae and invertebrates found along the coast from Yakutat to the western Aleutian Islands. We also discuss the ecology of intertidal communities found both on the outer coast and in protected inner waters, and review research on the effect of natural and man-induced land-level change on intertidal communities.

Because many of the more recent intertidal studies also include subtidal observations, and research on the effects of sea otter predation on nearshore communities encompasses both intertidal and subtidal habitats, we also consider some research results from the subtidal region. In the final section of the chapter we discuss some aspects of subtidal kelp beds. Studies of both rocky and unconsolidated intertidal habitats are listed in this chapter, but our discussion emphasizes rocky intertidal research because these communities have historically received broader and more detailed attention than the infaunal intertidal communities.

Historical Research Review

The earliest observations and collections of intertidal organisms in the Gulf of Alaska were made at the beginning of the nineteenth century by the naturalists who accompanied expeditions of discovery into the region (Sauer 1802; Chamisso 1821). The beginnings of an extensive taxonomic literature on the algae and invertebrates of the region (Eschscholtz 1829–1833; Middendorff 1847, 1849; Brandt 1851; Grube 1855; and Dall 1884) followed soon after the observations of these naturalists were published. Lebednik and Palmisano (1977) and O'Clair (1977a) reviewed this early literature (with emphasis on the Aleutian Islands). Feder and Mueller (1972) reviewed the intertidal literature beginning with the Harriman Alaska Expedition (1899) and continuing through the 1960s (see also Zimmerman and Merrell 1976). Nybakken's (1969) study of the intertidal ecology of Three Saints Bay on Kodiak Island was the first quantitative study of intertidal communities in Alaska.

During the late 1960s and early 1970s, four major events occurred which precipitated a series of ecologically oriented studies of the Alaskan littoral zone. The first was the Great Alaskan Earthquake of 1964 (Baxter 1971; Haven 1971; Hubbard 1971; Johansen 1971; Nybakken 1971; and Paul, Paul, and Feder 1976). The second event was the initiation of the Amchitka Bioenvironmental Program in 1966 (O'Clair and Chew 1971; O'Clair 1977a, b; Lebednik, Weinmann, and Nor-

ris 1971; Lebednik and Palmisano 1977; Palmisano and Estes 1977; Simenstad, Estes, and Kenyon 1978; and Estes, Smith, and Palmisano 1978). The third was the Trans-Alaska Pipeline Project which followed the discovery of oil at Prudhoe Bay in 1969 (McRoy and Stoker 1969; Feder, Cheek, Flanagan, Jewett, Johnston, Naidu, Norwell, Paul, Scarborough, and Shaw 1976; Myren and Pella 1977; Dames and Moore 1979a; Feder and Paul 1980; and Feder and Keiser 1980). The fourth event was the establishment of the Outer Continental Shelf Environmental Assessment Program (OCSEAP) in 1974 (see review of Gulf of Alaska studies in Jarvela 1982). As a result of these and other more academic research efforts (Smith 1972; Duggins 1980a), a vast body of literature describing the species composition, community structure, and the ecology of intertidal biota has been accumulated during the last fifteen years. It is one objective of this chapter to indicate where these sources of information—most of which are still unpublished—may be found.

Aerial and Coastwide Surveys

The overall distribution of intertidal habitat types in the Gulf of Alaska was first described in a series of maps by Sears and Zimmerman (1977). Their data, extending from Yakutat (59°33'N, 139°50'W) to the Islands of the Four Mountains (52°45'N, 170°10'W), are based on aerial reconnaissance and describe 1) the general beach types (bedrock, boulder, gravel, sand, mud), 2) beach slopes, and 3) the percentage of the beach covered by intertidal biota. Zimmerman, Gnagy, Calvin, MacKinnon, Barr, Fujioka, and Merrell (1977) provide a breakdown of Sears and Zimmerman's (1977) data into the number of miles and the percentages of each beach type for several of the areas they surveyed. Concurrent with this work, several sections of the Gulf coastline were also mapped to provide information on coastal morphology and coastal vulnerability to oil spills. The first of these studies consisted primarily of maps indicating beach profiles, substrate types, grain sizes, and presumed vulnerabilities to oil retention; later work included detailed information on associated biota. By area, the early studies included:

- Glacier Bay National Monument (Molnia and Wheeler 1978)
- the northern Gulf of Alaska (Nummedal and Stephen 1976; Ruby 1977; Ruby and Hayes 1978; and Hayes and Ruby 1979a)
- the area from Montague Island to the Kenai Peninsula (Hayes 1980)
- the lower Cook Inlet region (Hayes, Brown, and Michel 1976; Michel, Hayes, and Brown 1978)
- the Kodiak Island region (Hayes and Ruby 1979b).

Surveys that also incorporated biological indices as part of the maps included Kodiak Island (Hayes 1982) and Shelikof Strait (Domeracki, Tjebeau, Getter, Sadd, and Ruby 1980). Additional data on intertidal habitats and associated biota, as indicated by aerial surveys or other large-scale reconnaissance methods, are found in:

- Arneson (1980) for the entire Gulf
- Rosenthal, Lees, and Maiero (1982) for Prince William Sound

- Lees (1978) for lower Cook Inlet
- Dames and Moore (1977a) for the outer coast of the Kenai Peninsula.

Many of these reports were reworked graphically and are found in Science Applications Inc. (1979, 1980a, b).

Intertidal and Shallow Subtidal Study Sites

Intertidal communities in the Gulf of Alaska have been described at approximately one hundred sites extending from Boca de Quadra in Southeast Alaska to Attu Island in the western Aleutians (Tables II-1a to II-1e). Research at almost all of these sites has resulted in detailed species lists and, in some measure, abundance and distributions data relative to tidal heights for the dominant species.

Southeast Alaska. From the perspective of littoral biology, Southeast Alaska is one of the least-described regions in the Gulf. No general aerial or coastwide surveys have ever been completed there; only six general areas have been studied in any detail on the ground (Table II-1a). Of these six, those that extended over the longest period of time and contain the most detailed observations include: 1) the intertidal work at Torch Bay by Quinn and Duggins (1977) and Paine (1980) and 2) the subtidal work at Torch Bay, Deer Harbor, and Surge Bay by Duggins (1980a, b; 1981a, b; and 1983). In addition to describing the seasonal distributions and the densities of dominant organisms, the Torch Bay work also describes the results of experiments that were designed to determine the role that three kinds of predators—sea urchins, the sea star *Pycnopodia*, and sea otters—play in the subtidal community.

Work at Starrigavin Bay (Hartman and Zahary 1983) describes species groups sampled throughout the intertidal region. The descriptions were part of a study aimed at differentiating the biogeographic regions along the west coast of the United States. Research by VTN (1982a, b, and 1983)—part of a comprehensive environmental baseline done prior

Table II-1a.
Intertidal and shallow subtidal sites sampled in Southeast Alaska (northern Queen Charlotte Islands to Yakutat).

SITE	SUBSTRATE	AUTHOR
Boca de Quadra, Smeaton Bay, Wilson Arm (55°10'N, 131°00'W) ^a	Rock, gravel, sand, silt	VTN 1982a, 1982b, 1983
Starrigavin Bay (57°06'N, 135°23'W)	Rock	Hartman and Zahary 1983
Hawk Inlet, Young Bay (58°10'N, 134°38'W)	Rock, gravel, sand, silt	International Environmental Consultants 1980; Holland <i>et al.</i> 1981
Auke Bay (58°22'N, 134°40'W)	Rock	O'Clair and Fritts 1980
Berner's Bay (58°42'N, 135°00'W)	Rock, gravel, sand, silt	Smith 1972; Calvin 1977
Torch Bay (58°20'N, 136°50'W)	Rock	Quinn and Duggins 1977; Paine 1980; Duggins 1980a, 1980b, 1981a, 1981b, 1983

^a In cases where geographic coordinates were not listed by the authors, those given by Orth (1967) have been used.

to the development of the Quartz Hill Molybdenum Project—provides data on year-to-year variations in both the abundances of selected species and dendrograms of species groups. A draft Environmental Impact Statement, which describes both the proposed development of this large molybdenum deposit and the environmental studies that accompanied the proposed action, is available from the Ketchikan Office of the USDA Forest Service (Administrative Document 133, undated).

Research was done by International Environmental Consultants (1980), Martin Marietta Corporation (Holland, Hiegel, and Richkus 1981), and Hancock (undated) as part of the Noranda/Greens Creek mining study. These studies provide data on the number of organisms per square meter in soft bottom samples as well as graphical depictions of biotic zonation at several sampling sites. A final Environmental Impact Statement (dated January 1983), which describes both the proposed development of this large lead/zinc/silver ore body on Admiralty Island and the environmental research which accompanied it, is available from the Juneau Office of the USDA Forest Service. Smith (1972)—later published as Calvin (1977)—gives qualitative observations on the species that occur at eight sites in the Berner's Bay area. O'Clair and Fritts' (1980) experimental data from studies in Auke Bay are discussed in more detail later in this chapter.

Data on substrate types, benthic profiles, and associated biota recorded during subtidal investigations of approximately 75 additional sites may be found in the Special Investigations Files of the National Marine Fisheries Service in Juneau, Alaska. These studies, usually limited to a single set of observations occurring over a one- or two-day period, were undertaken as part of a regional survey of proposed log transfer and rafting sites in Southeast Alaska. Results from 32 of these sites are summarized in Schultz and Berg (1976). A final Environmental Impact Statement (dated October 1984) describes subtidal work done in conjunction with a proposed log transfer facility at Cube Cove on Admiralty Island. This is available from the U.S. Army Corps of Engineers office in Anchorage.

Northeastern and Central Gulf. As evidenced from aerial surveys, exposed sand and gravel beaches predominate in this region. They account for almost 60% of the intertidal substrata (Zimmerman *et al.* 1977), but this estimate does not include Prince William Sound. Data from many of the individual sites within this area are found in Zimmerman and Merrell (1976) and O'Clair, Hanson, MacKinnon, Gharrett, Calvin, and Merrell (1978); both of these reports resulted from a single geographically extensive study of the intertidal biota of the Gulf—a study funded by the Outer Continental Shelf Environmental Assessment Program (OCSEAP). Transect lines or random point sampling methods were used to collect quantitative quadrat samples at each site. Zimmerman and Merrell (1976) and O'Clair *et al.* (1978) contain figures and tables describing the densities and the distributions of organisms relative to tidal heights. Additional work completed as part of this project includes a study of the accumulation of drift biota at three sites over several seasons (Palmisano 1976); Rosenthal, Lees, and Rosenthal's (Dames and Moore 1976a, 1977b) charac-

terization of subtidal biota at three sites adjacent to Zimmerman and Merrell's (1976) intertidal sites; and a feasibility study using aerial multispectral scanning techniques to map the distribution of biota in intertidal zones (Roller and Polcyn 1978).

Other geographically extensive studies have also been completed in this region (Table II–Ib). Rosenthal, Lees, and Maiero (1982) provide qualitative descriptions and general observations at 22 sites along the shoreline of Prince William Sound. Lees and Rosenthal (Dames and Moore 1977a) describe the intertidal and subtidal zones at three sites along the outer coast of the Kenai Peninsula. These data include quantitative determinations of the densities, distributions, and percent cover of several numerically abundant species—as well as general 'nature walk' descriptions. Lees and Rosenthal also paid special attention to the biology of the eelgrass beds and the mussel beds which they encountered.

Nickerson (1975) reports on razor clam populations and associated organisms at eleven sites across the northern Gulf and also provides descriptions of substrate types. Research results following the Great Alaskan Earthquake of 1964 describe the effects that tectonic changes in land levels have on populations of 1) benthic algae (Johansen 1971), 2) clams (Baxter 1971), and 3) other intertidal invertebrates (Haven 1971). This earthquake-related work was based on a coordinated, vessel-based survey of thirty-three sites from upper Orca Inlet to the southwestern islands of the Sound.

Several additional studies report on the distribution of intertidal communities at a single site or in a geographically restricted area. These include:

- earthquake-related work at Olsen Bay (Hubbard 1971; Paul, Paul, and Feder 1976)
- a time-series study of the effect of oil development in the Valdez area on *Macoma balthica* populations (Myren and Pella 1977)
- a three-year field study of the effects of crude oil on intertidal populations of bacteria, meiofauna, and *Macoma balthica* at Port Valdez (Feder *et al.* 1976)
- a pre-oil baseline survey in the Valdez area (McRoy and Stoker 1969)
- a study of several intertidal and shallow subtidal sites north of the oil terminal in the Valdez area (Dames and Moore 1979a; Lees, Erikson, Driskell, and Boettcher 1979)
- a nineteen-month time series study of species densities, settlement, and recruitment at three permanent sites in Port Valdez (Feder and Keiser 1980)
- a study of seasonal trends in meiofaunal abundance on two beaches in Port Valdez (Feder and Paul 1980)
- a zonation study at Resurrection Bay (Hartman and Zahary 1983).

Cook Inlet Region. Aerial surveys (Lees 1978) indicate that protected habitats—most often composed of unconsolidated cobble, gravel, sand, or silt—dominate this coastline. Most littoral research has occurred in the southern sector of the Inlet; with the exception of salt marsh studies in

Table II–Ib.
Intertidal and shallow subtidal sites sampled in the northeastern and central Gulf of Alaska (Yakutat to Cook Inlet).

SITE	SUBSTRATE	AUTHOR
Yakutat (59°32.3'N, 139°52.5'W)	Rock	Zimmerman and Merrell 1976; O'Clair <i>et al.</i> 1978
Yakutat (59°32'N, 139°53'W)	Sand	Palmisano 1976
Yakataga (62°03.8'N, 142°25.9'W)	Rock	Zimmerman and Merrell 1976; O'Clair <i>et al.</i> 1978
Yakataga (62°04'N, 142°26'W)	Sand	Palmisano 1976
Cape St. Elias (59°47.8'N, 144°36.3'W)	Rock	O'Clair <i>et al.</i> 1978
Kayak Island to Shelikof Strait	Sand	Nickerson 1975
Kanak Island (60°7.5'N, 144°20'W)	Sand, silty sand	O'Clair <i>et al.</i> 1978
Katalla Bay (60°16.5'N, 144°36.5'W)	Rock	Zimmerman and Merrell 1976; O'Clair <i>et al.</i> 1978
Softuk Spit (60°12'N, 144°42'W)	Sand	O'Clair <i>et al.</i> 1978
Orca Inlet to Sawmill Bay (60°39.9'N, 145°37.4'W 60°03.4'N, 148°02.5'W)	Rock, sand, to silt	Johansen 1971; Haven 1971; Baxter 1971
Big Egg Island (60°22'N, 145°44'W)	Sand	O'Clair <i>et al.</i> 1978
Hartney Bay to LaTouche Island (60°29'N, 145°53'W to 59°57'N, 148°03'W)	Rock, sand, silt	Rosenthal <i>et al.</i> 1982
Olsen Bay (60°42.2'N, 146°12.3'W)	Rock	Hubbard 1971
Olsen Bay (60°24.6'N, 146°06.3'W)	Gravel	Paul <i>et al.</i> 1976
Boswell Bay (60°24.6'N, 146°06.3'W)	Silt	Zimmerman and Merrell 1976; O'Clair <i>et al.</i> 1978
Hook Point (60°20'N, 146°15'W)	Sand	O'Clair <i>et al.</i> 1978
Middleton Island (59°25.2'N, 146°22.5'W)	Rock	Zimmerman and Merrell 1976; O'Clair <i>et al.</i> 1978
Middleton Island (59°25'N, 146°23'W)	Sand	Palmisano 1976
Cape Hinchinbrook (60°14.3'N, 146°38.8'W)	Rock	O'Clair <i>et al.</i> 1978
Point Barber (60°19.8'N, 146°39.5'W)	Rock	O'Clair <i>et al.</i> 1978
Port Valdez (60°05'N, 146°21'W)	Sand, silt	Feder <i>et al.</i> 1976
Port Valdez (60°05'N, 146°21'W)	Rock, gravel, sand, silt	McRoy and Stoker 1969
Port Valdez (60°05'N, 146°21'W)	Sand, silt	Myren and Pella 1977
Port Valdez (60°05'N, 146°21'W)	Rock, sand, silt	Dames and Moore 1979a; Lees <i>et al.</i> 1979
Port Valdez (60°05'N, 146°21'W)	Boulder, cob- ble sand, silt	Feder and Keiser 1980
Port Valdez (60°05'N, 146°21'W)	Sand, silt	Feder and Paul 1980
Zaikof Bay (60°17.9'N, 147°00'W)	Rock	Zimmerman and Merrell 1976; O'Clair <i>et al.</i> 1978
Zaikof Bay (60°17.9'N, 147°00'W)	Rock	Roller and Polcyn 1977
Zaikof Bay (60°17.9'N, 147°00'W)	Subtidal rock, sand, silt	Dames and Moore 1976a, 1977b
MacLeod Harbor (59°53.4'N, 147°47.7'W)	Rock	Zimmerman and Merrell 1976; O'Clair <i>et al.</i> 1978
MacLeod Harbor (59°53.4'N, 147°47.7'W)	Subtidal rock, sand, silt	Dames and Moore 1976a, 1977b

SITE	SUBSTRATE	AUTHOR
Latouche Point (59°57.1'N, 148°03.4'W)	Rock	O'Clair <i>et al.</i> 1978
Latouche Point (59°57.1'N, 148°03.4'W)	Subtidal rock	Dames and Moore 1976a; 1977b
Squirrel Bay (59°59.8'N, 148°08.4'W)	Rock	Zimmerman and Merrell 1976; O'Clair <i>et al.</i> 1978
Anchor Cove (59°59.7'N, 149°06'W)	Rock	Zimmerman and Merrell 1976; O'Clair <i>et al.</i> 1978
Resurrection Bay (149°25'N, 60°6'W)	Rock	Hartman and Zahary 1983
Port Dick (59°13.2'N, 151°01'W)	Rock	O'Clair <i>et al.</i> 1978
Port Dick (59°13'N, 151°01'W)	Rock, cobble, sand	Dames and Moore 1977a
Chugach Bay (59°11'N, 151°34'W)	Rock, cobble, sand	Dames and Moore 1977a
Koyukolik Bay (59°14.3'N, 151°56.3'W)	Rock, cobble, sand	Dames and Moore 1977a

the upper part of the Inlet (Macdonald, Wolfe, and Savage 1979; Vince and Snow 1984; and Snow and Vince 1984), all other littoral work in this region has occurred south of Kalgin Island (Table II-1c). Intertidal and shallow subtidal research in this region began with a description of marine plant (Dames and Moore 1976b) and shallow subtidal (Driskell and Lees 1977) communities in Kachemak Bay. This work was expanded geographically to include a reconnaissance of representative sites on both sides of the Inlet (Lees 1978; Lees and Driskell 1980) and was completed with a detailed investigation of the ecology of rock, sand, and silt habitats on both sides of the Inlet (Dames and Moore 1979b, 1980a). Throughout all of this work, stratified random sampling along transect lines was generally used to obtain data on species distributions, abundances, and standing stocks. Seasonal patterns of primary productivity, growth, and standing crops of macrophytes were also examined. Additional studies of limited geographical areas include a multi-seasonal study of sixteen transect lines along both sides of the Homer Spit (Lees, Erikson, Driskell, and Treesh 1981), and a reconnaissance of inshore areas at the Phillips Petroleum lease blocks at Spring Point in Chinitna Bay (Lees 1976). A study of beach drift composition similar to Palmisano's work in the eastern Gulf was also completed in lower Cook Inlet (Cunning 1977).

Kodiak Area. Beaches in the Kodiak area are composed primarily of bedrock, boulder, and gravel. Bedrock comprises almost 50 percent of all beach types found on Kodiak and associated islands; sand and silt substrates account for less than ten percent (Zimmerman *et al.* 1977), but this estimate does not include the Alaska Peninsula. Ecological research on intertidal communities was initiated on Kodiak Island with Nybakken's thesis work at Three Saints Bay (Nybakken 1969). Two studies since then have greatly expanded the data from this area. These were: 1) a qualitative and quantitative study of the intertidal biota and subtidal kelp communities occurring around Kodiak Island (Zimmerman, Hanson, Fujioka, Calvin, Gharrett, and MacKinnon 1979; O'Clair, Hanson, Myren, Gharrett, Merrell, MacKinnon, and Calvin 1981), and 2) a detailed study of

Table II-1c.
Intertidal and shallow subtidal sites sampled in the Cook Inlet region (North of 59°N).

SITE	SUBSTRATE	AUTHOR
Seldovia Point (59°28'N, 151°42'W)	Rock, cobble	Dames and Moore 1976b, 1979b, 1980; Lees and Driskell 1980
Jakalof Bay (59°28'N, 151°32'W)	Rock, cobble	Dames and Moore 1976b; Lees and Driskell 1980a
Sadie Cove (59°30.5'N, 151°28'W)	Rock	Dames and Moore 1976b
Gull Island (59°35.1'N, 151°19.7'W)	Rock	Dames and Moore 1976b, 1979b, 1980
Homer Spit (59°37'N, 151°27'W)	Sand	Dames and Moore 1979b, 1980a; Lees <i>et al.</i> 1981
Archimandritof Shoals (59°36'N, 151°27'W)	Rock, sand	Dames and Moore 1976b, 1979b, 1980a
Seafair Beach, Bishop's Beach, Bluff Point (59°40'N, 151°41'W)	Boulder, cob- ble, gravel, sand	Lees 1978
Whiskey Gulch (59°50'N, 151°49'W)	Cobble, sand	Lees 1978
Deep Creek (60°02'N, 151°42'W)	Sand	Dames and Moore 1977a, 1979b, 1980a
Clam Gulch (60°14.5'N, 151°24'W)	Sand	Lees 1978
Kasilof (60°23.3'N, 151°17.8'W)	Sand, silt	Lees 1978
Potter Marsh (61°03'N, 149°48'W)	Salt marsh	Macdonald <i>et al.</i> 1979
Susitna Flats (61°15'N, 151°30'W)	Salt marsh	Vince and Snow 1984; Snow and Vince 1984
Polly Creek (60°17'N, 152°27'W)	Sand	Lees 1978
Spring Point (59°52'N, 152°48'W)	Cobble, sand	Lees 1976
Chinitna Bay (59°51'N, 152°54'W)	Sand, silt	Dames and Moore 1977a, 1979b, 1980a; Lees and Driskell 1980
Scott Island (59°38'N, 153°26'W)	Rock	Dames and Moore 1979b, 1980a; Lees and Driskell 1980
Iniskin Bay (59°39'N, 153°27'W)	Rock, sand, silt	Lees 1978
Knoll Head Lagoon (59°38.5'N, 153°30'W)	Rock, cobble	Dames and Moore 1979b, 1980a; Lees and Driskell 1980
White Gull Island (59°37'N, 153°34'W)	Rock	Dames and Moore 1979b, 1980a; Lees and Driskell 1980
Bruin Bay (59°22.5'N, 153°57'W)	Rock, gravel, sand, silt	Lees 1978
Amakdedori Beach (59°16.6'N, 154°07.5'W)	Rock, sand	Lees 1978
Douglas River (59°04.5'N, 153°48.5'W)	Rock, sand, silt	Lees 1978

razor clam distributions and populations in the Kodiak/Shelikof Strait region (Kaiser and Konigsberg 1977). Both of these studies covered wide geographic areas (Table II-1d).

The reports of Zimmerman *et al.* (1979) and O'Clair *et al.* (1981) primarily describe the abundances and tidally related distributions of rocky intertidal communities; Kaiser and Konigsberg's (1977) report provides data on sandy beaches and associated biota. All three publications contain extensive species lists. Additional reports, which review the available literature or provide lists of shallow subtidal organisms

Table II-Id.
Intertidal and shallow subtidal sites sampled in the Kodiak Island vicinity (North of 56°N from 152° to 155°W).

SITE	SUBSTRATE	AUTHOR
Sud Island (58°54.3'N, 152°12.4'W)	Rock	Zimmerman <i>et al.</i> 1979
North Shuyak Island (58°36'N, 152°31'W)	Rock	Zimmerman <i>et al.</i> 1979
Sea Otter Island (58°31'N, 152°13'W)	Rock	Zimmerman <i>et al.</i> 1979
Tonki Bay (58°16'N, 152°09'W)	Rock	Zimmerman <i>et al.</i> 1979
Pillar Cape (58°09'N, 152°05'W)	Rock	Zimmerman <i>et al.</i> 1979
Spruce Island (57°54'N, 152°21'W)	Rock	Zimmerman <i>et al.</i> 1979
Whale Island (57°56'N, 152°45'W)	Rock	Zimmerman <i>et al.</i> 1979
St. Paul Harbor (57°46'N, 152°28'W)	Rock, sand, silt	Marine Advisors 1971
St. Paul Harbor (57°46'N, 152°28'W)	Rock	Zimmerman <i>et al.</i> 1979
Chiniak Bay (57°41'N, 152°25'W)	Rock	Zimmerman <i>et al.</i> 1979
Narrow Cape (57°25'N, 152°20'W)	Rock	Zimmerman <i>et al.</i> 1979
Lagoon Point (57°11.3'N, 153°3.4'W)	Rock	Zimmerman <i>et al.</i> 1979
South Sitkalidak Lagoon (57°08'N, 153°02'W)	Silt	Zimmerman <i>et al.</i> 1979
Ocean Bay (57°06.7'N, 153°10'W)	Sand	Kaiser and Konigsberg 1977
Three Saints Bay (57°08'N, 152°29'W)	Rock	Nybakken 1969; Nybakken 1971
Three Saints Bay (57°07.8'N, 152°28.7'W)	Rock	Zimmerman <i>et al.</i> 1979
Cape Kaguyak (56°52.4'N, 153°40.9'W)	Rock	Zimmerman <i>et al.</i> 1979
Geese Islands (56°43'N, 153°53'W)	Rock	Zimmerman <i>et al.</i> 1979
Cape Sitkinak (56°33.7'N, 153°52.1'W)	Rock	Zimmerman <i>et al.</i> 1979
Whirlpool Point (57°37'N, 154°08'W)	Gravel	Zimmerman <i>et al.</i> 1979
Sundstrom Island (58°54.3'N, 152°12.4'W)	Rock	Zimmerman <i>et al.</i> 1979
Dolina Point (56°36.9'N, 154°13.2'W)	Rock	Zimmerman <i>et al.</i> 1979
Tugidak Island (56°30.7'N, 152°28.7'W)	Sand	Kaiser and Konigsberg 1977
Tanner Head (56°52.8'N, 154°13.3'W)	Sand	Kaiser and Konigsberg 1977
Low Cape (57°59.5'N, 154°31.1'W)	Boulder, Cobble	Zimmerman <i>et al.</i> 1979
Bumble Bay (57°21.6'N, 154°13.3'W)	Sand	Kaiser and Konigsberg 1977
Cape Nukshak (58°23'N, 153°59'W)	Rock	O'Clair <i>et al.</i> 1981
Swikshak (58°36.6'N, 153°43.2'W)	Sand	Kaiser and Konigsberg 1977
Big River (58°35.7'N, 153°52.2'W)	Sand	Kaiser and Konigsberg 1977
Village Beach (58°34.2'N, 153°51.5'W)	Sand	Kaiser and Konigsberg 1977
Hallo Bay (58°20.2'N, 154°04.3'W)	Sand	Kaiser and Konigsberg 1977
Kukak Bay (58°21.3'N, 154°40.5'W)	Sand	Kaiser and Konigsberg 1977
Dakavak Bay (58°03.7'N, 154°41.2'W)	Sand	Kaiser and Konigsberg 1977

SITE	SUBSTRATE	AUTHOR
Katmai Bay (58°01.2'N, 154°55'W)	Sand	Kaiser and Konigsberg 1977
Kashvik Bay (57°56.7'N, 155°05.7'W)	Sand	Kaiser and Konigsberg 1977
Alinchak Bay (57°49.9'N, 155°20.2'W)	Sand	Kaiser and Konigsberg 1977

collected during studies on the effects of sewer outfalls or canneries, include Arctic Environmental Information and Data Center (AEIDC) (1974), Marine Advisors (1971), and Fisheries Research Institute (1971).

Western Gulf of Alaska. Beaches in the western Gulf of Alaska are composed primarily of bedrock and boulders. From Unimak Pass to the Islands of the Four Mountains, these two substrates account for over 86% of beaches surveyed (Zimmerman *et al.* 1977). Most of the intertidal research in this area has been a direct result of either the OCSEAP Program or the Amchitka Bioenvironmental Program.

The research funded through the OCSEAP Program (Zimmerman *et al.* 1979; O'Clair *et al.* 1981) was primarily reconnaissance in nature and extended only as far as Makushin Bay on Unalaska Island (Table II-1e). The research done on Amchitka Island was more intensive, extending over several seasons to determine the effect of the Milrow and Cannikin experiments (O'Clair 1977a, b; Estes and Palmisano 1974; Lebednik and Palmisano 1977; and Palmisano and Estes 1977). Reports resulting from both the OCSEAP and Amchitka research, as well as a study of intertidal and subtidal habitats near the Unalaska Airport (Dames and Moore 1980b), contain detailed species lists, along with tables and figures describing abundances and tidally related distributions of dominant biota. Additional studies related to the distribution and productivity of eelgrass beds in Alaska (most of which have been studied north of Unimak Pass) are found in McRoy (1970).

Biogeography

A great deal of attention has been paid to the delineation of the marine biogeographical boundaries along the eastern North Pacific coast. Valentine (1966) reviews the provincial classification systems for Mollusca proposed by various authors. Hartman and Zahary (1983) provide a more recent review including classification schemes suggested by workers studying other invertebrate phyla and algae. Although most workers recognize an Aleutian Province (which includes the Gulf of Alaska) within the Eastern Pacific Boreal region (Briggs 1974; Hartman and Zahary 1983), their provincial boundaries are based on latitude. In the Gulf of Alaska, most latitudes intersect two coastal segments. The longitudinal boundaries of the Aleutian Province are much broader than those of other provinces along the Pacific coast of North America. While longitudinal boundaries of the other provinces never include more than 10 degrees of longitude, those of the Aleutian Province include 60 degrees. Further, the Aleutian Archipelago appears to be an

Table 11-le.
Intertidal and shallow subtidal sites sampled in the western Gulf of Alaska (156°W to 179°E).

SITE	SUBSTRATE	AUTHOR
Chirikof Island (55°49.6'N, 156°44.1'W)	Rock	Zimmerman <i>et al.</i> 1979
Spectacle Island (55°07.2'N, 159°44.6'W)	Rock	O'Clair <i>et al.</i> 1981
Sennet Point (54°29.1'W, 164°54.4'W)	Rock	O'Clair <i>et al.</i> 1981
Akun Island (54°08.5'N, 165°38.7'W)	Rock	O'Clair <i>et al.</i> 1981
Unalaska Airport (53°54'N, 166°33'W)	Rock, cobble, gravel, sand	Dames and Moore 1980b
Eider Point (53°57.5'N, 166°35.1'W)	Rock	O'Clair <i>et al.</i> 1981
Makushin Bay (53°44'N, 166°45.8'W)	Rock	O'Clair <i>et al.</i> 1981
Adak Island (51°45'N, 176°45'W)	Rock	Palmisano and Estes 1977
Amchitka Island (51.5°N, 179°E)	Rock	Lebednik and Palmisano 1977
Amchitka Island (51.1°N, 179°E)	Rock	O'Clair 1977a, 1977b
Shenya Island (52°43'N, 174°07'E)	Rock	Palmisano and Estes 1977
Attu Island (52°55'N, 172°55'E)	Rock	Palmisano and Estes 1977

area of transition between the Asiatic and North American biotas. Because of these facts, east-west trends in biogeographical distributions of invertebrates and algae within the Aleutian Province seem to warrant further resolution.

Biotic Similarity. We compared assemblages of algae and invertebrates in the rocky intertidal region at 28 localities (27 for the algae) bordering the Gulf of Alaska (Fig. 11-1). Data on presence or absence of species at each of these sites were taken from Lebednik and Palmisano (1977), Zimmerman *et al.* (1979), O'Clair (1977a), O'Clair *et al.* (1978), and O'Clair *et al.* (1981). Sites at each of the localities were sampled with transects laid perpendicular to the shoreline

or by means of intertidal arrays. Quadrats, usually 1/16 or 1/64 m² in area, were placed systematically either along transects or randomly in arrays. All macrobiota were removed from within the quadrat, fixed with 10% formalin, and returned to the laboratory for sorting and identification. For further details on the sampling methods, Lebednik and Palmisano (1977), see Zimmerman *et al.* (1979), O'Clair (1977a), O'Clair *et al.* (1978), and O'Clair *et al.* (1981). The 28 sampling localities included in the present work are shown in Figure 11-1 and listed in Tables 11-lb, d, and e.

Only organisms identified to species are included—except in those few cases when organisms obviously unique within the composite collection considered here could be identified only to generic or higher taxonomic level. Members of the following taxa were not identified to species level at most sites:

- Porifera
- Anthozoa
- Platyhelminthes
- Nemertea
- *Sipuncula*
- Nematoda
- Oligochaeta
- Pseudoscorpionida
- Harpacticoida
- Acarina
- Insecta (except *Emplectonema*)
- Brachiopoda
- Urochordata

Similarity in biotic composition between localities was quantified with Jaccard's (1902) coefficient of similarity, calculated as follows:

$$CJ = c/(a + b - c)$$

where a and b are the number of species present at each locality, and c is the number of species common to both localities. CJ varies between 0 (dissimilar) and 1 (similar) and was multiplied by 100 to remove the decimal.

Patterns of similarity in biotic composition in the rocky intertidal region from Yakutat to the western Aleutian Islands were evaluated from cluster analysis by the unweighted pair-group average analysis of the CJ's (Dixon, Brown, Engelman, Frane, Hill, Jennrich, and Toporek 1983). Separate similarity matrices and dendrograms were constructed for algae and invertebrates (Figs. 11-2 through 11-4, and 11-6).

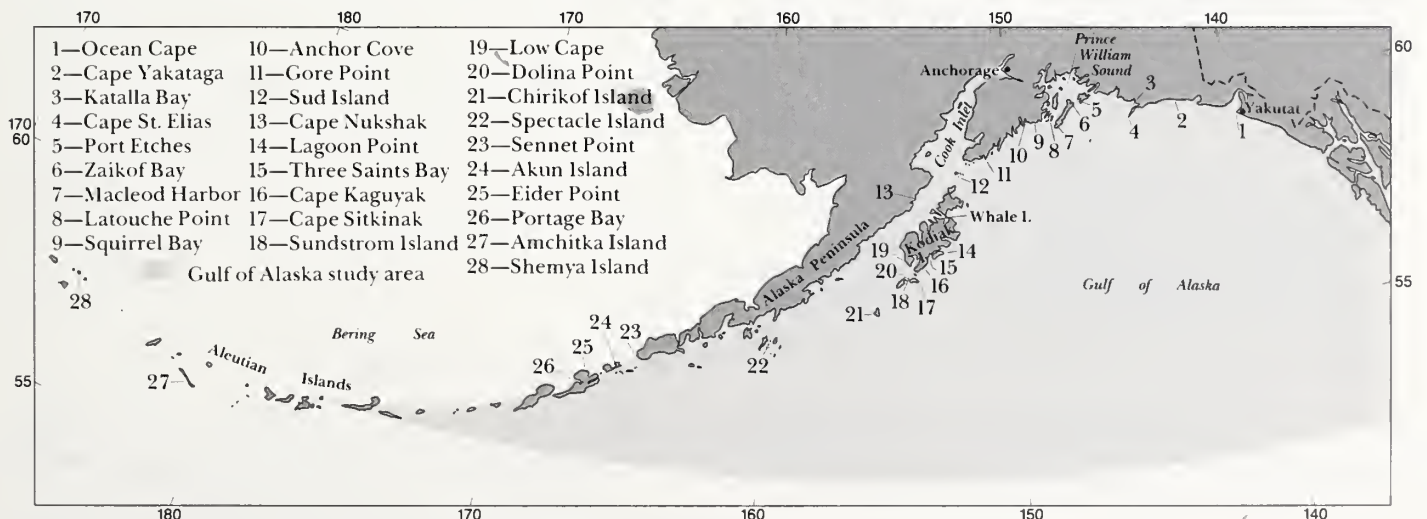


Figure 11-1. Map showing locations used in the biogeographical analyses.

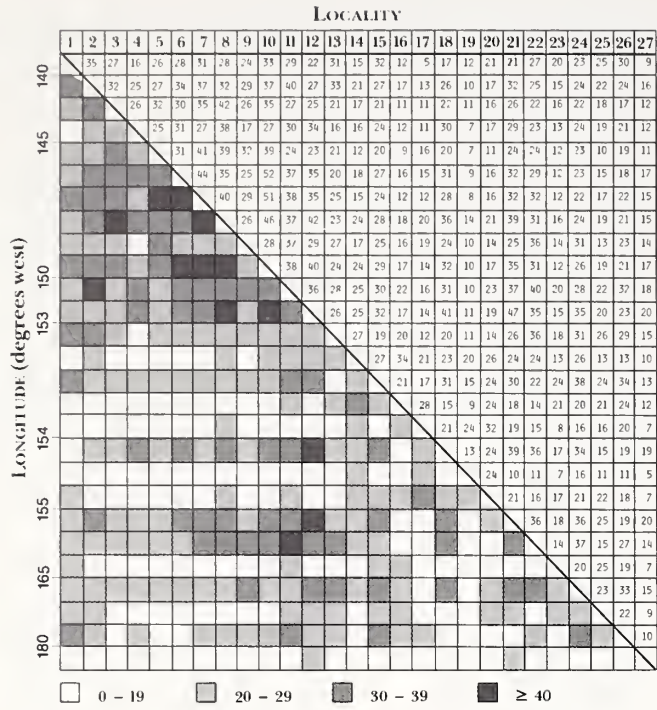


Figure 11-2. Similarity matrix (Jaccard's index) for algae at 27 sites in the Gulf of Alaska. Locality numbers correspond to the localities shown in Figure 11-1.

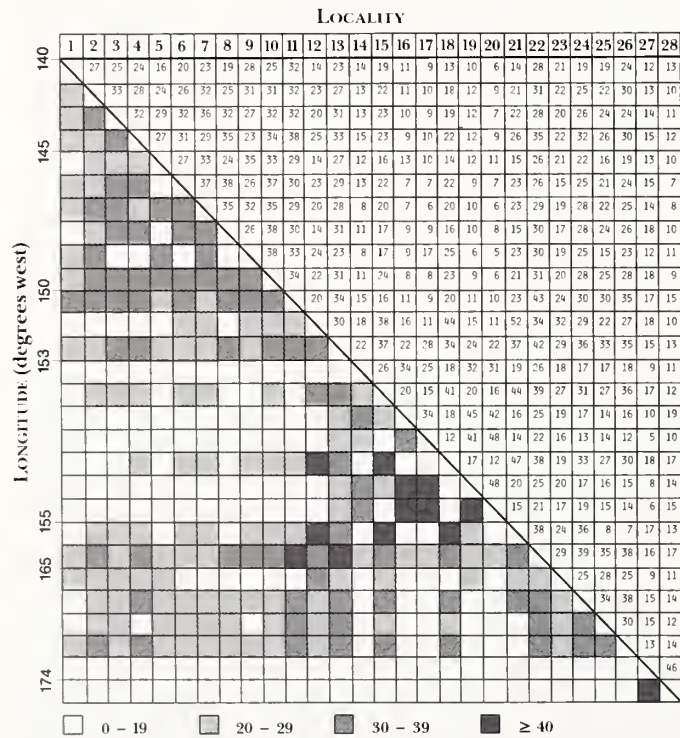


Figure 11-3. Similarity matrix (Jaccard's index) for invertebrates at 28 sites in the Gulf of Alaska. Locality numbers correspond to localities shown in Figure 11-1.

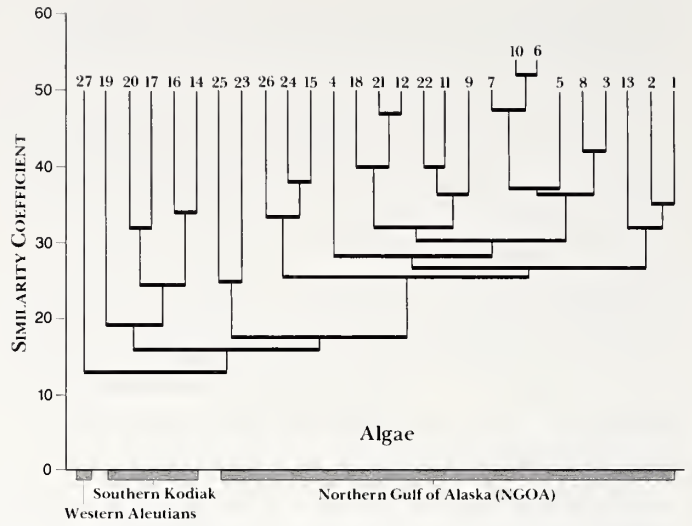


Figure 11-4. Dendrogram depicting the similarity of intertidal sites in the Gulf of Alaska with respect to algal species composition. Numbers correspond to localities shown in Figure 11-1.

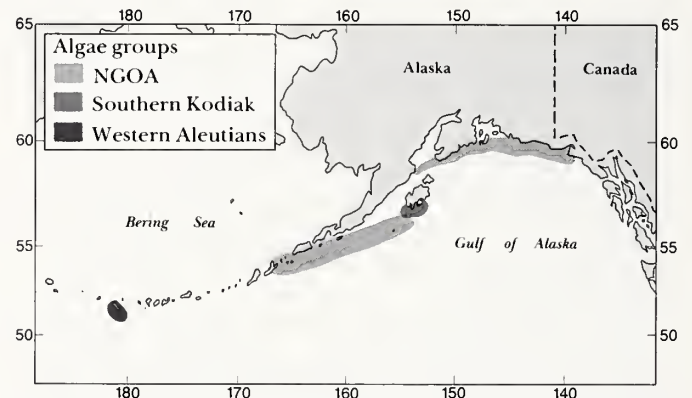


Figure 11-5. Map showing the distribution of major biogeographic groups of algae between Yakutat (Ocean Cape) and the western Aleutian Islands.

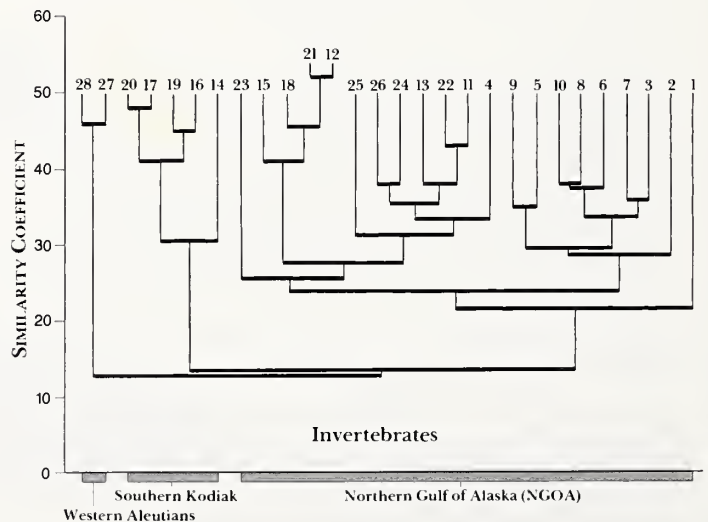


Figure 11-6. Dendrogram of similarity coefficients for invertebrates. Numbers correspond to localities shown in Figure 11-1.

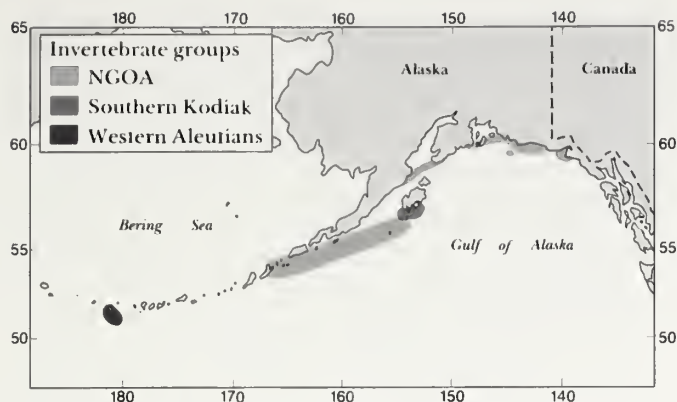


Figure 11-7. Map showing distribution of major biogeographic groups of invertebrates between Yakutat (Ocean Cape) and the western Aleutian Islands.

Analysis of the algal data revealed two distinct groups of sites with low between-group similarity and low similarity with Amchitka Island in the western Aleutians (Figs. 11-2 and 11-4). The first group comprised most of the sites studied in the northern Gulf of Alaska (NGOA). The second group was composed of five localities at the southern end of Kodiak Island: Lagoon Point (14), Cape Kaguyak (16), Low Cape (19), Cape Sitkinak (17), and Dolina Point (20) (Figs. 11-4 and 11-5). (Numbers in parentheses refer to locality numbers in Figure 11-1.)

The similarity matrix and dendrogram for invertebrates showed similar groupings to those for the algae. Cluster analysis distinguished a NGOA group, a southern Kodiak group, and a western Aleutian group consisting of Amchitka and Shemya Islands (Figs. 11-3, 11-6, and 11-7).

With the exception of the localities in the southern Kodiak group, most of the localities from Yakutat to the eastern Aleutian Islands fell within the same cluster with respect to both algal- and invertebrate-species composition. The Kodiak sites were characterized by either complete or partial exposure to open ocean waves and, at four of the five sites, they were characterized by exposure to unstable substrates of boulders or boulders and bedrock. Algae and invertebrates at these sites were characterized by low species richness (Zimmerman *et al.* 1979). The species richness for algae at the sites averaged less than half of the species richness for the NGOA group (Table 11-2). The low algal species richness at four of the Kodiak sites was probably due

to disturbances that resulted when boulders on the predominantly boulder-strewn beaches were moved during storms.

Invertebrate species richness within the southern Kodiak group was also low—especially in the case of Polychaeta and Crustacea. Crustacean species richness was low because few gammarids were present in collections from the area. Analysis of invertebrate geographical distribution for two major taxa on the Kodiak sites showed a similar pattern of species distribution among zoogeographical categories to the pattern for species from sites in the NGOA group. This indicated that the intertidal communities at sites within these two groups were probably quite similar. Low species richness within the Kodiak group—caused at least in part by disturbance, rather than by pronounced qualitative differences in community composition—was probably responsible for the dissimilarity between the Kodiak and the NGOA groups.

Biogeographic Affinities of Biota. Species of four major taxa—Polychaeta, Mollusca, Crustacea, and Echinodermata—that were found in the rocky intertidal region at our Gulf of Alaska sites were categorized according to their geographic distribution. Each species was assigned to one of seven zoogeographical categories:

- 1) widely distributed species—including those species whose distributions extend into the tropics and Southern Hemisphere as well as those which are cosmopolitan or bipolar
- 2) arctic-boreal species—including circumpolar forms which range into the Arctic
- 3) amphiboreal species—including those in the boreal fauna of the Atlantic and Pacific Oceans, but whose ranges do not extend into the Arctic
- 4) North Pacific species—whose ranges extend into the Bering Sea as far north as Bering Strait and to both Asiatic and North American shores
- 5) Asiatic species—whose ranges extend beyond the Aleutian Province only to shores of the western Pacific
- 6) North American species—whose ranges extend beyond the Aleutian Province only to shores of the eastern Pacific
- 7) endemic species—which are restricted to the Aleutian Province as originally defined by Bartsch (1912) and subsequently supported by Valentine (1966; see also Briggs 1974).

Table 11-2. Number of species in major taxonomic groups within clusters of sites in the Gulf of Alaska.

CLUSTER ^a	NUMBER OF SPECIES									
	PLANTS		POLYCHAETES		MOLLUSKS		CRUSTACEANS		OTHER	
	\bar{x}	SD	\bar{x}	SD	\bar{x}	SD	\bar{x}	SD	\bar{x}	SD
NGOA ^b	57	24	36	16	34	12	32	13	23	8
Southern Kodiak	25	8	2	1	23	9	12	2	13	5
Amchitka	89	— ^c	46	—	51	—	63	—	56	—
Shemya	—	—	1	—	39	—	11	—	17	—

\bar{x} = mean; SD = standard deviation.

^a Number of sites: NGOA, 21; southern Kodiak, 5.

^b NGOA = Northern Gulf of Alaska.

^c Dashes indicate missing data or no value for SD because cluster includes only one location.

Our definition of "endemic" was less restrictive than that of O'Clair (1977a); consequently, the species distribution among zoogeographic categories at Amchitka will differ from his. The western boundary of the Aleutian Province has not been precisely established, but may be at or just east of the Commander Islands (O'Clair 1977a). For comparison, we also present data from O'Clair (1977a), who categorized species of littoral polychaetes that had been listed for Bering Island by Annenkova (1934) and species of intertidal mollusks that were listed by Dall (1884), Barabash-Nikiforov (1947), Scarlato (1960), and Golikov and Kussakin (1962) for the Commander Islands according to their geographical distributions (Table 11-3). Data in Table 11-3 for Amchitka and the Commander Islands are similar to those presented by O'Clair (1977a: Table 5), except for 1) recent additions to the species list of Amchitka and 2) the inclusion of all species found intertidally at each site—including those whose ranges have been reported to extend below 60 m in depth.

Intertidal species composition in the western Aleutian and Commander Islands differed markedly from that in NGOA as reflected in the distribution of species among zoogeographical categories (Table 11-3). The percentage of North American species in major taxa was significantly less in the western Aleutian and Commander Islands—except in

the Polychaeta found at Amchitka Island. Conversely, the percentage of Asiatic species was significantly greater among the Mollusca and Echinodermata in the western Aleutians than at the NGOA sites (Table 11-3). Percentages of Asiatic polychaetes and crustaceans at Amchitka Island and Asiatic polychaetes and mollusks in the Commander Islands could not be statistically compared with the same taxonomic groups at the NGOA sites because the large number of zeros in the NGOA data precluded the use of parametric statistics. We know of no nonparametric test for comparing a sample with a single observation. Nevertheless, the percentages of Asiatic Polychaeta and Crustacea at Amchitka and Asiatic Mollusca in the Commander Islands exceeded the Asiatic percentages of these taxa at every NGOA site; the percentage of Asiatic polychaetes at Bering Island exceeded the percentage of Asiatic polychaetes at all but two NGOA sites.

Although the percentage of endemic polychaetes remained relatively constant over all sites, endemism among the mollusks and echinoderms was significantly higher in the western Aleutian Islands than in NGOA (Table 11-3). Endemism among mollusks in the western Aleutians averaged 12%—about the same percentage as for Crustacea at Amchitka and half of that reported by Valentine (1966) for

Table 11-3.

Percent of species of four major taxonomic groups of intertidal invertebrates in the Gulf of Alaska (NGOA) and western Aleutian Islands categorized according to geographical distribution.

TAXON	ENDEMIC		ASIATIC		NORTH AMERICAN		NORTH PACIFIC		ARCTIC-BOREAL		AMPHI-BOREAL		WIDELY DISTRIBUTED		TOTAL SPECIES x̄
	%	SD	%	SD	%	SD	%	SD	%	SD	%	SD	%	SD	
Polychaeta															
NGOA	5.4	4.5	0.2	0.8	23.6	5.7	9.2	4.8	21	7.2	7.2	5.4	33.5	9.7	28
Amchitka Island	3	— ^a	9	—	15	—	9	—	27	—	3	—	33	—	33
Bering Island	6	—	2	—	4	—	10	—	38	—	4	—	36	—	50
Test Statistic	ts = 0.14 n.s. ^b		21 ^c		ts = 1.57 n.s.		ts = 0.09 n.s.		ts = 0.82 n.s.		ts = -0.46 n.s.		ts = -0.002 n.s.		
	ts = 0.38 n.s.		19		ts = -4.47***		ts = 0.26 n.s.		ts = 2.01 n.s.		ts = -0.26 n.s.		ts = 0.274 n.s.		
Mollusca															
NGOA	2.3	3.2	1.3	1.8	39.8	10	27.2	8.3	23	5.3	1.6	2.0	4.7	2.0	26
Western Aleutians	12.5	2.1	8.5	0.7	23.5	0.7	26.5	0.7	23.5	0.7	0	0	5	0	40
Commander Islands	8	—	14	—	8	—	27	—	38	—	3	—	3	—	37
Test Statistic	z = 2.29* ^d		z = 2.29*		ts = -2.25*		ts = 0.05 n.s.		ts = -0.17 n.s.		z = 1.06 n.s.		ts = -0.33 n.s.		
	19		21		ts = -3.59**		ts = 0.02 n.s.		ts = 2.38*		13		ts = -0.60 n.s.		
Crustacea															
NGOA	0.1	0.6	1.5	3.2	53.3	8.3	32.4	5.6	2.4	3.7	4.2	4.3	5.8	4.0	20
Amchitka	13	—	13	—	33	—	36	—	0	—	5	—	0	0	39
Test Statistic	21		21		ts = -2.409*		ts = 0.63 n.s.		0		ts = 0.47 n.s.		ts = 1.60 n.s.		
Echinodermata															
NGOA	0.6	3.1	1.4	6.3	78.7	21.0	1.6	7.2	17.6	16.4	0	0	0	0	3
Western Aleutians	27.5	7.8	19.5	3.5	19.5	3.5	0	0	33	0	0	0	0	0	8
Test Statistic	z = 2.291*		z = 2.073*		ts = 3.023**		z = 0.56 n.s.		z = -1.27 n.s.		z = 0 n.s.		z = 0 n.s.		

x̄ = mean; SD = standard deviation; ts = student t statistic; z = Mann-Whitney U-Test statistic; n.s. = not significant; * = p < 0.05; ** = p < 0.01; *** = p < 0.001.

^a Dash indicates no value for SD because only one locality is included.

^b All tests are two-tailed. The upper statistic of each pair compares NGOA with Amchitka (or Western Aleutians); the lower compares NGOA with Bering Island (or Commander Islands). See Sokal and Rohlf (1981) for t-test comparing a sample mean with a single observation. Percentages were transformed ($\arcsin \sqrt{p}$) to render their distribution more nearly normal.

^c Where test statistics are not identified, statistical comparisons could not be made. Values shown indicate the number of comparisons (total 21) in which the percentage for Amchitka Island or Bering Island (or Commander Islands) exceeded those for the NGOA sites.

^d The Mann-Whitney U-test was used when a large number of zeros in the NGOA data precluded the use of parametric statistics.

mollusks in the Aleutian Province. Endemism was highest (28%) in the echinoderms of the western Aleutians, but the total number of species was small. Although endemic mollusks in the Commander Islands and endemic crustaceans at Amchitka could not be compared statistically with those at the NGOA sites for the same reason stated above, the endemic percentages at Amchitka and the Commander Islands were greater than those at no less than 90% of the sites in NGOA (Table II-3).

In the Commander Islands, Arctic-boreal polychaetes and mollusks showed virtually identical percentages, but only the molluscan percentages were significantly greater than those for sites to the east (Table II-3). This difference probably reflected the influence of the Kamchatka Current, a southward-flowing stream of arctic water that passes to the east of the Kamchatka Peninsula and probably brings the propagules of more northerly species south to the Commander Islands (O'Clair 1977a).

Trophic Distribution. We compared the distribution of species among trophic levels in NGOA with those at Amchitka. The southern Kodiak sites and Shemya were excluded from this analysis because Polychaeta and Gammaridea were clearly under-represented at these sites. Trophic groups included benthic autotrophs, herbivores (grazers and browsers), suspension feeders, carnivores, deposit feeders, omnivores, and scavengers (including macrophagous detritivores).

The trophic distribution of the rocky intertidal biota of Amchitka was quite similar to that of the NGOA sites (Table II-4). Our results are similar to those reported by Hartman and Zahary (1983) for trophic levels in the Aleutian Province with the exception of the relative percentage of grazers. (Most of the herbivores in our study were grazers.) Grazers appear to have outnumbered both suspension feeders and carnivores in Hartman and Zahary's study, although one cannot determine from their data whether the differences were significant because they present no estimate of variability within trophic levels. The present analysis revealed about an equal number of species of herbivores, suspension feeders, and carnivores in NGOA and at Amchitka (Table II-4).

Table II-4.
Trophic distribution of rocky intertidal benthic biota in the Gulf of Alaska as expressed as percent of species^a.

TROPIC LEVEL	NGOA ^b		AMCHITKA
	\bar{x}	SD	
Autotrophs	31	7	33
Herbivores	15	3	16
Suspension feeders	16	3	14
Carnivores	18	3	16
Deposit feeders	11	4	12
Omnivores	4	1	3
Scavengers	5	2	5

\bar{x} = mean; SD = standard deviation.

^a Parasites and commensals are excluded from table, therefore percentages do not sum to 100.

^b NGOA = Northern Gulf of Alaska; number of sites = 21.

Ecology of Rocky Shores

In recent years, the interest of marine ecologists has centered on how natural populations of marine organisms interact within the spatial and the temporal constraints of the physical environment so that local patterns of community structure may be determined. There have been few attempts to examine the processes controlling benthic community structure in the Gulf of Alaska, with the exception of 1) Estes and Palmisano's (1974) description of the results of a natural experiment (see effects of sea otter predation below) in the western Aleutians, 2) Dayton's (1975b) experimental evaluation of competitive interactions among sublittoral kelps at Amchitka Island, and 3) Duggins' (1980a, b and 1983) systematic and comprehensive study of the role of herbivory and predation in structuring subtidal communities in Torch Bay. However, evidence from the short-term descriptive studies that have been conducted in the Gulf of Alaska suggests factors that are likely to be important in certain communities.

Physical Factors

Both physical disturbance and biological interactions combine in varying degrees to influence community structure on the outer coasts of the Gulf. However, the descriptive nature of intertidal studies conducted thus far has only allowed an examination of those situations where one or the other category was of overriding importance. Physical disturbance was clearly of overriding importance at only three (Cape Yakataga, Low Cape, and Whale Island) of the 29 sites described in Zimmerman *et al.* (1979) and O'Clair *et al.* (1978). Unstable substrates in exposed outer-coast environments were the chief source of the physical disturbances that affected the rocky intertidal communities at these three sites.

At Cape Yakataga, two factors were reflected in the composition of the species assemblages on our intertidal transects: 1) the periodic scouring of the rock by sand and/or ice (from Icy Bay) and 2) probable burial of intertidal biota by sand deposited on the rock platform in some seasons or during storms. We sampled Cape Yakataga using intertidal arrays and transects during three periods: late spring, late summer, and fall. The data indicated that populations of many of the species there were transitory and spatially patchy. *Mytilus edulis* was common but was represented by small individuals.

Filamentous brown and green algae and diatoms were the most numerous algae on the three transects (O'Clair *et al.* 1978). Intertidal recolonization studies by Lebednik and Palmisano (1977) showed that these algal species were the earliest colonizers of disturbed rocky substrates on Amchitka Island. The abundance of these algal species on the intertidal platform at Cape Yakataga during the three sample periods indicates a high frequency of disturbance for Cape Yakataga.

At Low Cape and southeast Whale Island, the cobble and small-boulder beaches are subject to heavy wave action which results in the heavy scouring and battering of the rock surfaces there. The cobble and boulders at both sites were sparsely covered with algae, and few invertebrates were found. The *Mytilus edulis* collected during quantitative sam-

pling at Low Cape were small (Zimmerman *et al.* 1979). At Whale Island, recently settled barnacles and diatoms were found on small rocks. Large boulders had a sparse cover of filamentous and foliose green algae. Crevices in the large boulders harbored barnacles and mussels. The lower surfaces of large boulders were bare up to a height of 45 cm above the substrate—presumably as a result of cobble scouring. In contrast, the same substrate on the protected southwest shore of Whale Island had a heavy cover of intertidal species (Zimmerman *et al.* 1979).

It seems unlikely to us that the community patterns described above for Cape Yakataga, Low Cape, and the southwest shore of Whale Island were the result of biological rather than physical disturbance. Herbivory by sea urchins of the genus *Strongylocentrotus* can produce extensive barren areas lacking in both benthic algae and sessile invertebrates, similar to the barren areas observed at Low Cape and Whale Island; however, *Strongylocentrotus* spp. were not evident at either of these two sites (Zimmerman *et al.* 1979). The portion of the intertidal region sampled at Cape Yakataga was probably above the upper tidal limit of urchin grazing.

Predatory gastropods such as *Nucella* spp. and large starfish could conceivably reduce both the barnacle and the adult mussel populations to the low levels seen at all three sites, but no large invertebrate predators were found to be abundant at any of the sites. At Cape Yakataga *Nucella lamellosa* and *N. lima* were present, but not in great abundance (O'Clair *et al.* 1978). Aggregations of *N. lamellosa* were observed feeding on small- to medium-sized *Semibalanus cariosus* on large boulders, but *Nucella* was not evident over most of the cobble- and boulder-covered shore (Zimmerman *et al.* 1979). No large starfish were observed at either Cape Yakataga or at Low Cape. Neither *Nucella* spp. nor large starfish were found on the southwest shore of Whale Island.

In locations such as Cook Inlet, Prince William Sound, southerly along the coast between Prince William Sound and Cape Yakataga, Glacier Bay, and southern Southeast Alaska, there may be significant disturbance of the rocky intertidal communities either by floating glacial ice which has calved off the face of tidewater glaciers or by ice floes and slush ice that form on the surface of the water in protected bays in winter. Waveborn ice may create bare patches of rock substrate by scraping or bashing intertidal organisms from the rock surface in a fashion similar to the way logs create patches of bare rock on the outer coast of Washington (Dayton 1971). Feder and Keiser (1980) listed large ice floes and slush ice as notable winter stresses for intertidal organisms at Port Valdez. At Koyuktolik Lagoon on the outer Kenai Peninsula, ice-scouring created broad furrows through beds of *Mytilus edulis*. The furrows were quickly colonized by *Porphyra* sp. and subsequently became sites of dense recruitment by juvenile mussels (Dames and Moore 1977a). Where ice-scour is extensive, intertidal communities become impoverished and are dominated by pioneer species such as were found at Cape Yakataga (O'Clair *et al.* 1978) and on the lower west side of Cook Inlet (Dames and Moore 1980).

In inner waters such as those in Prince William Sound and in southeastern Alaska, greatly fluctuating salinities

result both from glacial runoff (in the late spring and summer) and from heavy rainfall (in the fall). Widely fluctuating salinities restrict the number of intertidal species to those that are relatively euryhaline, and may alter the relationships of species that are found in both inner waters and on the outer coast. Localized, heavy freshwater run-off in spring may affect intertidal and shallow subtidal communities near the heads of some bays on the outer coast (*e.g.*, Port Dick; Dames and Moore 1977a), and may further stress intertidal organisms in estuaries (Feder and Keiser 1980).

Biological Interactions

In the two sections that follow we discuss in some detail examples in which competition and/or predation may be controlling the abundance of species in intertidal communities at specific localities in the Gulf of Alaska. We emphasize these examples because they involve species that are widely distributed on rocky shores in the Gulf of Alaska, and are likely to play important roles in the rocky intertidal communities there. The examples involve intertidal systems that are amenable to a mechanistic approach which we believe is more useful in sorting out the key factors involved than is the descriptive approach that has been emphasized in past studies in the Gulf of Alaska.

Relative Abundance of *Semibalanus balanoides* and *Balanus glandula*. *Semibalanus balanoides* and *Balanus glandula* occur together only on the Pacific coast of North America from Unalaska to the northern end of the Strait of Georgia, British Columbia (Pilsbry 1916; Haven 1973). The two species are ecologically similar; *B. glandula* has been referred to as the ecological counterpart of *S. balanoides* in the eastern Pacific. *Semibalanus balanoides* also occurs in the North Atlantic (Newman and Abbott 1980). It is likely that these species are potential competitors. Barnes (1958) proposed that the southern limit of distribution for *S. balanoides* on the Pacific coast of North America was set by *B. glandula* and (in the lower intertidal zone) by *Semibalanus cariosus*, but he did not suggest a mechanism.

Sessile filter-feeding invertebrates usually compete for space rather than for food (Branch 1984). Competition for space between *S. balanoides* and *Chthamalus stellatus* has been shown in Scotland (Connell 1961). For these and related species, competitive ability was related to growth rate, resulting in hierarchies of adult size and competitive ability that were identical (Connell 1961; Dayton 1971). Comparative growth rates of *S. balanoides* and *B. glandula* in the Gulf of Alaska are not known, but the adult sizes of the two species are about equal—suggesting that where space is limited, the outcome of competition between them may be more sensitive to local factors that influence both the relative growth rate and perhaps recruitment as well.

Semibalanus balanoides and *B. glandula* overlap extensively in vertical distribution in the mid-littoral zone on shores of both the outer coast and inner waters of the Gulf. However, the relative abundances of the two species differ between outer coast and inner waters (at least in Prince William Sound). The relative abundance of *S. balanoides* and *B. glandula* was estimated at nine sites in Prince William Sound (Fig. 11-8, Appendix 11-1).

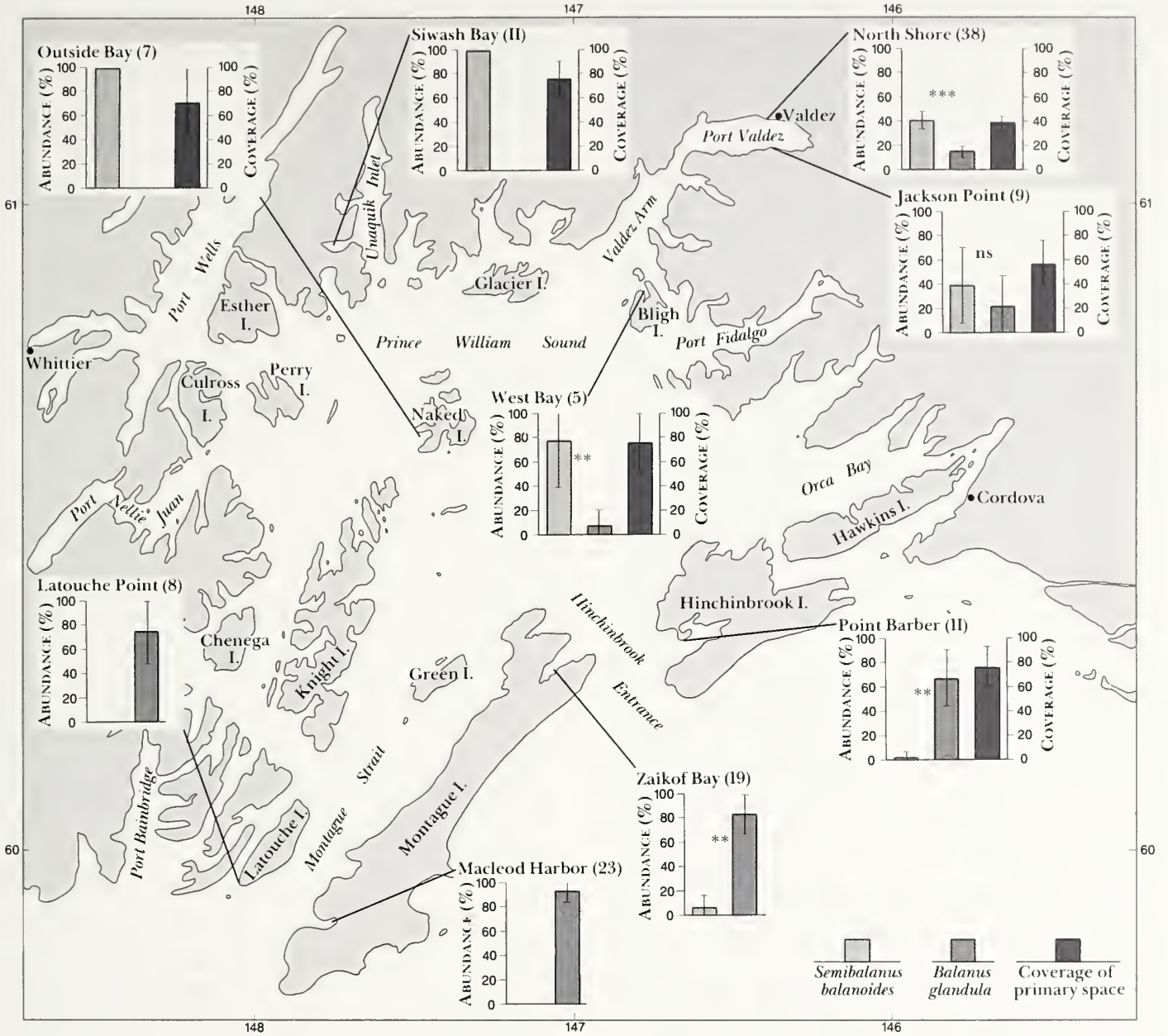


Figure II-8. Relative abundance (percent of total barnacles) of *Semibalanus balanoides* and *Balanus glandula* at nine sites and coverage of primary space at six sites in Prince William Sound. Error bars are 95% confidence intervals. Asterisks indicate significance of statistical tests (*** = $p < 0.001$; ** = $p < 0.01$; ns = not significant). At North Shore, Jackson Point, and West Bay sites, t-tests for paired comparisons were used to test the differences in the abundances of *S. balanoides* and *B. glandula*. Data from Point Barber and Zaikof Bay sites did not meet the assumptions of the t-test; therefore Wilcoxon's signed-ranks test was used to test barnacle abundances. At locations where either species was absent from all quadrats, statistical tests were not performed. *B. glandula* was observed at Outside Bay, but was absent from the quadrats. Numbers in parentheses represent number of quadrats sampled.

Semibalanus balanoides dominated in coverage in upper Prince William Sound, whereas *B. glandula* dominated in coverage or abundance in the outer Sound (Fig. 11-8). (Only data from quadrats in which one or both species was recorded were included when preparing Fig. 11-8.) Coverage of *S. balanoides* in quadrats significantly exceeded that of *B. glandula* on the north shore of Port Valdez (but not at Jackson Point) and at Bligh Island (Fig. 11-8). *Semibalanus balanoides* also outnumbered *B. glandula* at all tide levels where they occurred together at Island Flats in spring 1977 (Feder and Keiser 1980: Table 8.14). At Siwash Bay and Naked Island, *B. glandula* was virtually absent from the quadrats, but was observed within the sampling area at Naked Island. Although the sample size was generally small, the results showed that *S. balanoides* usually had significantly greater percent cover than *B. glandula* at the sites in the upper Sound. Conversely, at study sites on Hinchinbrook, Montague, and Latouche Islands in outer Prince William Sound, *B. glandula* either had consistently greater coverage or outnumbered *S. balanoides*.

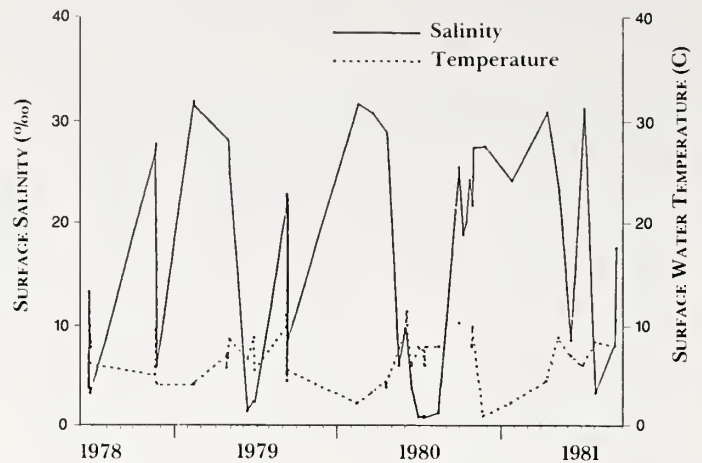
Elsewhere on shores bordering the Gulf of Alaska, a similar situation prevailed. At Auke Bay—a protected inner bay in southeastern Alaska where the amplitude of salinity fluctuations is about half that at Port Valdez (Figs. 11-9A, 11-10)—the relative percent cover of *S. balanoides* was double that of *B. glandula* (paired *t*-test, $t = 2.30$, $p = 0.02$). Along the outer coast of the Gulf, *S. balanoides* was recorded at only 9 of the 28 rocky intertidal sites described in Zimmerman *et al.* (1979), O'Clair *et al.* (1978), and O'Clair *et al.* (1981). *B. glandula* was present at 24 of these locations.

The above authors do not include enough data on the relative abundances of *S. balanoides* and *B. glandula* at most sites to determine which species was dominant. However, Zimmerman *et al.* (1979) observed that *S. balanoides* was dominant in the upper intertidal zone at Whale Island and on one of three transects at Lagoon Point; *S. balanoides* also had greater biomass than *B. glandula* on the upper part of the quantitative transect at Low Cape. Two of the three sampling areas at Whale Island were subject to heavy freshwater runoff (Zimmerman *et al.* 1979). *B. glandula*, but not *S. balanoides*, was present at the eight rocky intertidal sites studied by Dames and Moore (1977a, 1980) both on the outer coast of the Kenai Peninsula and in lower Cook Inlet.

The differences in relative abundance for *S. balanoides* and *B. glandula* in outer-coast habitats (as compared with abundances on inner shores) may simply reflect differences in the tolerances that these species have for changes in the regimes of salinity, temperature, wave shock, or siltation. Parts of upper Prince William Sound are influenced by glacial runoff in summer. Salinities in Port Valdez fluctuate greatly, dropping to near 0‰ at the surface in summer (Fig. 11-9A; see also Muench and Nebert 1973 and Feder and Keiser 1980). However, with the exception of Siwash Bay, the surface salinities at the other sites in upper Prince William Sound do not appear to fluctuate any more than salinities in the lower Sound (Table 11-5).

Both *Semibalanus balanoides* and *Balanus glandula* are euryhaline, with similar tolerance limits to low salinities. *S. balanoides* can acclimate to salinities in the range of 12 to 50‰ (Foster 1970). The lower end of this range is identical

A. PORT VALDEZ, NORTH SHORE



B. PRINCE WILLIAM SOUND

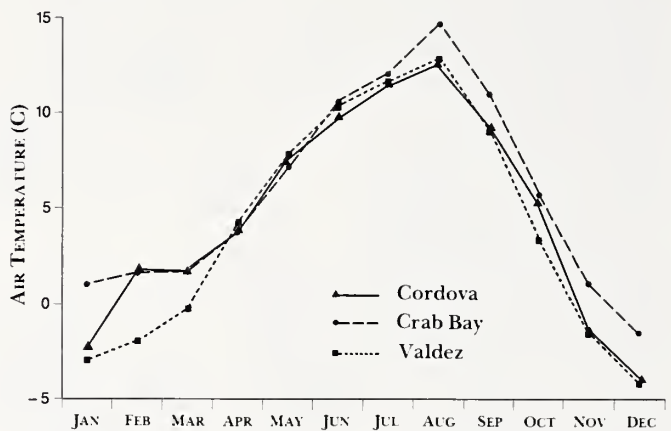


Figure 11-9. A. Surface salinities and water temperatures at the north shore of Port Valdez from June 1978 to September 1981. B. Average monthly air temperatures at three stations in Prince William Sound. Data for 1978 obtained from Climatological Data, Annual Summary, U.S. Department of Commerce, National Climatic Center.

AUKE CAPE, AUKE BAY

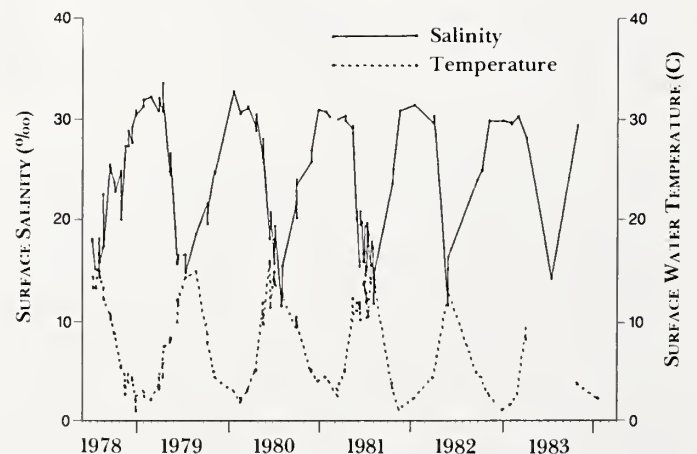


Figure 11-10. Surface salinities and water temperatures at Auke Cape, Auke Bay from April 1978 to February 1984.

Table 11-5.
Surface salinities (‰) at four locations in Prince William Sound.
Means and ranges are shown when available.

LOCATION	1977			1978	1979
	MAY	JULY	OCTOBER	MAY	MAY
Siwash Bay	—	16.5	13.9 5.3-22.5	22.1	28.3
West Bay	23.1	24.8	27.6 27.6-27.7	25.0	28.5
Outside Bay	31.6	27.6	26.6	29.2	30.0
Point Barber	31.0	25.1 24.7-25.5	—	—	28.4 27.7-29.1

to the lowest salinity at which (under normal temperatures) the first stage nauplii of *S. balanoides* remain mobile (Bhatnagar and Crisp 1965). Twelve parts per thousand also falls within the range of salinities (10–15‰) recorded either at or near the inner limit of penetration of *S. balanoides* into both the Baltic Sea (Barnes and Barnes 1962) and Conway Estuary (Foster 1970). Adult *B. glandula* can tolerate 0 to 300‰ seawater for 72 h but apparently do not feed below 50‰ (about 16‰) seawater (Bergen 1968), which is 2‰ higher than the salinity at which acclimated *S. balanoides* cease activity (Foster 1970). Bergen (1968) gives salinities in percent of normal water only. Embryos of *B. glandula* can tolerate salinities in the range of 50 to 200‰ seawater (Bergen 1968). *S. balanoides* may therefore be favored in habitats where salinities periodically drop below 16‰, but this would seem to include habitats only at Port Valdez and possibly Siwash Bay. Dominance of *S. balanoides* over *B. glandula* at Outside and West Bays cannot be explained by reduced salinities that act directly on the barnacle populations at these sites.

Surface water temperatures fluctuate throughout most of Prince William Sound and ranged from 1 to 11.8°C in the lower Sound to 2.1 to 12.6°C in the upper Sound in 1972 to 1973 (data extracted from Figs. 4 to 28 in Muench and Schmidt 1975). Surface-water temperature ranges for Port Valdez (Fig. 11-9; see also Muench and Nebert 1973 and Feder and Keiser 1980) do not differ substantially from those recorded by Muench and Schmidt (1975) in the lower Sound. However, air temperatures at Port Valdez are lower than those in lower Prince William Sound in winter and early spring (Fig. 11-9B). During this period, both the final embryonic maturation and the release of nauplii take place in *S. balanoides* and *B. glandula* in Port Valdez (Feder and Keiser 1980).

Barnes (1959) argues that nauplii release for *S. balanoides* is not temperature dependent, but rather is under endogenous control and synchronized with the vernal diatom bloom. The period of embryonic development may be controlled more by availability of food for the adult and the ventilation frequency of the adult's mantle cavity during feeding than by temperature. Barnes (1959) further suggests that larval release in other northern species may also be controlled endogenously, but does not consider *B. glandula*. One should be cautious about extending Barnes' argument for endogenous control of larval release in *S. balanoides* to popu-

lations of *B. glandula* at Port Valdez. *S. balanoides* ranges as far north as Bering Strait (Shelford 1930), and its northern limit is thought to be set by 1) the amount of time that is available for release of the nauplii, 2) the development of the planktonic phase, and 3) settlement of the cyprids during the ice-free period in the Arctic (Barnes 1957). *B. glandula*, on the other hand, has not been observed north of Port Valdez (Pilsbry 1916). Nothing is known about the factors that set the northern limit of *B. glandula*, and one cannot discount the possibility that lower winter air temperatures in Port Valdez (as compared with lower Prince William Sound) limit *B. glandula* development in Port Valdez.

The roles that sediment deposition and wave shock play in controlling *S. balanoides* and *B. glandula* distributions in Prince William Sound are even more difficult to evaluate. Appreciable amounts of glacial silt enter Port Valdez in the form of suspended sediment in the freshwater outflow from the Lowe River, Valdez Glacier Stream, and Mineral Creek (Sharma and Burbank 1973). This silt is deposited on the shores of Port Valdez from June through August (Feder and Keiser 1980). The layer of fine silt that covers the shore during this period may cause considerable stress—especially to recently settled barnacles—but we know of no information on the relative sensitivities of the spat of *S. balanoides* and *B. glandula* to sediment deposition. Noticeable accumulations of sediment were not observed on the shore at West and Outside Bays.

The intertidal habitats at our sites in upper Prince William Sound were protected from heavy wave action, and although habitats in the lower Sound were more exposed, none of our sites could be considered in the category of exposed outer coast. Both *S. balanoides* and *B. glandula* are found in exposed as well as protected habitats (Stubbings 1975; Barnes and Barnes 1956). In laboratory tests, *S. balanoides* can withstand a relatively high impact force compared with other North Atlantic barnacles (Barnes, Read, and Topinka 1970); *B. glandula*'s resistance to impact has not been tested.

Although *B. glandula* was not observed at our site at Siwash Bay, both the results shown in Figure 11-8 and the observations and relative abundance estimates made by O'Clair in a number of estuaries in southeastern Alaska indicate that *B. glandula* is rarely completely absent from protected inner shores—even when those shores are exposed to widely fluctuating salinity regimes. *S. balanoides* apparently cannot exclude *B. glandula* from inner shores—either because it is not competitively superior to *B. glandula*, or because it is prevented from excluding *B. glandula* by a third agent such as predation or disturbance. The relatively high percentage of primary space (bare rock) available at all of the sites in Prince William Sound for which we have data (Fig. 11-8) indicates that space was not a limiting factor at those sites and that barnacle populations were held in check either by predation or disturbance.

Ice floes and slush ice on the shore in winter at Port Valdez (Feder and Keiser 1980) may bash or scrape barnacles from the rocks there. Physical disturbance by ice is probably not an important factor in central and lower Prince William Sound, although predation may be. The number of species

that prey on barnacles increases from upper to lower Prince William Sound (Table II-6). If one assumes that the effectiveness of any individual species of barnacle predator is not drastically reduced (except perhaps in extreme exposure), the intensity of predation is probably greater in lower Prince William Sound.

One cannot rule out competition as being important to the distribution of *S. balanoides*. The complete absence of *S. balanoides* in our samples from McLeod Harbor and Latouche Point, and from 19 of the other 28 outer-coast intertidal sites discussed in Zimmerman *et al.* (1979), O'Clair *et al.* (1978), and O'Clair *et al.* (1981), indicates that *B. glandula* may exclude *S. balanoides* in certain exposed situations. This is consistent with the results of Menge (1976) and Peterson (1979), who found that exposure to wave action renders predators less effective in controlling sessile filter-feeders, resulting in intense competition among the filter-feeders.

In the absence of experimental evidence, one cannot decide conclusively among the possible mechanisms controlling the geographical trends in the relative abundances of *S. balanoides* and *B. glandula* in Prince William Sound and on the outer coast of the Gulf of Alaska. However, the evidence at hand suggests that while competition may play a dominant role in exposed outer coast situations, in sheltered habitats, predation and/or disturbance prevent competitive exclusion of one species of barnacle by the other. Fluctuating salinity is probably the most important physical factor influencing barnacle abundances in inner waters. However, except where salinities drop well below 16‰, they may not directly alter the competitive hierarchy between *S. balanoides* and *B. glandula*, but may control the distributions of the predators that prey on these species, thereby favoring *S. balanoides* over *B. glandula*.

The Role of Predators in Community Organization.

Evidence has accumulated in recent years suggesting that predation frequently surpasses competition in the organization of natural communities. In some systems predation

Table II-6.
Species of barnacle predators at nine intertidal sites in Prince William Sound.

LOCATION	SPECIES OF PREDATOR ^a	TOTAL
Port Valdez, North Shore	NA, ET	2
Jackson Point	NA, ET	2
Siwash Bay	NA, OB	2
West Bay	PO, ET	2
Outside Bay	NL, PO, ET, LH	4
Point Barber	EG, NL, NE ² , SD,	7
	PO, ET, LH	
Zaikof Bay	EG, NL, NC, SD,	7
	PO, ET, LH	
MacLeod Harbor	EG, NA, NL, NC,	6
	SD, PO	
Latouche Point	EG, NA, NL,	5
	SD, LH	

^a Abbreviations are: EG = *Emplectonema gracile*; NA = *Nucella lima*; NL = *Nucella lamellosa*; NE = *Nucella emarginata*; NC = *Nucella canaliculata*; SD = *Scarlesia diria*; OB = *Onchidoris bilamellata*; PO = *Pisaster ochraceus*; ET = *Evasterias troschelii*; LH = *Leptasterias hexactis*.

exerts its overriding influence by reducing the impact of competitive dominants. Perhaps because of the lower structural heterogeneity typical of marine intertidal habitats, predation appears to exert a stronger influence in these habitats than in any other (Sih, Crowley, McPeck, Petranka, and Strohmeier 1985). In the Gulf of Alaska studies of the impact of predation on intertidal and shallow subtidal communities have focused on the role of large seastars and sea otters. In the following two sections we review the results of these studies.

Predatory Seastars. Large predatory seastars frequently play important roles in shaping community structure in the rocky intertidal region at temperate and subpolar latitudes (see review by Menge 1982; Paine, Castillo, and Cancino 1985). On the outer coast of Washington the seastar *Pisaster ochraceus* clearly exerts strong control over the structure of the rocky intertidal community by preying preferentially on the mussel *Mytilus californianus*, the dominant competitor for space (Paine 1966, 1974; Dayton 1971, 1975a). However, *Pisaster* does not appear to exert the same organizational control at Torch Bay in southeastern Alaska because it and *M. californianus* are less abundant there (D.O. Duggins, Friday Harbor Laboratories, pers. comm., 1985; Paine 1980). Although *Mytilus edulis* constituted the greatest proportion of the diet of *Pisaster* at Torch Bay, the mussel population may be controlled by the predatory gastropod *Nucella* (= *Thais*) *canaliculata* (Paine 1980), but this remains to be demonstrated.

As at Torch Bay, *Pisaster's* influence on the structure of intertidal communities in lower Prince William Sound may be reduced compared to its influence on the outer coast of Washington. *Mytilus californianus* was absent from Point Barber (Hinchinbrook Island) and Zaikof Bay (Montague Island) when we visited these sites during 1977 through 1980 (O'Clair *et al.* 1978 contains initial results from this study). In May and July, adult *M. edulis* were found in small scattered patches at Point Barber, although an extensive area of the intertidal region was covered by very small *M. edulis* where adult mussels had dominated four years earlier (N.I. Calvin and J. Landingham, Auke Bay Laboratory, pers. comm., 1977). Adult *M. edulis* were low in abundance at the Zaikof Bay site as well. As at Torch Bay, the diet of *Pisaster* at both sites was low in species richness, but unlike Torch Bay, barnacles dominated, rather than *M. edulis* (Table II-7).

In the inner waters of Prince William Sound and southeastern Alaska, *Evasterias troschelii* usually replaces *P. ochraceus* as the most common large intertidal seastar. (*Evasterias* is also common in more oceanic locations on the east side of Cook Inlet and in bays on the outer coast of the Kenai Peninsula (Dames and Moore 1977a, 1980).) Casual observation of the shore at low tide in these areas reveals a sharp demarcation for the lower limit of distribution for *M. edulis*—below which free space (bare rock devoid of macroscopic organisms) can reach 80% of the lower intertidal zone (C.E. O'Clair, Auke Bay Laboratory, unpubl. data). Dames and Moore (1977a) found that *Evasterias* fed mainly on *Mytilus edulis* and *Littorina sitkana* at Dick's Head on the outer Kenai Peninsula, and they speculated that *Evasterias* was probably a major mortality factor for *Mytilus* both there and at Koyuktolik Lagoon. At Koyuktolik Lagoon, *Evasterias*

Table II-7.
Diets of *Pisaster ochraceus* at three locations in the Gulf of Alaska.
Unless otherwise noted, numbers in body of table are numbers of individuals consumed.

SPECIES	TORCH BAY ^a	POINT BARBER	ZAIKOF BAY
Barnacles			
<i>Balanus glandula</i>		71	
<i>Balanus cariosus</i>		13	4
<i>Balanus</i> spp.	182	15 ^b	29
Mussels			
<i>Mytilus edulis</i>	733	9	
Chitons			
<i>Katharina tunicata</i>	1		
<i>Mopalia ciliata</i>		1	4
<i>Mopalia</i> sp.		9	
Herbivorous Gastropods			
<i>Collisella pelta</i>		4	1
<i>Littorina</i> sp.		1	
Carnivorous Gastropods	6	1	
<i>Nucella lamellosa</i>		1	1
<i>Nucella lima</i>		1	
<i>Nucella</i> spp.		8	16
Decapod Crustacea			
<i>Pagurus beringanus</i>			1
Paguridae sp.			1
Annelids			
Sabellidae sp.		2	
<i>Serpula vermicularis</i>			1
Total			
No. observations	922	136	58
No. not feeding		479	462
No. species	4	13	9

^a After Paine (1980)

^b Value is number of observations. Several observations included many small *Balanus* that were not counted.

probably set the lower limit of *Mytilus* in some locations (Dames and Moore 1977a).

Beginning in spring 1978, O'Clair and Fritts (1980) conducted experiments at two sites in Auke Bay, Alaska (Fig. II-11) to determine 1) the role that *E. troschelii* plays in setting the lower limit of *M. edulis* and 2) whether release from predation by *Evasterias* allows *Mytilus* to invade and eventually monopolize the lower intertidal region. These experiments were extended to Port Valdez in late spring 1978 (Appendix II-2). At both localities, *Evasterias* preferred to eat *M. edulis*. *Mytilus* constituted 84% (n. observations, 120) and 81% (n., 395) of the diet of *Evasterias* at Auke Bay and Valdez, respectively.

At Auke Bay, the species which colonized the cages, plots, and roofs were species common to the mid- to upper-intertidal zones. Barnacles, particularly *Semibalanus balanoides*, and later *M. edulis*, colonized the cages (Figs. II-12 and II-13). By September 1978, the percentage of barnacles (mostly *S. balanoides* and a few *B. glandula*) found in the cages significantly exceeded the percentage found in roofs and plots at both the *Evasterias* removal and control sites (Figs. II-12 and II-13; Table II-8). Barnacles in the cages at the *Evasterias* removal site suffered heavy mortality during September and October in both 1978 and 1979 when the predaceous nudibranch *Onchidoris bilamellata* invaded the cages and ate numerous barnacles (Fig. II-14). *Onchidoris* was in low abun-

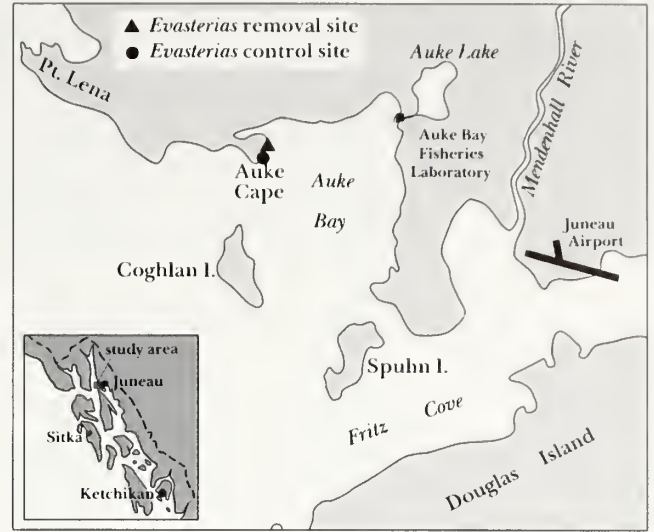


Figure II-11. Map of Auke Bay and vicinity showing study sites. (Modified from Bruce, McLain, and Wing 1977.)

dance at the control site—barnacle coverage remained high in the cages then gradually decreased as *Mytilus* colonized them (Fig. II-15; Table II-8).

Barnacles failed to increase both in the plots and under roofs at both sites in 1978 and 1979—probably because of predation by the sea urchin *Strongylocentrotus droebachiensis*, which may consume cyprids and juvenile barnacles while grazing. (*Nucella* was rare at both the *Evasterias* removal and control sites. Only a few *N. lima* were seen there during the entire study.) Urchins were abundant at both sites in 1978 and 1979. In the summer of 1980, urchins unexplainably decreased at the *Evasterias* removal site. No urchins were found there in June 1980, whereas ~1,000 were counted at the control site. Barnacles, particularly *Semibalanus balanoides*, increased significantly at the *Evasterias* removal site between June 1979 and June 1980 (Table II-8). In July, *Onchidoris* returned in great numbers and by September 1980, barnacle populations were significantly reduced in plots and under roofs (Fig. II-14; Table II-8).

The suppression of barnacle populations by *Strongylocentrotus droebachiensis* and *O. bilamellata* may indirectly inhibit *Mytilus* recruitment by reducing the preferred settling substrate for *Mytilus*. At Auke Bay, larval *M. edulis* settle in large numbers on barnacle shells, perhaps because filamentous algae are uncommon there (C.E. O'Clair, pers. obs.); D. Duggins has observed *M. edulis* to settle abundantly on *Balanus* at Torch Bay, Alaska, as well (D.O. Duggins, Friday Harbor Laboratories, pers. comm., 1985). *S. droebachiensis* may also directly limit *Mytilus* recruitment by preying on plantigrades and juvenile mussels.

Mytilus began settling within the cages in 1979; settlement in plots and roofs was generally later (Figs. II-12 and II-13). At the *Evasterias* removal site, *Mytilus* coverage increased in all treatments to the end of the study. However, increases in *Mytilus* coverage in the plots and under roofs was less than expected in the absence of *Evasterias*. By August 1981, *Mytilus* coverage in the cages significantly exceeded the coverage both in plots and under roofs at the *Evasterias* removal site. *Mytilus* coverage in plots and roofs at the *Evasterias* removal

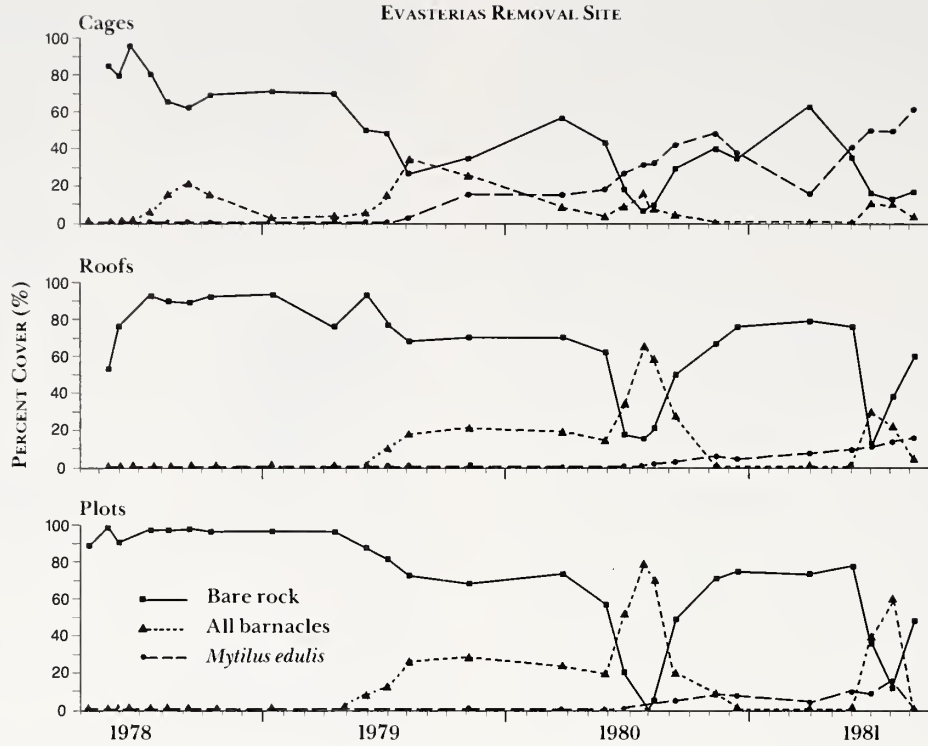


Figure 11-12. Percent cover of *Mytilus edulis*, all barnacles, and bare rock in cages, roofs, and plots at the *Evasterias* removal site at Auke Cape in Auke Bay from April 1978 to September 1981.

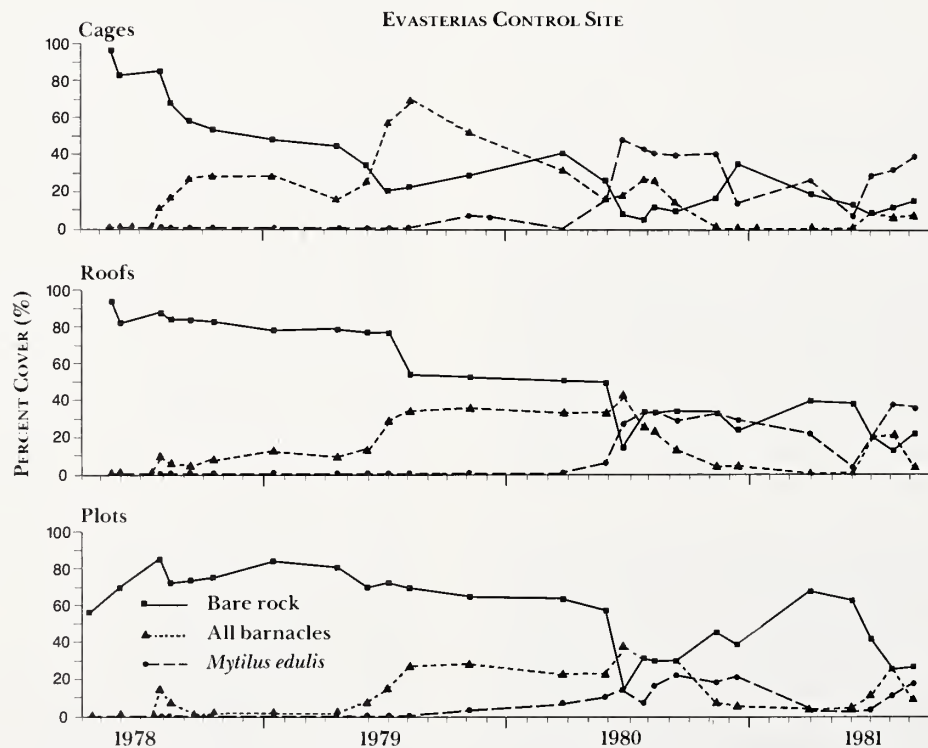


Figure 11-13. Percent cover of *Mytilus edulis*, all barnacles, and bare rock in cages, roofs, and plots at the *Evasterias* control site at Auke Cape in Auke Bay from April 1978 to September 1981.

Table 11-8.
Statistical tests for *Evasterias troschelii* removal experiment at Auke Bay, June 1978–September 1981.

SPECIES	SITE	COMPARISON	TYPE OF ANALYSIS ^a	SIGNIFICANCE LEVEL	INTERACTIONS
Barnacles ^b	<i>Evasterias</i> removal	Cages vs. roofs & plots	2-way anova	p < 0.001	n.s.
		September 1978	t-test	p < 0.001	
	Control	Cages vs. roofs & plots	2-way anova	p < 0.001	n.s.
		September 1978	t-test	p < 0.001	
	<i>Evasterias</i> removal	Cages vs. roofs & plots	3-way anova	p < 0.01	n.s.
		July 1979	t-test	n.s.	
	Control	Cages vs. roofs & plots	3-way anova	p < 0.01	n.s.
		July 1979	t-test	p < 0.05	
	<i>Evasterias</i> removal	June 1979 vs. June 1980	2-way anova	p < 0.01	n.s.
		plots and roofs	Scheffes-test	p < 0.05	
	Control	June 1979 vs. June 1980	2-way anova	p < 0.01	n.s.
		plots and roofs	Scheffes-test	p < 0.05	
<i>Evasterias</i> removal	June 1980 vs. Sept. 1980	3-way anova	p < 0.001	n.s.	
	plots and roofs	Scheffes-test	p < 0.05		
Control	June 1980 vs. Sept. 1980	3-way anova	p < 0.001	n.s.	
	plots and roofs	Scheffes-test	n.s.		
Mytilus	<i>Evasterias</i> removal	Cages vs. roofs & plots	2-way anova	p < 0.05	n.s.
		August 1981	t-test	p < 0.01	
	Control	Cages vs. roofs & plots	2-way anova	p < 0.05	n.s.
		August 1981	t-test	n.s.	
	<i>Evasterias</i> removal and control	ER vs. control	2-way anova	p < 0.05	n.s.
		plots & roofs, August 1981	t-test	n.s.	

ER = *Evasterias* removal site; n.s. = not significant.

^a Data were transformed ($\arcsin \sqrt{p}$ or $\sqrt{100p}$; p = proportion of coverage) to stabilize variances before analysis. Bartlett's test was used to verify homogeneity of variances. Individual comparisons of simple main effects were made with a t-test (*a priori*; Winer 1971) or Scheffes test (*a posteriori*) and were one-tailed.

^b Mostly *Semibalanus balanoides* with some *Balanus glandula*.

site did not exceed those at the control (Table 11-8). Nevertheless, near the center of the *Evasterias* removal site on a 6-m long stretch of shore, *Mytilus* had extended its former lower limit 2 m into the lower intertidal zone—apparently because *Evasterias* was removed.

The results of O'Clair and Fritts's (1980) experiments in Auke Bay are summarized in Figure 11-16. *Strongylocentrotus droebachiensis* directly limits *Mytilus* recruitment by preying on plantigrades and juvenile *Mytilus*, or indirectly limits recruitment by consuming barnacles that are *Mytilus*' preferred settling substrate. When *Onchidoris bilamellata* is present, it consumes the barnacles that have escaped urchin predation. This prevents *Balanus* from maintaining populations in the lower intertidal zone and probably delays *Mytilus* recruitment. *Evasterias* may ultimately preclude *Mytilus* from dominating the lower intertidal zone, but the activities of *Strongylocentrotus* and *Onchidoris* usually prevent *Mytilus* from even becoming accessible to *Evasterias* predation.

The intertidal community at Port Valdez was less complex. *S. droebachiensis* and *O. bilamellata* were absent from both the *Evasterias* removal and the control sites and *Nucella* was rare. The results of the Port Valdez experiments supported the hypothesis that *Evasterias* controlled the lower limit of distribution for *Mytilus* on the north shore of Port Valdez. By the end of the experiment (September 1981), cov-

erage of *M. edulis* had increased significantly compared to coverage at the beginning of the experiment (June 1978). This was true for all treatments at the *Evasterias* removal site and for the cages at the control site (Table 11-9). Coverage of *Mytilus* averaged between 70 and 80% in these treatments by September 1981. *Mytilus* coverage in the plots and under the roofs at the control site did not increase significantly between June 1978 and September 1981 (Table 11-9). However, *Mytilus* coverage was quite variable in the plots and roofs at the control site in September 1981.

We could not stabilize coverage-estimate variances, so we used the less powerful Mann-Whitney U-test to make comparisons. The results were significant, but not as striking as one would expect if *Evasterias* exerted complete control over the lower limit of *Mytilus*. Why *M. edulis* increased in some plots and roofs at the control site is open to speculation. *Evasterias* on the north shore of Port Valdez averaged 104 g fresh (drip-dried) weight and were significantly smaller (p < 0.001, one way anova) than *Evasterias*, which had an average fresh weight of 275 g at Auke Bay. The small size of *Evasterias* may have allowed *Mytilus* to successfully colonize some of the plots and roofs at the control site in Port Valdez.

Sea Otters. In the western Aleutian Islands, large sea otter populations (*Enhydra lutris*) inhabit certain islands and consume a variety of invertebrates—especially sea urchins

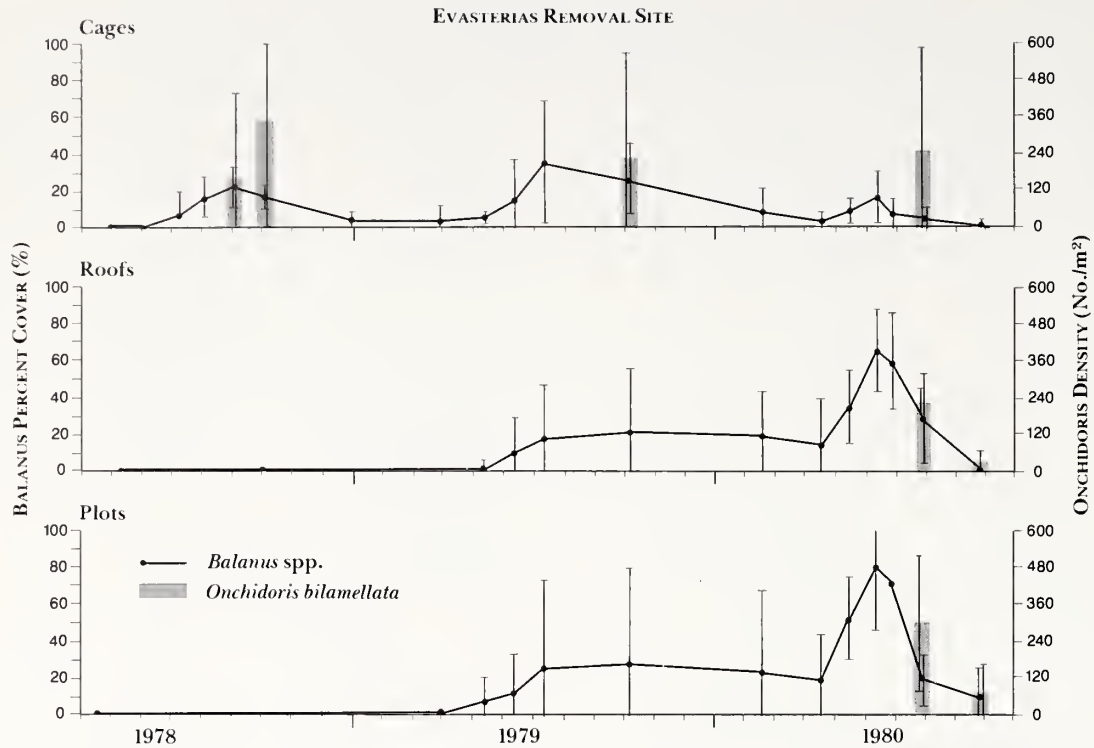


Figure 11-14. Percent cover of barnacles and density of *Onchidoris bilamellata* in cage sets at the *Evasterias* removal site at Auke Cape in Auke Bay from April 1978 to September 1980. Error bars are one standard deviation from either side of the mean.

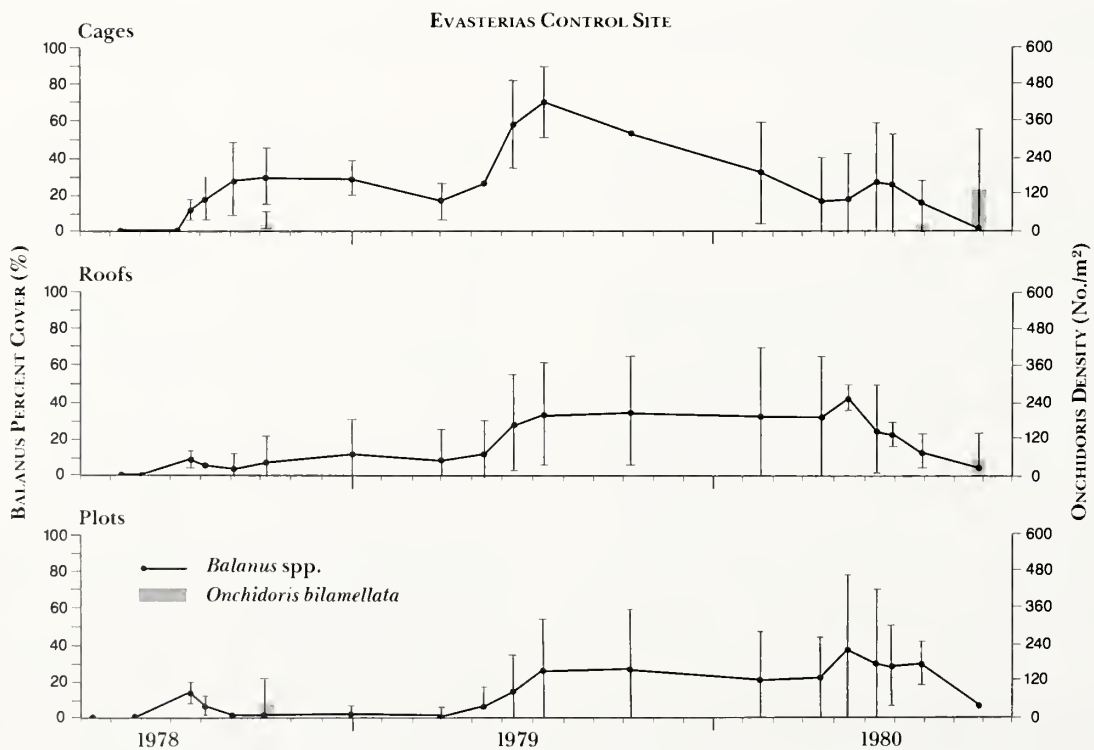


Figure 11-15. Percent cover of barnacles and density of *Onchidoris bilamellata* in cage sets at the *Evasterias* control site at Auke Cape in Auke Bay from April 1978 to September 1980. Error bars are one standard deviation from either side of the mean.

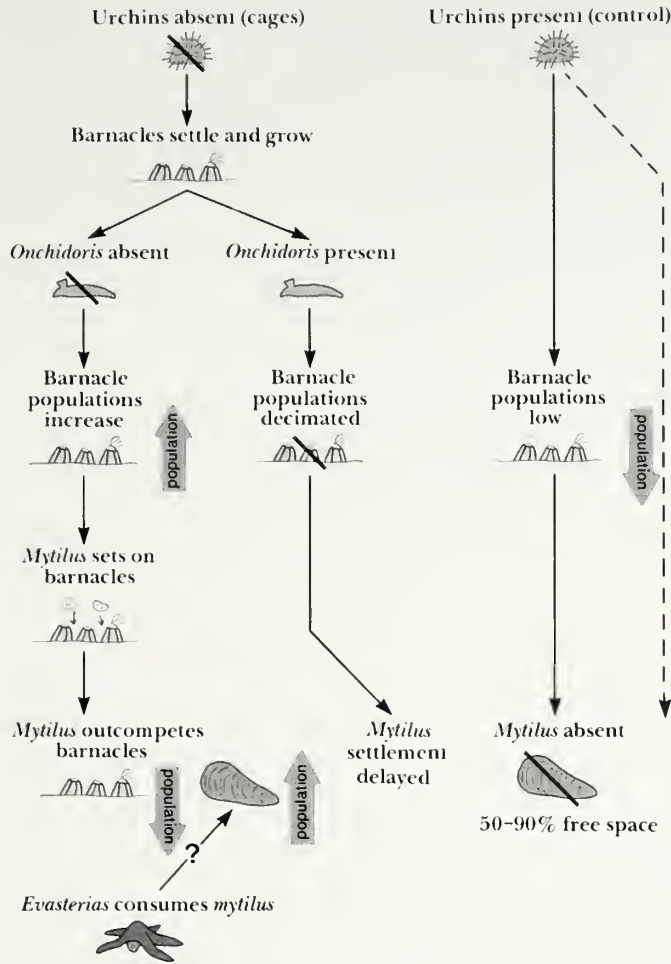


Figure 11-16. Summary of the results of an experiment at Auke Cape in Auke Bay in which *Evasterias troschelii* was removed. Successful colonization of the low intertidal zone by *Mytilus* depended on reduction in abundance of urchins (*Strongylocentrotus droebachiensis*) and *Onchidoris bilamellata*. Barnacles include *Balanus glandula* and *Semibalanus balanoides*.

(*Strongylocentrotus polyacanthus*) and bottom fish (Kenyon 1969; Burgner and Nakatani 1972; and Estes, Jameson, and Rhode 1982). The sea urchins that are preyed upon by the otters are important grazers on marine algae. Other species of *Strongylocentrotus* have been shown to cause large-scale kelp bed destruction which may persist for many years (Leighton 1971; Breen and Mann 1976; and Mann 1977). Estes and Palmisano (1974) compared the sublittoral and lower intertidal communities on Amchitka Island (with its populations of sea otters) to the same nearshore communities on Shemya Island (without sea otters). They found striking differences in the nearshore communities between the two islands. Amchitka Island had fewer and smaller sea urchins, especially in the shallow sublittoral region above the 15- to 18-m range—the apparent lower limit of effective sea otter foraging (Fig. 11-17; Estes *et al.* 1978). The reduced sea urchin biomass on Amchitka was accompanied by extensive intertidal and subtidal kelp beds (*Laminaria* spp., *Alaria fistulosa*, *Agarum cribrosum*, and *Thalassiophyllum clathrus*) as well as reduced populations of mussels, barnacles, limpets, and chitons in the intertidal region (Estes and Palmisano 1974; Palmisano and Estes 1977; and O'Clair 1977a). There was also an abundant, diverse nearshore ichthyofauna (Simenstad, Isakson, and Nakatani 1977). At Shemya, offshore kelp beds were sparse, and the lower intertidal algae were heavily grazed by the large, abundant sea urchins (Estes and Palmisano 1974) (Fig. 11-17). Dense populations of mussels (*Mytilus edulis*) and barnacles (*Semibalanus cariosus* and *Balanus glandula*) occupied the shore at Shemya Island (Palmisano and Estes 1977).

Simenstad *et al.* (1978) examined faunal remains in the strata of a prehistoric Aleut midden at Amchitka Island and found a temporal pattern of faunal composition which was consistent with the spatial pattern observed by Estes and Palmisano (1974) at Amchitka versus Shemya Islands. Simenstad *et al.* (1978) found an inverse relationship between the number of sea otters, fish, and harbor seals that were harvested by the Aleuts and the number of sea urchins and limpets harvested by the Aleuts for the same time period.

Table 11-9. Statistics for coverage of *Mytilus edulis* in *Evasterias* removal experiment at Port Valdez, June 1978 to September 1981.

EVASTERIAS	TREATMENT	MYTILUS MEAN COVER (%)		TYPE OF ANALYSIS	SIGNIFICANCE LEVEL	INTERACTIONS
		JUNE 1978	SEPT. 1981			
Removal	Cages	12	71	2-way anova t-test	p < 0.001 p < 0.001	n.s.
	Plots	21	78	2-way anova t-test	p < 0.001 p < 0.001	n.s.
	Roofs	27	71	2-way anova t-test	p < 0.001 p < 0.025	n.s.
Control	Cages	20	71	1-way anova	p < 0.05	—
	Plots	29	58	Mann-Whitney U-test	n.s.	—
	Roofs	32	65	Mann-Whitney U-test	n.s.	—

n.s. = not significant.

^a Data were transformed (arcsin \sqrt{p} , p = proportion of coverage) to stabilize variances for parametric tests. Homogeneity of variance was verified with Bartlett's test. Individual comparisons of simple main effects were made with t-tests (Winer 1971) when variances were homogeneous, otherwise with the Mann-Whitney U-test. All tests are one-tailed.

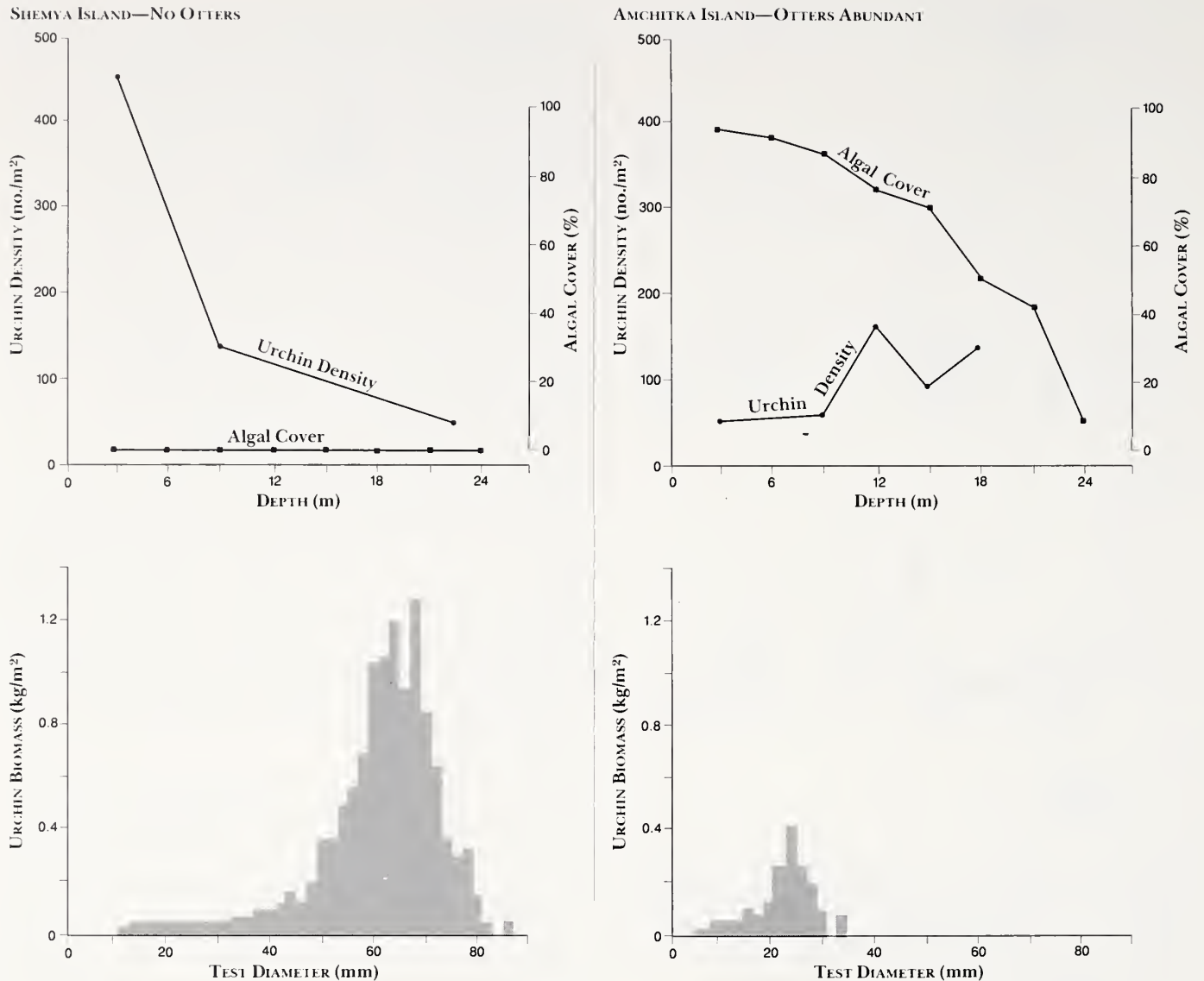


Figure 11-17. Comparative relationships of sea urchin population densities to algal cover and sizes of individual sea urchins to urchin biomass between Aleutian islands with sea otters (Amchitka) and without sea otters (Shemya). (Modified from Estes and Palmisano 1974.)

Simenstad *et al.* (1978) attributed the stratigraphic replacement of the former species assemblage by the latter species assemblage to overexploitation of sea otters—an exploitation that caused a shift in the nearshore community from one dominated by sea otters to one with few sea otters and abundant sea urchins and limpets.

Without the grazing pressure normally exerted by sea urchins at Amchitka, competition for light and space assumed a more important role in organizing the benthic macrophyte populations. Dayton (1975b) manipulated algal canopies in the sublittoral region at Amchitka and found that in the shallow areas, removing the stipes and fronds of *Laminaria longipes* resulted in complete recolonization by that species. The rhizoidal growth pattern of *L. longipes* presumably gives that species an advantage over *Laminaria* spp., *Alaria*, and *Agarum cribrosum* following disturbance if the holdfasts of *L. longipes* remain intact (Dayton 1975b).

Dayton's (1975b) experiments in the deeper subtidal area indicated that *Laminaria* spp. suppressed the growth of *Agarum cribrosum*, and that either *Laminaria* or *Agarum* could suppress the recruitment and growth of *Alaria fistulosa*. Despite its larger size and dominance in the floating canopy, *Alaria fistulosa* behaved as a fugitive species in Dayton's (1975b) experiments.

Duggins (1980a, b) simulated sea otter dominance, then examined competitive interactions among kelps (*Laminaria groenlandica*, *Nereocystis luetkeana*, *Alaria fistulosa*, *Cymathere triplicata*, and *Costaria costata*) in a shallow subtidal community at Torch Bay, Alaska. Duggins mimicked the influence of sea otters by removing sea urchins (*Strongylocentrotus franciscanus*, *S. purpuratus*, and *S. droebachiensis*) from plots with an area of ~50 square meters. Plots where sea urchins were removed were initially colonized by both annual (especially *Nereocystis*) and perennial kelps. By the second year of the

experiment, *L. groenlandica* dominated the experimental plots, resulting in a reduction in both the biomass and diversity of kelps when compared with the first year after the urchins were removed.

Without sea otters, the shallow subtidal community at Torch Bay became a mosaic of kelp patches. The patches were created when the kelps were temporarily released from grazing pressure because the sea star *Pycnopodia helianthoides* began preying on *Strongylocentrotus droebachiensis* and *S. purpuratus*, forcing them into a three-species aggregation with *S. franciscanus* in order to escape predation (Duggins 1981a, 1983). The faster growing annual species (e.g., *Nereocystis* and *Alaria*) in this community occasionally escaped urchin herbivory long enough to reach a large size (thereby avoiding further grazing by urchins) when the urchins temporarily switched from grazing the benthic macroalgae to eating ephemeral abundant food sources such as drift algae, diatoms, or (unusually) salps (Duggins 1981b, 1983).

Community Response to Sudden Land-Level Changes

Both the continental coasts and the islands that rim the Pacific Ocean have an active seismic history. Sudden uplift of the shore is often the greatest source of earthquake-related mortality among marine organisms (see review by Brongersma-Sanders 1957). Mass mortalities of marine organisms resulting from land-level changes caused by major earthquakes have been recorded at a variety of places, including Chile (Graham 1824; Fitz-roy 1839; and Davison 1936), Mexico (Bodin and Klinger 1986), Alaska (Tarr and Martin 1912; Haven 1971; and Johansen 1971), and Japan (Kaburaki 1928). In the Gulf of Alaska, sudden changes in the land level that followed both the Great Alaskan Earthquake of 1964 and the underground nuclear testing on Amchitka Island have permitted studies of the changes in intertidal and shallow subtidal communities that take place following either an uplift or a downthrust of the shore.

The Great Alaskan Earthquake lifted some littoral shores in Prince William Sound as much as 10 m, displacing the entire intertidal region to a position above the range of the tides. Several researchers, including Johansen (1971), Haven (1971), Hubbard (1971), and Baxter (1971), recorded population changes for algae and invertebrates in the intertidal and shallow subtidal regions of Prince William Sound following the Alaska Earthquake. Fifteen months after the earthquake—when Johansen and Haven first visited the disturbed sites—virtually all the intertidal organisms and those sublittoral species that were lifted into the intertidal region on the maximally uplifted shores had died (Johansen 1971; Haven 1971). A conspicuous white zone composed of the calcareous remains of coralline algae, serpulid worm tubes, bryozoans, and mollusk shells extended from the pre-earthquake lower mid-littoral zone down to ~9.0 m below the pre-earthquake zero tide level (Haven 1971).

On moderately uplifted shores, the amount of effect the uplift had depended on several factors, including its magnitude, the type of habitat, the species, and (for algae) the age

of the individual (Johansen 1971; Haven 1971). With the exception of barnacles (*Balanus glandula*, *Semibalanus* [= *Balanus*] *cariosus*, and *Chthamalus dalli*) which Haven (1971) found alive nearly 1 m above their normal upper limits, organisms that were lifted above their pre-earthquake upper limits were killed. On intertidal shores which had subsided into the sublittoral region, mussels, barnacles, and *Fucus* were alive in the post-earthquake *Laminaria* zone and appeared to be inhibiting the development of *Laminaria* and associated fauna (Haven 1971).

Species composition and the vertical ranges and relative abundances of species in the post-earthquake mid-littoral zone 15 months after uplift were generally similar to the inferred pre-earthquake conditions. However, Haven (1971) found evidence that some post-earthquake communities were at a relatively early stage of development. Film-forming algae rather than *Verrucaria* occupied the post-earthquake *Verrucaria* zone. On those uplifted shores that rose the highest, *Porphyra* rather than *Fucus* dominated the mid-littoral zone. In contrast to the relative abundances inferred for pre-earthquake barnacles, after the earthquake, *Semibalanus balanoides* rather than *Balanus glandula* appeared to dominate the upper mid-littoral zone (Appendix 11-3). *Mytilus edulis* were frequently attached to algae rather than rock—the substrate usually occupied by mussels beyond the plantigrade stage. The overall rate of development of the post-earthquake community appeared highest in the *Laminaria* zone and decreased from there upward (Haven 1971).

Grazing, both by limpets (*Collisella* [= *Acmaea*] *pelta*, *C. strigatella* [= *A. paradigitalis*], *C. digitalis*, *Notoacmea* [= *Acmaea*] *scutum*, *N. persona*, and *Siphonaria thersites*) and by littorines (*Littorina sitkana* and *L. scutulata*), may have influenced the development of algal populations in the post-earthquake mid-littoral zone. This was evidenced by 1) inverse correlations between limpet populations and both the membranous and the filamentous algae in the upper mid-littoral zone, 2) a grazing line found at the lower limit of the vertical distribution of encrusting microalgae which occupied the post-earthquake *Verrucaria* zone—below which *Collisella strigatella* and littorines were actively feeding, and 3) *Porphyra* becoming dominant in the post-earthquake *Fucus* zone on stretches of shore where grazers were rare (Haven 1971).

Haven returned to Prince William Sound four and one-half years after the earthquake and generally found that post-earthquake communities were essentially the same as pre-earthquake communities that were inferred for the same tidal level. *Balanus glandula* had replaced *Semibalanus balanoides* to various degrees as the dominant barnacle, and *Fucus* had replaced *Porphyra* as the dominant alga in the post-earthquake upper mid-littoral zone. *Mytilus* was attached to both rocks and barnacles beneath the canopy algae, and its lower limit appeared to be set by seastar predation. However, a distinct *Verrucaria* zone had not formed.

When viewed as an intertidal experiment in land-level change, the underground nuclear testing on Amchitka Island allowed for experimental designs that could detect and quantify those changes in the intertidal communities that were caused by uplift more sensitively than the designs

that could have been employed following the Great Alaska Earthquake. In contrast to the earthquake, the timing of each detonation was controlled, and the pre-blast distribution and abundance for intertidal organisms were accurately estimated. While geologists could not predict the exact location, nature, or magnitude of the land-level change, knowing the epicenter let scientists choose experimental and control (reference) sites with reasonable confidence.

The underground nuclear test designated *Milrow* (Fig. 11-18) was fired on October 2, 1969, and lifted ~ 4 ha of intertidal bench on the Pacific side of Amchitka 12 cm as a result of a shift along a pre-existing fault line (Lebednik 1973). The uplift, which was 13% of the mean tide range at Amchitka, was equivalent to a 40-cm (13% of the mean tide range at Cordova, Alaska) displacement in Prince William Sound.

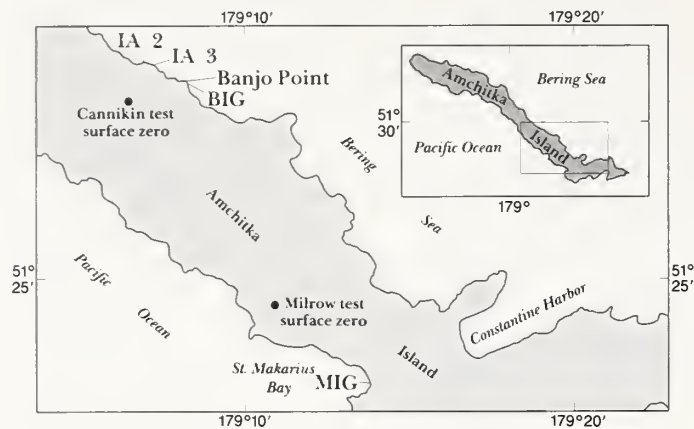


Figure 11-18. Map of Amchitka Island showing the location of study sites.

Haven (1971) considered uplift of 60 cm or less to be negligible relative to the vertical range of most organisms in Prince William Sound. Nevertheless, after uplift five of the 25 algal species that Lebednik (1973) studied showed substantial mortality, with most mortality occurring in the first six months after the test. These five species were apparently at their upper physiological limits before uplift.

During the spring and summer following the Milrow detonation, one species, *Fucus distichus*, increased markedly in frequency of occurrence on study plots occupied by *Hedophyllum sessile* before uplift. This increase was consistent with Lebednik's observations on the abundance of *F. distichus* at similar tidal elevations elsewhere on Amchitka. Three and one-half years after uplift, changes in the abundances of major canopy species (*Alaria crispa* and *Fucus distichus*) were still occurring (Lebednik and Palmisano 1977).

The underground nuclear test designated *Cannikin* (Fig. 11-18) was fired on November 6, 1971, and caused detectable uplift in a range between 3 and 110 cm of the intertidal bench along at least 7.8 km of Bering Sea coastline on Amchitka (Kirkwood and Fuller 1972). Lebednik and Palmisano (1977) observed mortality of intertidal algae along 6.1 km of the coast. In addition, about $3.0 \times 10^4 \text{ m}^3$ of rock and turf from cliffs and sea stacks adjacent to the intertidal benches on the Bering Sea coast of Amchitka fell on the benches (Fuller and Kirkwood 1977) (Fig. 11-19). Although the rock and turf falls covered as much as 29% of the intertidal region at Banjo Point (O'Clair 1977b; Figs. 11-20 and 11-21), most of the material was deposited on the beach shoreward of the intertidal benches and affected intertidal organisms only in localized areas (Lebednik and Palmisano 1977).

The effects of Cannikin varied with 1) the magnitude of land level change, 2) the degree to which the uplifted rock



Figure 11-19. View northwest from Banjo Point, taken nine months after the Cannikin underground test, showing rock falls and the uplifted intertidal bench. Photograph taken in August 1972 by C.E. O'Clair.



Figure II-20. Oblique view of the Banjo Point study site two months before the Cannikin underground test. Photograph taken in August 1971 by C.E. O'Clair.



Figure II-21. Oblique view of Banjo Point study site nine months after the Cannikin underground test. Photograph taken on 10 August 1972 by C.E. O'Clair.

bench was exposed to open ocean waves, 3) the species, and 4) the tidal level on the shore at sites with moderate uplift such as Banjo Point. (Community attributes at higher shore levels changed in a different manner than attributes at lower shore levels.) Maximum uplift in the range of 50 to 110 cm (59 to 129% of the mean tide range) caused virtually complete mortality in all intertidal algae and most species of invertebrates within a year after the uplift occurred (Lebednik and Palmisano 1977; O'Clair 1977a, b). Although the increased exposure to open-ocean waves delayed community extinction near the outer edges of the benches that were lifted the highest, it did not prevent the extinction (O'Clair 1977b).

The only intertidal species that persisted throughout the year following Cannikin in those plots that experienced maximum uplift were littorines and barnacles (O'Clair 1977b). *Littorina aleutica* and *L. atkana* survived, and at least one of them reproduced in the uplifted plots in the year following Cannikin. Adults of *Balanus glandula* and *Semibalanus cariosus* that were lifted 90 to 95 cm survived on the vertical surfaces at the outer edge of the uplifted bench for at least 2.5 years. *S. cariosus*, at least, had been lifted well above its pre-detonation upper limit (O'Clair 1977b). The persistence of these intertidal species notwithstanding, all of the original study plots at the areas of maximum uplift were colonized by species of the supralittoral fringe, such as: 1) the insects Collembola, Diptera (*Saundersia marinus* and *Paraculnio alaskensis*), and Acarina (*Neomolgus littoralis* and *Parasitus* sp.), 2) the isopod *Ligia pallasii*, and 3) the gammarid amphipod *Orchestia* sp. Supralittoral species remained the dominant organisms on all but one of these plots until the end of the study (33 months after Cannikin). The remaining plot was gradually colonized by upper intertidal species.

On the moderately uplifted (28% of the mean tide range) shore at Banjo Point nine months after the Cannikin detonation, the effects of uplift depended on tidal level (O'Clair 1977b). In the *Halosaccion-Fucus* zone (the highest intertidal zone) the dominant species of algae died in quantities large

enough to leave 88% of the area covered by this zone as bare rock (Figs. 11-20 and 11-21). In the lower zones, extensive loss of fronds among the dominant algal species occurred within nine months of the test. Distinct bands of frondless *Alaria crispera* and *Laminaria longipes* appeared in the upper 66 and 77% of the *Alaria-Hedophyllum* and *Laminaria* zones, respectively (Figs. 11-22 and 11-23). Within nine months, species richness of invertebrates and algae had either remained the same or had increased in the *Laminaria* zones, but richness decreased at higher intertidal levels. The difference in the effect of uplift with tidal level was attributed to both species loss at higher tidal levels (resulting from emigration or die-off) and to no change or a net gain in the number of species in the *Laminaria* zone (resulting from the addition—either by settlement or by immigration—of those species that are characteristic of higher intertidal levels) (O'Clair 1977b).

At the moderately uplifted site, herbivory did not appear to influence colonization of the uplifted *Laminaria* zone by upper intertidal algae. Although the abundances of herbivorous mollusks were nearly the same nine months after the detonation as before in the uplifted *Laminaria* zone at Banjo Point, isopods and gammarids increased (O'Clair 1977b). Nevertheless, by nine months after the Cannikin test, such species as *Halosaccion glandiforme*, *Fucus distichus*, *Iridaea cornucopiae*, *Microcladia borealis* and *Porphyra* sp. had colonized the uplifted *Laminaria* zone. Herbivores may have made it easier for these algae to settle by cropping early colonizers such as diatoms and ulvoids, but the colonization schedule of *H. glandiforme*, *F. distichus*, and *Iridaea cornucopiae*, at least, was consistent with the schedule noted by Lebednik and Palmisano (1977) in their colonization studies where herbivory was apparently not a factor.

Those intertidal communities which became established in the new intertidal zone within 33 months after the uplift tended to show upper limits below those of comparable intertidal communities before uplift (O'Clair 1977b). The depressed limits may have resulted because uplifted, for-

IA 2

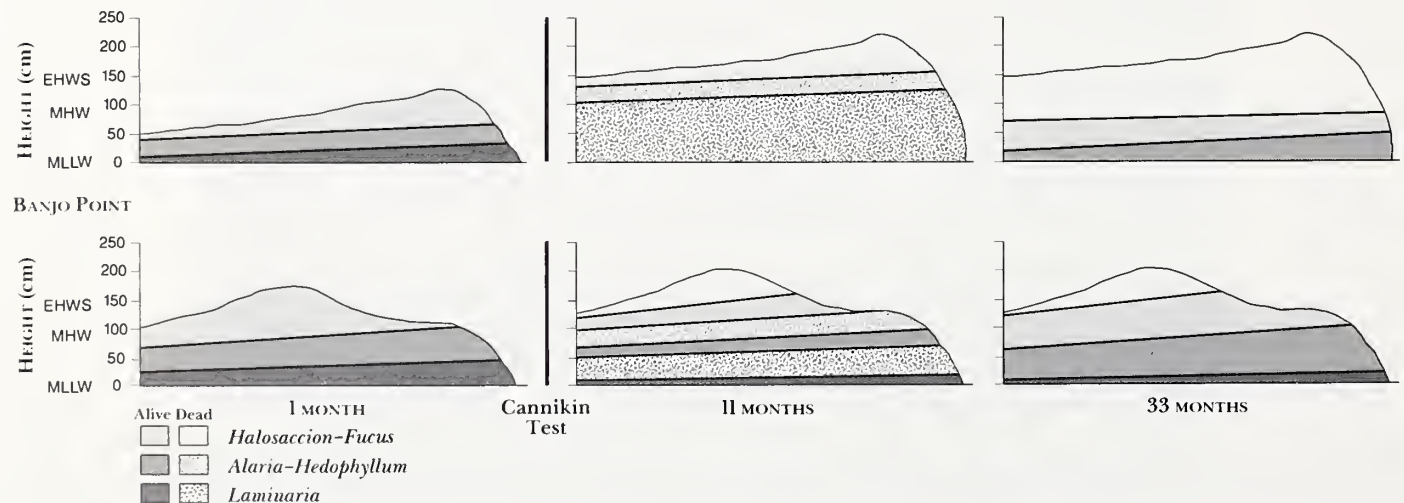


Figure 11-22. Profiles of intertidal benches at maximally uplifted (IA-2) and moderately uplifted (Banjo Point) sites one month before and 11 and 33 months after the Cannikin underground test. Changes in zones of the dominant algae are shown.

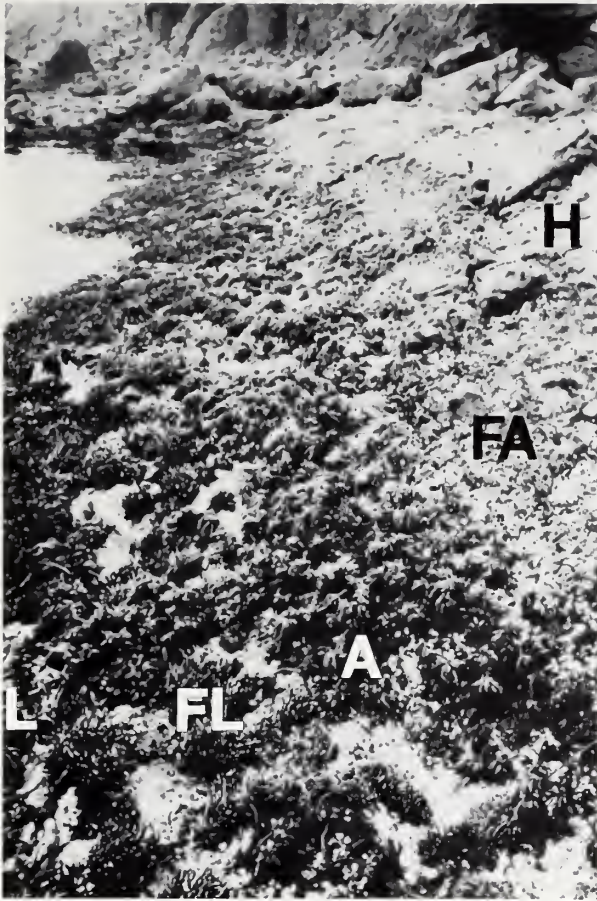


Figure 11-23. View of the shore zones at Banjo Point nine months after the Cannikin underground test showing zones of frondless *Alaria crispera* and frondless *Laminaria longipes*. Photograph taken on 10 August 1972 by C.E. O'Clair. H = live *Halosaccion glandiforme*; FA = frondless *Alaria*; A = fronded *Alaria*; FL = frondless *Laminaria*; L = fronded *Laminaria*.

merly subtidal offshore reefs and knolls sheltered the intertidal benches from waves, or may have been because the upward extension of the upper limits of intertidal communities is a gradual process that depends upon periods that are favorable enough for young sporophytes of dominant macrophytes to become established at the higher levels. As the macrophytes grow large enough to modify the environment beneath their fronds, they aid the settlement of sub-dominant species.

C.E. O'Clair returned to the uplifted sites on Amchitka in July 1985, 13.6 years after the Cannikin detonation. On those shores that were lifted highest, the upper surface of the pre-detonation intertidal bench was bare (Fig. 11-24). No colonization had taken place by either intertidal or maritime species. Well-developed communities similar to the pre-event intertidal communities occupied the vertical surfaces both at the edge of the uplifted bench and on boulders in surge channels at sites of the maximum uplift. Similar communities were found on post-event intertidal surfaces at the moderately uplifted site (Banjo Point). These communities were dominated by: 1) *Halosaccion glandiforme*, *Iridaea cornucopiae*, and *Porphyra* sp. in the upper intertidal area, 2) *Pal-*

maria palmata and *Alaria crispera* (and *Odonthalia floccosa* at Banjo Point) in the mid-intertidal area, and 3) *Laminaria longipes* in the sublittoral fringe. *Littorina* spp. and *Siphonaria thersites* were common among the *Halosaccion* plants. Small *Mytilus edulis*, *Semibalanus cariosus*, and *Balanus glandula* were common among *Alaria* and *Odonthalia* plants at Banjo Point.

Fucus seemed to be less abundant at both the maximally uplifted sites and at Banjo Point than it was before uplift occurred, although it was common in inner surge channels. *Hedophyllum sessile* had not recolonized Banjo Point, though it had maintained a small population there before uplift occurred. *Porphyra* had colonized the rock bench above the post-event (+33 mo) *Halosaccion* zone, and there was some evidence that the upper limits of the *Halosaccion* and *Alaria* zones were higher at Banjo Point than those limits had been at 33 months after detonation (Figs. 11-25, 11-26). However, there was little evidence of an upward extension of the upper limit of the highest intertidal community at the maximally uplifted sites since August 1974 (+33 mo).

Subtidal Kelp Beds

Distribution and Standing Stock

Early in the twentieth century, the United States Department of Agriculture, in an attempt to lessen dependence on German potash, began investigating alternative sources for this compound. Chemical analyses indicated that three species of west-coast kelp (*Nereocystis luetkeana*, *Macrocystis pyrifera*, and *Alaria fistulosa*) had relatively high average potash values (9–20% dry weight) (Cameron 1915). In 1911, the Bureau of Soils began a survey of Pacific kelp beds and, in 1913, expeditions were made to Southeast Alaska (Frye 1915) and western Alaska (Rigg 1915).

Frye's group located 1,133 beds in the area from Dixon Entrance to Chatham Strait. Rigg's group located 358 beds in the area from Prince William Sound to the Shumagin Islands. Standing stocks of kelp in Southeast Alaska were estimated at 7.88×10^6 t (7.15×10^6 mt), occupying an area of 1.83×10^4 ha (= 39 kg/m²). Western Alaska was estimated to contain 3.6×10^6 t (3.26×10^6 mt) of kelp with the beds occupying an area of 4.61×10^3 ha (= 70 kg/m²).

Subsequent research indicates that although many of the beds discovered by Frye and Rigg still occur in much the same locations they described (Sears and Zimmerman 1977; Zimmerman *et al.* 1979), the earlier values for standing stocks were probably overestimated by an order of magnitude. Calvin and Ellis (1978) reported that standing stocks at nine kelp-bed sites in the southern Kodiak Island area ranged from 4.8 to 18.3 kg/m²; Dames and Moore (1980) found an overall standing stock biomass of 1.98 kg/m² at sites in the Cook Inlet area with a maximum value of 31.75 kg/m² at Latouche Point in western Prince William Sound. Summaries of worldwide values for standing stocks of benthic kelp (Calvin and Ellis 1978) indicate values usually less than 30 kg/m².

Growth and Primary Production. Growth of subtidal *Laminaria groenlandica* has been measured over several sea-



Figure II-24. Oblique view of maximally uplifted (IA-2) site 13.6 years after the Cannikin underground test. The quadrat on the bench surface is 0.25 m². Photograph taken on 4 July 1985 by C.E. O'Clair.



Figure II-25. Oblique view of Banjo Point study site 13.6 years after the Cannikin underground test. The quadrat on the intertidal surface is 0.25 m². Photograph taken on 4 July 1985 by C.E. O'Clair.



Figure 11-26. View of zonation on shore at Banjo Point 13.6 years after the Cannikin underground test. Photograph taken on 4 July 1985 by C.E. O'Clair.

sons in Southeast Alaska (Duggins 1980a, b; Calvin and Ellis 1981) and in the Cook Inlet region (Dames and Moore 1979b). Calvin and Ellis found that *L. groenlandica* increased in blade length from January to June with a peak growth rate of 0.6 to 0.8 cm/d in late March and early April. Very little growth in blade length occurred from July through November. Dames and Moore similarly found low growth rates of *L. groenlandica* during August through October (0.005 cm/d) and that the highest rates (avg. 0.4 cm/d) occurred from March through late May. Calvin and Ellis (1981) also noted that although maximum rates of growth in blade length occurred in March and April, blades underwent their greatest increase in weight between June and September. Plants at lesser depths showed a greater increase in weight than plants at greater depths.

Growth rates for *Alaria fistulosa* and *Agarum cribosum* have also been determined (Dames and Moore 1980a). *A. fistulosa* had a high natural mortality rate after an average of 105 days of observation. Growth rates for this species were determined to be lowest in fall and mid-winter, but increased rapidly during April and May. Growth generally exceeded 6.40 cm/d in March through June, but fell below 4.24 cm/d for the rest of the year. The slowest growth rates that were observed for an individual plant were 0.84 cm/d for February; most rapid rates of growth were 18.77 cm/d in late May

and early June. Growth of *A. cribosum* was lowest in fall and early winter (0.05 cm/d) and highest in April (0.33 cm/d). Average rates generally exceeded 0.2 cm/d from March to June but fell below 0.12 cm/d from August to mid-February.

In addition to the studies that related kelp growth to changes in blade length and weight, Palmisano and Sheng (1977) also studied factors causing changes in the blade width for *Laminaria longipes*. Although they noted that the width of *L. longipes* blades varied during growing seasons, water movement appeared to be the primary factor determining blade width. Plants growing in exposed areas had significantly narrower blades than those collected from sheltered sites during the same season.

Primary production for several kelp species has been estimated at various sites and depths in lower Cook Inlet and Prince William Sound by using: 1) algal-size data, 2) length-weight regressions, 3) average growth increments, and 4) estimates of standing stocks (Dames and Moore 1980a). High variability was found between species, seasons, sites, and depths (Table 11-10). The highest combined values (37.4 to 71.9 kg/m²y fresh weight) were found in the -9 to -12 m depth range at Latouche Point.

Conclusions

Biotic Composition

We analyzed the biotic composition of the rocky intertidal region at sites ranging from Yakutat to the western Aleutian Islands. We combined this analysis with an analysis of the zoogeographic affinities of species from the major invertebrate phyla for these sites and found that no major discontinuities existed in the biotic composition between the Yakutat sites and sites in the eastern Aleutian Islands. However, the composition of intertidal species found both at Amchitka and at the Shemya Islands in the western Aleutians differed markedly from the species composition found in the Gulf of Alaska and eastern Aleutians. The western Aleutians had fewer North American and more Asiatic species than did sites in the eastern Gulf of Alaska.

There was a higher percentage of endemic species among mollusks, crustaceans, and echinoderms in the western Aleutian Islands than in the Gulf of Alaska. However, there was no significant difference in the percentage of endemic polychaetes between the western Aleutians and the Gulf. The trophic distribution was similar at all the sites that we studied. Study of intertidal species composition on islands along the Aleutian chain between Unalaska and Amchitka Islands will reveal whether there is a gradual transition in Asiatic versus North American species in this region or an abrupt discontinuity in species composition at some point along the chain.

Physical Control Over Intertidal Communities

Only three of 29 sites studied in the Gulf of Alaska showed clear evidence of physical control over intertidal community structure. Further evidence as to the impact physical factors have in influencing intertidal communities

Table 11-10.

Comparison of estimates of primary production (kg/m²y fresh weight) by macrophytes at various sites and depths in lower Cook Inlet and NEGEOA (from Dames and Moore 1980a).

DEPTH ZONE (m)	LOWER COOK INLET			NEGEOA			
	SOUTH SIDE, KACHEMAK BAY AND KENNEDY ENTRANCE	NORTHERN SHELF, KACHEMAK BAY	KAMISHAK BAY SITES ^a	ZAIKOF POINT, MONTAGUE ISLAND	ZAIKOF BAY, NMFS SITE, MONTAGUE ISLAND	SEA LION PINNACLES, DANGER ISLAND	LATOUCHE POINT, LATOUCHE ISLAND
+2 to MLLW	2.1 <i>Fucus</i> and <i>Rhodomenia</i> spp.	Negligible <i>Fucus</i>	4.0 <i>Fucus</i> and <i>Rhodomenia</i> spp.	— ^b	—	—	—
MLLW to -3	5.0 <i>L. groenlandica</i> and <i>Alaria</i> spp.	Negligible <i>L. groenlandica</i>	5.4 <i>Rhodomenia</i> spp. and <i>L. groenlandica</i>	15.6-23.4 <i>L. dentigera</i> and <i>Pleurophycus</i>	—	—	—
-3 to -6	18.5 <i>Nereocystis</i> and <i>L. groenlandica</i>	2.1 <i>L. groenlandica</i>	<0.1 <i>Agarum</i>	15.5 ^c <i>Nereocystis</i> and <i>L. dentigera</i>	2.0-2.9 <i>Agarum</i>	—	—
-6 to -9	22.0 <i>Nereocystis</i>	5.0 <i>L. groenlandica</i>	0	3.1 ^c <i>Nereocystis</i> and <i>L. dentigera</i>	1.1-1.6 <i>Agarum</i>	7.1-10.6 <i>Laminaria</i> spp. and <i>Pleurophycus</i>	—
-9 to -12	7.1 <i>Nereocystis</i> and <i>L. groenlandica</i>	5.0 <i>L. groenlandica</i>	0	3.1 <i>L. groenlandica</i>	1.1-1.6 <i>L. groenlandica</i> and <i>Agarum</i>	7.1-10.6 ^c <i>Nereocystis</i> and <i>Laminaria</i> spp.	37.4-71.9 <i>Nereocystis</i> and <i>Laminaria</i> spp.
-12 to -18	0.8 <i>L. groenlandica</i> and <i>Agarum</i>	0.4 <i>Agarum</i>	0	<0.1 <i>Desmarestia</i>	Sand bottom	7.6-11.4 ^c <i>Nereocystis</i> and <i>Laminaria</i> spp.	—
-18 to -21	0.4 <i>Agarum</i>	Negligible <i>Callophyllis</i>	0	Sand bottom	Sand bottom	0.1-0.2 <i>Agarum</i>	—

^a Rough estimates based on biomass data from spring and summer 1978.

^b — indicates no data are available.

^c *Nereocystis* dominant but productivity estimate does not include its production.

will require further intensive study of selected sites around the Gulf. Physical regimes along gradients ranging from exposed outer coast to inner protected bays are influenced by large inflows of turbid freshwater from glacial runoff. These inflows alter the species composition along the gradient and may also subtly alter the relative abundances of species such as *Semibalanus balanoides* and *Balanus glandula*—both of which can tolerate large changes in these regimes. A comprehensive study of how both physical and biological factors contribute to the control of the distribution and the abundance of *S. balanoides* and *B. glandula* could provide insight into how communities in inner waters are organized—compared with those communities on the outer coast.

Although *Pisaster ochraceus* on the outer coast and *Evaersterias troschelii* in inner waters may limit the vertical distribution of *Mytilus edulis*, *M. edulis* is more vulnerable to the activities of other predators than is *M. californianus*. Therefore, in Alaska, neither *P. ochraceus* nor *E. troschelii* seems to play as important a role in shaping community structure as *P. ochraceus* plays in shaping community structure on the outer coast of Washington.

The Effect of Uplift on Intertidal Communities

Studies of intertidal communities following an uplift of the intertidal region by earthquakes and underground

nuclear tests supports the argument that the upper limit of distribution of most species of algae and invertebrates is controlled by physical factors associated with emersion. Most species lifted above their upper limits either die or emigrate. However, *Balanus glandula*, *Semibalanus cariosus*, and *Chthamalus dalli* can survive when lifted nearly 1 m above their normal upper limits. It normally takes three years before community development within the new uplifted intertidal region approximates the same species composition and relative abundances of comparable communities before an uplift occurs.

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Appendix II-1

We estimated percent cover of each species of barnacle at Port Valdez, Siwash, West, and Outside Bays, Point Barber, and (for comparison) Auke Bay, Alaska, by means of belt transects or arrays of quadrats placed in the mid-littoral zone. Each transect was 1.3 m in width and was laid perpendicular to the shoreline. Transects were divided into strata along their length—based on total barnacle abundance. Arrays were usually placed in the lower mid-littoral zone. Quadrats 150 cm² in size were positioned in arrays or within strata on transects using coordinates drawn from a random-number table. Percent cover of all barnacle species was usually estimated by using Connell's (1970) method. In a few situations when a camera was not available, estimates were made in the field using Menge's (1976) method, that is, using a sheet of Plexiglas with 100 randomly distributed points on its surface. The method was modified for 150 cm² areas.

Data on the relative abundances of *Semibalanus balanoides* and *Balanus glandula* at the remaining three sites (Zaikof Bay, MacLeod Bay, and Latouche Point) in lower Prince William Sound were collected using transects and random arrays. (For details on the sizes and the orientations of the transects and arrays at each site, see O'Clair *et al.* [1978].) Quadrats 1/16 m² in size on the transects and arrays were scraped clean of macroscopic organisms which were then placed in plastic bags and fixed in a 10% formalin solution. Each species of barnacle was counted in the laboratory. Although barnacles are usually damaged when scraped from the rocks in groups, the opercular plates which contain the most useful structures for distinguishing these two species usually remained intact.

Appendix II-2

Two intertidal sites were established at each of the two localities. Each site was a 30- to 35-m stretch of bedrock or large boulder shore. The sites at Auke Bay and Port Valdez were separated, respectively, by ~170 m and 114 m of cobble/gravel or cobble/boulder beach. *Evasterias* was removed and counted from one site but not disturbed at the other (control) site. Other large predators (*Pycnopodia helianthoides*, *Strongylocentrotus droebachiensis*, and *Elassochirus tenuimanus*) were excluded from patches of rock 150 cm² in area by using stainless-steel wire mesh enclosures (cages). Controls for the enclosures included 1) a roof (sideless enclosure) to control shading and 2) an undisturbed plot. Control plots were placed adjacent to each enclosure. Three sets of these

installations were randomly placed at each site at Auke Bay; five sets were randomly placed at each site in Port Valdez. Cages, roofs, and plots at Auke Bay were photographed monthly or semimonthly in spring and summer and at irregular intervals in fall and winter. Port Valdez was less accessible than Auke Bay; cage sets were photographed seasonally there. The photographs were analyzed using the method described for estimating *Balanus* coverage above (see Appendix II-1).

Appendix II-3

Haven (1971: Fig.15) includes a photograph to illustrate the dominance of *Semibalanus balanoides* in the post-earthquake barnacle zone. It is noteworthy that the large individuals in Figure 15 are *Balanus glandula* rather than *S. balanoides* as stated in the caption. In Prince William Sound, Auke Bay (O'Clair, pers. obs.), and Unalaska, Alaska (Henry 1942), *S. balanoides* can be easily distinguished from *B. glandula* in the field as well as in clear, closeup photographs by "two black areas roughly parallel with the occludent margin" on each scutum (Henry 1942). The black areas are translucent rays through which the lining of the scutum can be seen (Henry 1942). *B. glandula* has one of these black rays on each scutum, as do the barnacles in Figure 15 of Haven (1971). Other less obvious differences, such as the shape and slope of the opercular plates, can be used to distinguish these two species in the field without removing them from the rock surface. Haven did not learn how to distinguish *S. balanoides* from *B. glandula* until after he had completed his fieldwork in Prince William Sound, and therefore he had to rely on a few specimens that were collected as well as rely on photographs and observations for drawing conclusions on the relative abundance of *Semibalanus* and *Balanus* in the post-earthquake barnacle zone there. The misidentification of the *B. glandula* in Haven's Figure 15 leads one to question the identifications of the barnacles in the rest of Haven's photographs.

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ABSTRACT

This chapter considers the subtidal benthos of the Gulf of Alaska shelf, the Gulf's embayments, and its fjords. It presents a brief historical review of both fisheries and non-fisheries work, examines benthic data in order to assess both infaunal and epifaunal species–distribution patterns and biomass, discusses those environmental variables that are responsible for community composition, and briefly considers trophic groups and the feeding interactions between invertebrates and fishes. Benthic production estimates for the shelf of the northeast Gulf and for lower Cook Inlet are also calculated. The mean macrofaunal production for the northeast Gulf of Alaska (NEGOA) is estimated at 4.5 g C/m²y, with total benthic (microflora, meiofauna, and macrofauna) production estimated at 13.7 g C/m²y. Infaunal production estimates for lower Cook Inlet vary between 2.5 and 10 g C/m²y. The chapter also covers the relationships between the physiographic and the oceanographic features of the Gulf as well as those carbon–concentrating mechanisms that lead to benthic enrichment.

Introduction

The shelf, embayments, and fjords of the Gulf of Alaska are characterized by many epifaunal invertebrate and demersal fish species of actual or potential commercial importance. These species include shrimps, crabs, snails, scallops, flatfishes, and cod. Since many of these species feed—in whole or in part—on infaunal and epifaunal residents of the bottom (Feder and Jewett 1981a; Feder and Paul 1980; Feder, Jewett, McGee, and Matheke 1981; Feder, Paul, Hoberg, and Jewett 1981), changes in either the distribution or the abundance of these prey organisms will affect the commercially important species that feed on them (Zenkevitch 1963; Feder, Paul, Hoberg, and Jewett 1981; and Feder and Jewett 1981a, b).

There are a number of industrial activities taking place on the shelf that have been shown to affect other shelf systems. These activities include:

- offshore mining and petroleum activities
- intensified bottom fishing
- coastal development, including dredging activities for port improvement and increased sewage input into coastal waters

(Zijlstra 1972; McIntyre 1977; and Pearson and Rosenberg 1978). Preliminary assessment of the benthos on the Gulf shelf suggests that the fauna is influenced by the Alaska Coastal Current in conjunction with heavy sediment loads that originate from glacial meltwater (H.M. Feder, University of Alaska, unpubl. OCSEAP data; Royer, Hansen, and Pashinski 1979; Feder and Matheke 1980a; and Royer 1981, 1982, 1983). Thus, potential alteration of the benthic environment of the Gulf must be considered in the context of both human activity and naturally occurring stresses.

Infaunal benthic organisms are frequently chosen to monitor the long-term effects of pollution, and often reflect the biological health of marine areas (Pearson 1971, 1972, 1975; Rosenberg 1973). Benthic organisms in the Gulf (primarily infauna, but also epifauna) were emphasized in the biological studies of the 1970s which were sponsored by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) (Feder and Matheke 1980a). OCSEAP-sponsored programs broadened the historical data, developed an inventory of benthic species, examined community structure, and initiated investigations of the food habits of dominant species.

In this chapter, the continental shelf, along with its embayments and fjords, is discussed in terms of both the qualitative and the quantitative data that exist on infaunal and epifaunal species composition and distribution. The environmental variables responsible for community structure of the benthos are also discussed. Two additional subject areas considered in this chapter are the feeding interactions among infaunal, epifaunal, and nektobenthic predators, and benthic production estimates for two regions of the shelf—northeast Gulf of Alaska (NEGOA) and lower Cook Inlet. Finally, the relationships between physiographic and oceanographic features of the Gulf are briefly examined, as well as those carbon-concentrating mechanisms that may lead to benthic enrichment.

In benthic studies, those invertebrates sampled by either grab or trawl methods are termed infauna and epifauna, respectively. Occasionally, organisms may be taken by both sampling methods and in these cases they are usually categorized as either infauna or epifauna, depending on the method used to capture it. This classification rationale is followed in the Soviet, National Marine Fisheries Service (NMFS), and OCSEAP investigations discussed in this chapter. For example, small surface-dwelling organisms such as seastars, ophiuroids, heart urchins, and sand dollars are typically characterized as infauna, but when abundant they are also captured in trawls. Including these organisms in trawl-capture data sets can provide useful information for categorizing a benthic area.

In most benthic studies, some of the species that are collected by grab methods—and that are used in subsequent analyses—are slow-moving surface dwellers. These organisms are often categorized as infauna in order to permit the assessment of abundance, biomass, and production of the small species that can be captured by this equipment. The latter approach—used in the investigations of Shevtsov (1964a, b), Semenov (1965), Feder and Matheke (1980a), and Bakus and Chamberlain (1975)—is also used in this chapter.

Historical Review

General

The Gulf of Alaska has historically been the site of a number of important fisheries, including:

- Dungeness crab (*Cancer magister*)
- Tanner crab (*Chionoecetes bairdi*)
- red king crab (*Paralithodes camtschatica*)
- shrimps (Family Pandalidae)
- scallop (*Pecten caurinus*)
- Pacific cod and walleye pollock (Family Gadidae)
- flatfishes (Family Pleuronectidae)
- rockfishes (Family Scorpaenidae)

(Alaska Department of Fish and Game 1985a, b, c, d; Ronholt, Shippen, and Brown 1978; and Smith, Hadley, French, Nelson, and Wall 1981). Most of these species use benthic organisms as a major component of their diet (Alton 1974; Feder and Paul 1980; Feder, Haflinger, Hoberg,

and McDonald 1980; Feder and Jewett 1981a, b; Feder, Paul, Hoberg, and Jewett 1981; and McDonald, Feder, and Hoberg 1981). However, despite the obvious trophic importance of the benthos to the Gulf ecosystem, little biological data were available for these organisms until the OCSEAP-sponsored studies were initiated in 1974.

The biological literature and unpublished data on the Gulf benthos collected through 1976 are summarized in Feder (1977) as well as in the review of the renewable resources of the northern Gulf found in Rosenberg (1972). Shevtsov (1964a, b) and Semenov (1965) describe infaunal as well as dominant epifaunal Gulf species assemblages, and discuss the relationships between the water depth, the substrate type, and the prevalent feeding modes (see summary in Cooney 1972). They divide the continental shelf and upper slope between Unimak Pass and Graham Island (in Southeast Alaska) into western, northern (NEGOA), and eastern regions. They define the boundary between the western and northern areas as a line running to the southeast from the southern tip of the Kenai Peninsula. Their boundary of the eastern area coincides with the geomorphological boundary of the eastern areas of the shelf and the continental slope (approximately off Cape Spencer). Although few data were available for the eastern area, the low organic carbon content of the sediment and the strong tidal currents there led them to separate this region from the northern area. The relative importance of the various trophic groups and associated bottom type by region, on the shelf and slope, is also considered by Semenov (1965) (Tables 12-1 through 12-3).

NEGOA Shelf

A summer survey by Bakus and Chamberlain (1975) examined the infauna and epifauna in a small area on the NEGOA shelf south of the Bering Glacier. The results of this study are similar to those of Shevtsov (1964a, b), Semenov (1965), Feder, Mueller, Matheke, and Jewett (1976), Feder and Matheke (1980a), and Feder and Jewett (University of Alaska, unpubl. OCSEAP data on file at the National Oceanographic Data Center [NODC], Washington, D.C. 20235) for the entire NEGOA shelf. Hickman and Nesbitt (1980) describe the infaunal mollusk associations in the Yakataga-Yakutat regions of the northern Gulf.

Trawl surveys for resource assessment span nearly 30 years and provide detailed spatial, qualitative, and quantitative coverage of the epifauna of NEGOA. Ronholt *et al.* (1978) present a comprehensive historical review of commercially important shellfishes and finfishes for the years 1948 to 1976. This review, which covers the broad region from Cape Spencer to Unimak Pass, includes mostly unpublished surveys done by the NMFS (formerly Bureau of Commercial Fisheries) and by the International Pacific Halibut Commission (IPHC). Included in this review is a 1961 to 1962 survey from Kodiak Island to Cape Spencer (Hitz and Rathjen 1965) and a 1975 survey from Yakutat Bay to Cape Cleare (Ronholt, Shippen, and Brown 1976).

Two additional surveys examined the non-commercial epifauna in detail, as well as examining the commercial spe-

Table 12-1.
Relationship between the distribution of trophic groups and the type of bottom sediment (Semenov 1965).

BOTTOM TYPE	SEDIMENT ORGANIC CARBON	FILTER FEEDERS				DETritUS FEEDERS				CARNIVORES		TOTAL BIOMASS g/m ²
		NON-MOBILE		MOBILE		BROWSERS		NON-SELECTIVE		g/m ²	%	
		g/m ²	%	g/m ²	%	g/m ²	%	g/m ²	%	g/m ²	%	
Mud	0.80	0.66	1.0	1.27	2.0	11.16	11.7	41.90	66.4	8.15	12.9	63.14
Sandy mud	0.50	0.19	0.3	2.65	4.57	11.51	19.9	39.54	68.3	4.03	6.96	57.92
Muddy sand	0.51	12.88	32.5	1.08	2.72	15.55	39.6	5.75	14.4	4.54	11.4	39.80
Sand	0.39	0.64	1.3	19.13	40.1	20.26	42.5	0.51	1.12	7.17	15.0	47.71
Mud with admixture of pebbles and gravel	-	7.09	17.0	7.09	17.0	15.05	36.2	5.71	13.7	6.66	16.0	41.60
Sandy mud, gravel, pebbles	-	32.46	46.0	4.62	6.55	17.99	25.6	13.53	19.3	1.88	2.67	70.38
Muddy sand, gravel, pebbles	-	62.69	52.2	18.76	15.6	22.27	18.5	4.16	3.46	12.35	10.2	120.23
Pebbles, gravel, sand, stones, shells	-	15.82	31.7	9.55	19.0	12.22	24.5	1.35	2.70	11.00	22.1	49.94
Rocks	-	470.30	91.0	4.78	0.923	11.90	2.3	0.04	0.007	30.27	5.85	517.29

cies. In the summer of 1975, the first survey was conducted on the shelf between Yakutat Bay and Cape Cleare (H.M.Feder and S.C. Jewett, University of Alaska, unpubl. OCSEAP data on file at NODC; Ronholt *et al.* 1976), and in November 1979 the second survey covered the waters near Icy Bay extending southeasterly to near Lituya Bay (Feder, Jewett, McGee, and Matheke 1981). Portions of the region between Icy Bay and Yakutat Bay were sampled during both surveys.

Only limited information is available on the feeding habits of the epifauna and the demersal fishes of NEGOA (Smith, Paulson, and Rose 1978; Feder, Jewett, McGee, and Matheke 1981). However, feeding data from contiguous areas such as Cook Inlet, the Kodiak Archipelago, and the Kodiak shelf can be used to extrapolate data for NEGOA (Feder, Paul, Hoberg, and Jewett 1981; Rogers, Wangerin, and Rogers 1980; and Feder and Jewett 1981b).

Gulf Embayments and Fjords

The biological systems of these regions are influenced by the oceanographic features of the shelf waters, and particularly by the Alaska Coastal Current (Royer 1981, 1982, 1983; Royer *et al.* 1979). Although few biological investigations of these bodies of water are available, various reports, theses, and papers help to develop a preliminary understanding of these benthic environments.

Infauunal and epifaunal data available for Yakutat Bay are included in:

- Feder and Jewett (University of Alaska, unpubl. data on file at NODC)
- Feder, Jewett, McGee, and Matheke (1981).

Information on the bays and fjords of Prince William Sound, including Port Etches, Zaikof Bay, and Rocky Bay is presented by:

- Feder and Hoberg (1981)
- Hoberg (1986).

Paul and Feder (1975), Hoskin (1977), and Feder and Paul (1977) contain information on:

- Nelson Bay
- Simpson Bay
- Sheep Bay
- Port Gravina
- Port Valdez
- Columbia Bay
- Unaquik Inlet
- Port Wells
- Blackstone Bay
- Blue Fjord
- Derickson Bay
- McClure Bay
- Port Etches

Information on Port Valdez is included in:

- Hood, Shiels, and Kelley (1973)
- Colonell (1980)

Table 12-2.
The biomass distribution of trophic groups found on the shelf of the Gulf of Alaska (Semenov 1965).

TROPHIC GROUP	WESTERN REGION	NORTHERN REGION (NEGOA)	EASTERN REGION	ENTIRE SHELF ZONE
Non-mobile filter feeders				
g/m ²	111.87	13.13	3.2	50.84
%	62.15	20.4	13.8	48.37
Mobile filter feeders				
g/m ²	26.06	4.11	2.5	12.57
%	14.48	6.4	10.8	11.96
Browsing detritus eaters				
g/m ²	15.06	24.05	9.9	18.89
%	8.37	37.4	42.7	17.97
Non-selective detritus consumers				
g/m ²	15.97	18.92	2.1	15.83
%	8.87	29.4	9.1	15.06
Remainder (predators, scavengers)				
g/m ²	11.04	4.09	5.3	6.97
%	6.13	6.4	22.8	6.63
Total biomass				
g/m ²	180.0	64.3	23.2	105.1
No. of stations	24	30	7	61

- Feder and Matheke (1980b)
- Feder, Gosink, Naidu, and Shaw (1983)
- Feder and Shaw (1986)
- Feder and Jewett (in press).

Information on Resurrection Bay is included in:

- Heggie, Boisseau, and Burrell (1977)
- Feder, Paul, and McDonald (1979).

Aialik Bay is covered in material by Feder *et al.* (1979) and Carpenter (1983). Fjords are also reviewed by Pearson (1980) and Burrell (Ch. 7, this volume).

There is an extensive data base on the epifaunal invertebrates of lower Cook Inlet. Exploratory fishing was first undertaken there in 1958 when the Bureau of Commercial Fisheries conducted a demersal trawl survey that targeted shrimp and crab (USDI 1977; Ronholt *et al.* 1978). The status of the commercial shellfish fishery in the Inlet is updated annually by the Alaska Department of Fish and Game (ADF&G 1985b).

The exploration and development of potentially rich sources of petroleum in the Inlet in the early 1970s required further assessment of its abiotic and biotic components. Initial resource surveys made by ADF&G and the U.S. Department of Commerce (ADF&G 1976) were followed by investigations of the larval and/or the adult stages of commercially important shellfish (Hennick 1973; Feder 1977; Haynes 1977; Sundberg and Clausen 1977; Paul, Paul, Shoemaker, and Feder 1979; Paul and Paul 1980; and Feder, McCumby, and Paul 1980). Summaries of the food habits of adult crabs (Tanner, king, and Dungeness) and the food habits of pandalid shrimps in Cook Inlet are included in Crow (1977), Paul, Feder, and Jewett (1979), Feder and Paul (1980), Rice, McCumby, and Feder (1980), and Feder, Paul, Hoberg, and

Jewett (1981). Data on non-commercial, benthic invertebrates were initially not as extensive as those available for commercial species in the Inlet, although some data are included in Rosenberg, Natarajan, and Hood (1969), USDI (1977), and Bakus, Orys, and Hendrick (1979). However, the shallow subtidal region received a great deal of attention initially when it was identified as the region most likely to be impacted by petroleum-related activities (Lees 1976; Rosenthal and Lees 1976; Driskell and Lees 1977; Lees 1978; Lees and Driskell 1981; and Dames and Moore 1981, 1984). An investigation of the biology of crangonid shrimps in deeper water was conducted by Rice (1980), and surveys of infauna and epifauna from various depths throughout lower Cook Inlet are reported in Dames and Moore (1978), Feder and Paul (1981), and Feder, Paul, Hoberg, and Jewett (1981).

Western Shelf

The infauna of the western Gulf is best known from Shevtsov (1964a, b) and Semenov (1965). Additional data in Feder and Jewett (1981b; University of Alaska, unpubl. data) support the findings of the earlier investigations. Most of the biological information on epibenthic invertebrates (mainly non-commercial species) is from trawl surveys conducted on the Kodiak shelf and some of its embayments (Feder and Jewett 1977; 1981b). Shevtsov (1964a, b) and Semenov (1965) present some data on sessile epifauna of rocky-gravel substrates.

The stock status for various commercially important shellfish is presented annually in reports prepared by ADF&G (ADF&G 1985a). The estimated total biomass of the commercial invertebrates from this region for the years 1973 through 1976 was nearly 7.0×10^4 mt—higher than for any other region of the Gulf shelf (Ronholt *et al.* 1978).

Data compilations for the renewable resources of the Kodiak shelf are included in Arctic Environmental Information Data Center (1974) and Science Applications, Inc. (1980) reports. Ronholt *et al.* (1978) present a review of the commercially important invertebrates and fishes of the Kodiak shelf. Both inshore and limited offshore surveys of the Kodiak region examined the distribution of the invertebrate benthos as well as collected data on the food of selected epifaunal invertebrates. The species included were:

- Tanner crab (*Chionoecetes bairdi*)
- red king crab (*Paralithodes camtschatica*)
- pink shrimp (*Pandalus borealis*)
- sea star (*Pycnopodia helianthoides*).

These surveys also covered fishes, including:

- Pacific cod (*Gadus macrocephalus*)
- walleye pollock (*Theragra chalcogramma*)
- sculpins (*Myoxocephalus* spp. and *Hemilepidotus jordani*)
- flathead sole (*Hippoglossoides elassodon*)
- rock sole (*Lepidopsetta bilineata*)
- arrowtooth flounder (*Atheresthes stomias*)
- yellowfin sole (*Limanda aspera*)
- butter sole (*Isopsetta isolepis*)
- Atka mackerel (*Pleurogrammus monopterygius*)
- sablefish (*Anoplopoma fimbria*)

Table 12-3.
The biomass distribution of trophic groups found on the upper continental slope of the Gulf of Alaska (Semenov 1965).

TROPHIC GROUP	WESTERN REGION	NORTHERN REGION	EASTERN REGION	ENTIRE SHELF ZONE
Non-mobile filter feeders				
g/m ²	1.20	1.35	0.03	1.04
%	6.28	2.8	0.2	3.22
Mobile filter feeders				
g/m ²	3.00	0.44	0.22	1.22
%	15.71	0.9	1.5	3.78
Browsing detritus eaters				
g/m ²	9.51	13.66	4.18	10.43
%	49.79	28.2	28.9	32.29
Non-selective detritus consumers				
g/m ²	2.33	20.97	2.31	11.27
%	12.20	43.2	16.0	34.89
Remainder (predators, scavengers)				
g/m ²	3.06	12.08	7.73	8.34
%	16.02	24.9	53.2	25.82
Total biomass				
g/m ²	19.1	48.5	14.5	32.3
No. of stations	8	22	5	25

(Feder and Jewett 1977, 1981b; Jewett and Powell 1979; Jewett and Feder 1982, 1983; and Rogers *et al.* 1980).

Faunal Review by Region

Northeast Gulf of Alaska Shelf

General. Investigations of the shelf (<200 m) and its upper slope, troughs, and canyons (201–400 m) have been conducted primarily between Cape Clear (148°W) and Cape Fairweather (138°W). This portion of the Gulf has a relatively wide shelf (up to 100 km) with several banks or grounds bisected by submarine canyons or troughs (Fig. 12-1). The boundaries of these physiographic features are loosely defined and are based upon bathymetry (Hitz and Rathjen 1965; Science Applications, Inc. 1980). All banks and grounds, with the exception of Tarr Bank, have depths greater than 100 m and less than 200 meters. All troughs and canyons, with the exception of Egg Island Trough, are deeper than 200 meters.

The dominant shelf sediment is clayey silt that comes primarily from either the Copper River or from the Bering and the Malaspina Glaciers (Molnia and Carlson 1980; Hampton, Carlson, Lee, and Feely, Ch. 5, this volume). Once sediments enter the Gulf, they are generally transported to the west. High sedimentation rates throughout most of the shelf result in poorly consolidated sediments. Few sediments accumulate on the relatively shallow Tarr Bank because of scouring by strong bottom currents and frequent winter storm waves. Sand predominates nearshore, especially near the Copper River and the Malaspina Glacier (Carlson, Molnia, Kittelson, and Hampson 1977).

Infauna. Feder and Matheke (1980a) described over 400 invertebrate taxa from the shelf, representing eleven phyla. Fifteen taxa (primarily annelids and mollusks) occurred at 50% or more of the stations while 28 taxa (from eight phyla) represented 10% or more of the wet weight at one or more stations (Tables 12-4 and 12-5). Infaunal abundance on the shelf for the period 1974 to 1976 (Feder and Matheke 1980a) ranged from 67 to 1,654 individuals/m²; the biomass ranged from 7 to 776 g/m².

The mean abundance/biomass values for the major Shelf groups (Fig. 12-2) determined by Feder and Matheke (1980a) are given in Table 12-6. The mean diversity and species richness among station groups were highest in the region of Tarr Bank and the shelf break (Table 12-6). Among the major station groups (Feder and Matheke 1980a), the percentage of sessile organisms was relatively low inshore (32%), increased at the shelf break (44%), and was highest at Tarr Bank (53%).

Hickman and Nesbitt (1980) describe three recurring mollusk associations in the northern Gulf: 1) a shallow-water *Yoldia-Siliqua-Lyonsia* sand association, 2) a shallow-to-intermediate depth *Cyclocardia*-boreal turrid mud association (with a typical phase developing in offshore muds and a *Clinocardium-Nitidella* nearshore mud phase associated with Yakutat and Icy Bays), and 3) a deep-water *Cadulus* thin-shelled protobranch mud association. They report an abrupt faunal break at 180 m, separating the typical *Cyclocardia*-boreal turrid mud association from the *Cadulus* thin-shelled protobranch mud association. Although the two mud associations have species in common, many species drop out as the 180 m isobath is approached, and other species appear at or not far below it.

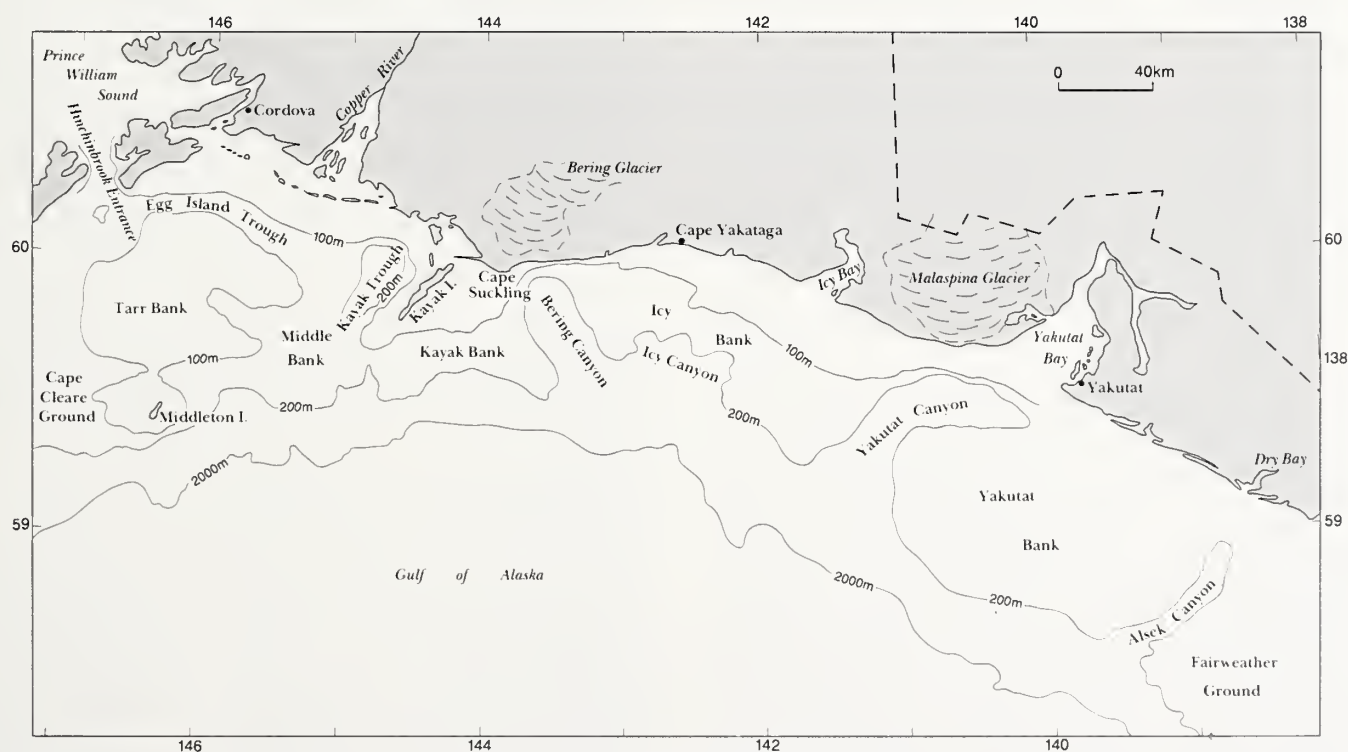


Figure 12-1. Shelf of the northeast Gulf of Alaska showing major physiographic features.

Shevtsov (1964a, b) found that the trophic zonation of infauna was well expressed in the Gulf, and noted that east of Kodiak Island the biomass of the shelf benthos decreased abruptly. This decrease was at the expense of suspension (filter) feeders which reached their highest biomass values (77% of the total) in the western Gulf. The biomass consisted mainly of deposit (detritus) feeders in the northeast

Table 12-4.

Taxa occurring at 50% or more of the stations sampled with a van Veen grab in the northeast Gulf of Alaska (NEGOA), Port Valdez, lower Cook Inlet, and Aialik Bay (Feder, Mueller, Matheke, and Jewett 1976; Feder 1979; Feder, Paul, Hoberg, and Jewett 1981; and Carpenter 1983).

TAXA	NEGOA	PORT VALDEZ	COOK INLET	AIALIK BAY
Annelida				
<i>Eteone longa</i>			+	
<i>Glyptis brevipalpa</i>		+		
<i>Nephtys punctata</i>	+	+		+
<i>Nephtys ciliata</i>			+	
<i>Nephtys cornuta</i>				+
<i>Nephtys longasetosa</i>			+	
<i>Onuphis irridescens</i>	+			
<i>Goniada annulata</i>		+		
<i>Glycera capitata</i>			+	
<i>Glycinde picta</i>			+	
<i>Lumbrineris</i> spp.	+	+	+	+
<i>Aricidea lopezi</i>		+		
<i>Ninoe gemma</i>		+		
<i>Haploscoloplos elongatus</i>			+	
<i>Prionospio malmgreni</i>		+	+	
<i>Magelona</i> sp.			+	
<i>Polydora</i> sp.				+
<i>Tharyx</i> sp.		+		+
<i>Sternaspis scutata</i>	+	+		
<i>Heteromastus filiformis</i>		+		+
<i>Praxillella gracilis</i>	+	+		
<i>Maldane glebifex</i>				+
<i>Scalibregma inflatum</i>			+	
<i>Myriochele heeri</i>	+		+	+
<i>Myriochele oculata</i>		+		+
<i>Amphicteis gunneri</i>		+		
<i>Lysippe labiata</i>				+
<i>Arlacama conifera</i>				+
<i>Terebellides stroemi</i>		+	+	+
<i>Disoma multisetosum</i>			+	+
<i>Melinna cristata</i>			+	+
Ampharetidae				+
Mollusca				
<i>Chaetoderma robusta</i>	+	+		+
<i>Nucula tenuis</i>	+		+	+
<i>Nuculana fossa</i>	+	+		+
<i>Yoldia</i> sp.	+	+		
<i>Axinopsida</i> spp.		+	+	+
<i>Macoma calcarea</i>			+	
Turridae				+
<i>Solariella</i> sp.			+	
<i>Thyasira flexuosa</i>	+			
<i>Odontogena borealis</i>	+			
<i>Psephidia lordi</i>	+			
<i>Cylichna alba</i>		+		
<i>Dentalium dalli</i>		+		
Arthropoda				
<i>Eudorella emarginata</i>		+		+
<i>Ampelisca macrocephala</i>			+	
<i>Byblis gaimardi</i>			+	
Echinodermata				
<i>Ctenodiscus crispatus</i>	+	+		
<i>Ophiura sarsi</i>	+			

Table 12-5.

Taxa representing 10% of the wet weight at one or more stations sampled with a van Veen grab in the northeast Gulf of Alaska (NEGOA), Port Valdez, lower Cook Inlet, and Aialik Bay (Feder, Mueller, Matheke, and Jewett 1976; Feder 1979; Feder, Paul, Hoberg, and Jewett 1981; and Carpenter 1983).

TAXA	NEGOA	PORT VALDEZ	COOK INLET	AIALIK BAY
Porifera	+			
Cnidaria				
Anemones	+			
<i>Ptilosarcus gurneyi</i>	+			
Alcyonacea				+
Annelida				
<i>Ancistrosyllis</i> sp.				+
<i>Nephtys</i> spp.		+		
<i>Nephtys punctata</i>	+			+
<i>Nephtys ciliata</i>				+
<i>Nephtys longasetosa</i>				+
<i>Goniada annulata</i>		+		
<i>Travisia brevis</i>				+
<i>Lumbrineris</i> spp.	+	+		
<i>Flabelligera mastigophora</i>		+		
<i>Sternaspis scutata</i>	+	+		
<i>Heteromastus filiformis</i>				+
<i>Praxillella gracilis</i>	+	+	+	
<i>Maldane glebifex</i>				+
<i>Myriochele heeri</i>	+			
<i>Myriochele oculata</i>		+		
<i>Terebellides stroemi</i>		+		
<i>Melinna cristatus</i>				+
<i>Amphicteis gunneri</i>		+		
Mollusca				
<i>Nuculana fossa</i>	+	+		
<i>Nuculana</i> sp.			+	+
<i>Yoldia thraciaformis</i>		+		
<i>Yoldia scissurata</i>	+			
<i>Yoldia secunda</i>	+			
<i>Yoldia montereyensis</i>		+		
<i>Axinopsida serricata</i>				+
<i>Clinocardium ciliatum</i>		+		
<i>Clinocardium</i> sp.				+
<i>Astarte alaskensis</i>	+			
<i>Astarte polaris</i>	+	+		
<i>Astarte esquimalti</i>	+			
<i>Glycymeris subobsoleta</i>				+
<i>Macoma brota</i>		+		
<i>Macoma calcarea</i>	+			+
<i>Macoma moesta alaskana</i>				+
<i>Tellina nuculoides</i>				+
<i>Natica clausa</i>				+
<i>Polinices pallida</i>				+
Arthropoda				
<i>Scalpellum</i> sp.	+			
<i>Balanus nubilis</i>	+			
<i>Balanus balanoides</i>				+
<i>Balanus crenatus</i>				+
Sipuncula				
<i>Golfingia margaritacea</i>	+	+		
Brachiopoda				
<i>Laqueus californianus</i>	+			
<i>Terebratalia transversa</i>	+			
Echinodermata				
<i>Echinarachnius parma</i>				+
<i>Strongylocentrotus</i> sp.	+			
<i>Brisaster townsendi</i>	+			+
<i>Ctenodiscus crispatus</i>	+	+		
<i>Unioplus macraspis</i>	+			
<i>Ophiocantha</i> sp.	+			
<i>Ophiopholis aculeata</i>	+			
<i>Ophiura sarsi</i>	+	+		
<i>Molpadia intermedia</i>	+			

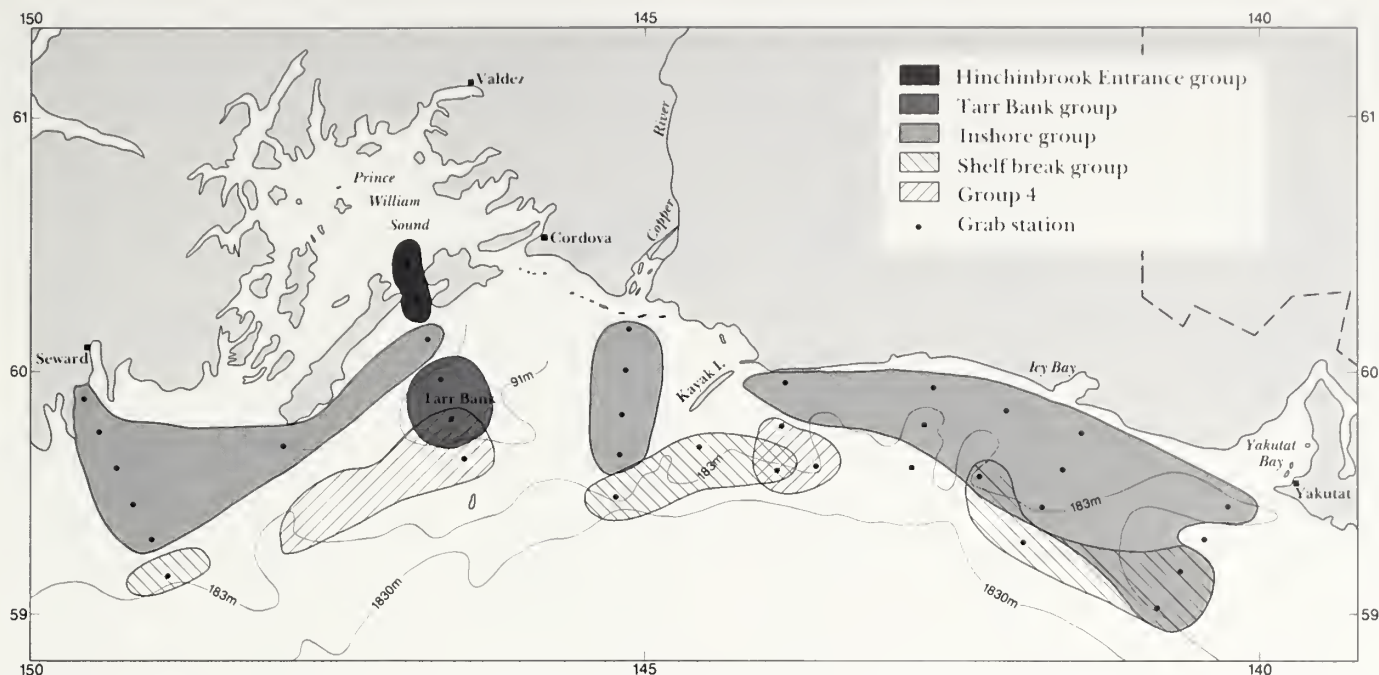


Figure 12-2. Major station groups formed by cluster analysis of 1974 to 1976 \ln -transformed infaunal data from the shelf of the northeast Gulf of Alaska. (Modified from Feder and Matheke 1980a.) At stations where samples were not always classified in the same station groups, two station groups overlap.

Gulf (67% of the total biomass) while suspension (filter) feeders represented only 27% of the total (Semenov 1965) (Table 12-2).

Deposit feeders dominated the abundance and biomass in all regions on the northeastern shelf (except Tarr Bank) that were investigated by Feder and Matheke (1980a) (Tables 12-7 and 12-8). Non-selective deposit feeders were most common in the canyons (such as Yakutat and Alsek), and on the continental slope. East of Yakutat Bay to the Queen Charlotte Islands, browsing detritus feeders (browsers and selective deposit feeders) were common. Suspension feeders were not common over most of the NEGOA shelf. However, the numbers and the biomass of species such as the sea pen (*Ptilosarcus gurneyi*) increased on both Tarr and Yakutat Banks, as well as off the Copper River (Station Group 6) (Figs. 12-1 and 12-2).

Table 12-6.

Mean abundance, biomass, and diversity of the fauna of station groups shown in Figure 12-2 and Station groups 5, 6, 42 (Tables 12-7, 12-8) of NEGOA delineated in a cluster analysis of combined grab data (July 1974–March 1976). Biomass values are in formalin wet weight (based on Feder and Matheke 1980a).

STATION GROUP	ABUNDANCE (No./m ²)	BIOMASS (g/m ²)	SHANNON DIVERSITY	SPECIES RICHNESS
Inshore Group	424	152	3.1	6.8
Shelf Break Group	625	46	3.6	11.1
Tarr Bank Group	1,040	302	3.8	15.0
Hinchinbrook Entrance Group	947	417	2.9	8.0
Station Group 4	709	68	3.2	9.0
Station Group 6	280	83	2.7	6.0
Station Group 5	258	39	3.0	6.5
Station Group 42	605	77	3.2	9.3

Infaunal carbon production estimates (H.M. Feder, University of Alaska, unpubl. data) were calculated by using the carbon-conversion values from Stoker (1978) and the P/B values from Stoker (1978), Robertson (1979), and Warwick (1980). Estimates for NEGOA station groups (Feder and Matheke 1980a) are:

- Hinchinbrook Entrance Group: 4.6 g C/m²y
- Inshore Group: 2.2 g C/m²y
- Tarr Bank Group: 9.3 g C/m²y
- Shelf Break Group: 1.9 g C/m²y.

The mean infaunal production for the NEGOA shelf is estimated as 4.5 g C/m²y (Table 12-9). Assuming that the microfloral/meiofaunal production rate is twice that of the macrofauna (Parsons, Ch. 18, this volume), and further assuming that epifaunal production on the shelf is 0.12 g C/m²y (H.M. Feder, University of Alaska, unpubl. data), then the total benthic production for the NEGOA shelf is estimated at 13.7 g C/m²y.

No discrete infaunal communities, such as those described by Petersen and Jensen (1911) and Thorson (1957), were identified in NEGOA by Feder and Matheke (1980a). In fact, the data suggest that species distribute themselves independently along environmental gradients (Whittaker 1970). It took a minimum of 28 species groups in order to describe the spatial distribution patterns found during a single month period, and it took 53 species groups to describe both the spatial and the temporal distribution patterns over a 21-month period. Moreover, there was variation in the species abundance patterns of species within these groups.

As the amount of sand and gravel in the sediment increased, faunal abundance changed, and there was an increase in both diversity and species richness. This indicates that sediment size is a major factor in controlling spe-

Table 12-7.

Dominant taxa (number/m²) in the major shelf groups of NEGOA determined by cluster analysis (Feder and Matheke 1980a). All samples collected by van Veen grab (see Fig. 12-2).

TAXA	FEEDING CLASS ^a	ABUNDANCE (No./m ²)	TAXA	FEEDING CLASS	ABUNDANCE (No./m ²)
Inshore Group			Group 42		
<i>Nucula tenuis</i>	DF	37	<i>Nucula tenuis</i>	DF	73
<i>Myriochele heeri</i>	DF	22	<i>Psephidia lordi</i>	SF	56
<i>Psephidia lordi</i>	SF	20	<i>Myriochele heeri</i>	DF	30
<i>Sternaspis scutata</i>	DF	20	<i>Spiophanes cirrata</i>	DF	22
<i>Axinopsida serricata</i>	SF	17	<i>Spio filicornis</i>	DF	18
<i>Lumbrineris similabris</i>	DF/P	17	<i>Lumbrineris zonata</i>	B	19
<i>Nuculana fossa</i>	DF	15	<i>Maldanae sarsi</i>	DF	18
<i>Ophiura sarsi</i>	DF/B/P	13	<i>Ophiura sarsi</i>	DF/B/P	12
Hinchinbrook Entrance Group			Tarr Bank Group		
<i>Ophiura sarsi</i>	DF/B	198	Ectoprocta	SF	192
<i>Sternaspis scutata</i>	DF	125	<i>Peisidice aspera</i>	S	56
<i>Eudorelloopsis integra</i>	DF	52	<i>Crenella decussata</i>	SF	42
<i>Eudorella emarginata</i>	DF	41	<i>Terebratulina unguicula</i>	SF	31
<i>Spiophanes cirrata</i>	DF	38	<i>Golfingia margaritacea</i>	DF	20
<i>Myriochele heeri</i>	DF	33	<i>Laqueus californianus</i>	SF	20
Group 4			Shelf Break Group		
<i>Ophiura sarsi</i>	DF/B/P	114	<i>Golfingia margaritacea</i>	DF	55
<i>Psephidia lordi</i>	SF	112	Ectoprocta	SF	37
<i>Crenella decussata</i>	SF	55	<i>Ophiura sarsi</i>	DF/B/P	25
<i>Cyclocardia ventricosa</i>	SF	29	Amphipoda	S	17
<i>Nucula tenuis</i>	DF	25	<i>Axinopsida serricata</i>	SF	17
<i>Cyclocardia crebricostata</i>	SF	25	<i>Odontogena borealis</i>	SF/DF	16

^a DF = deposit feeder; SF = suspension feeder; B = browser; P = predator; S = scavenger.

Table 12-8.

Dominant taxa (wet weight in g/m²) in the shelf groups of NEGOA determined by cluster analysis (Feder and Matheke 1980a). All samples collected by van Veen grab (see Fig. 12-2).

TAXA	FEEDING CLASS ^a	BIOMASS	TAXA	FEEDING CLASS	BIOMASS
Inner Shelf			Group Group 42		
<i>Molpadia intermedia</i>	DF	53	<i>Ophiura sarsi</i>	DF/B/P	21
<i>Ctenodiscus crispatus</i>	DF	15	<i>Ophiopholis aculeata</i>	SF/DF	10
<i>Brisaster townsendi</i>	DF	11	<i>Ctenodiscus crispatus</i>	DF	5
<i>Ophiura sarsi</i>	DF/B/P	5	<i>Myriochele heeri</i>	DF	2
Hinchinbrook Entrance Group			Tarr Bank Group		
<i>Molpadia intermedia</i>	DF	270	Anthozoa	P	9
<i>Ophiura sarsi</i>	DF/B/P	31	Unidentified brachiopod	SF	5
<i>Macoma brota</i>	DF	7	Virgulariidae	P	4
<i>Sternaspis scutata</i>	DF	4	<i>Ophiura sarsi</i>	DF/B/S	4
Group 4			Porifera	SF	4
<i>Ophiura sarsi</i>	DF/B/P	18	<i>Molpadia intermedia</i>	DF	3
<i>Golfingia margaritacea</i>	DF	3	Shelf Break Group		
Porifera	SF	3	<i>Golfingia margaritacea</i>	DF	5
Anthozoa	P	21	<i>Brisaster townsendi</i>	DF	5
Station Group 6			<i>Ophiura sarsi</i>	DF/B/S	4
<i>Ptilosarcus gurneyi</i>	SF/P	73	Group 5		
<i>Mitrella gouldi</i>	U	1	<i>Brisaster townsendi</i>	DF	16
<i>Pinnixa schmitti</i>	U	1	<i>Unio plus macraspis</i>	DF	3
<i>Nuculana fossa</i>	DF	1	<i>Sternaspis scutata</i>	DF	1

^a DF = deposit feeder; SF = suspension feeder; B = browser; P = predator; S = scavenger; U = unknown.

Table 12-9.

Mean biomass and production estimates of benthos from selected stations in the four major station groups of NEG OA, based on a cluster analysis of combined data (1974-1976) (Feder and Matheke 1980a). Differences in mean biomass values from Table 12-6 reflect the bias of specific stations within each station group selected for production estimations.

STATION GROUP	DOMINANT FEEDING TYPE ^a	BIOMASS (g/m ²)	CARBON ^b (g C/m ²)	PRODUCTION ^b (g C/m ² y)	CARBON REQUIRED/YEAR (10% CONVERSION EFFICIENCY)
1. Macrofauna ^c					
Inshore Group	DF	164	3.6	2.2	22
Shelf Break Group	Mixed SF/DF	48	1.1	1.9	19
Tarr Bank	SF	245	7.4	9.3	93
Hinchinbrook Entrance	Mixed SF/DF	<u>343</u>	<u>7.1</u>	<u>4.6</u>	<u>46</u>
\bar{x} of selected stations		200	4.8	4.5	45
2. Microflora and meiofauna (assuming production twice that of macrofauna; Schwinghammer 1981)					
	-	-	-	9.0	90
3. Mobile Epifauna ^d Mean value for shelf (Feder and Jewett, unpubl. data). A P/B value of 2.0 was applied					
	-	2.1	0.12	0.24	2.4
Total (macrofauna + epifauna + meiofauna)				13.7	92

^a DF = deposit feeder; SF = suspension feeder.

^b Calculations based on biomass data of Feder and Matheke (1980a) and literature values for carbon and P/B values (Stoker 1978; Robertson 1979; and Warwick 1980).

^c All organisms collected by van Veen grab.

^d All organisms collected by trawl.

cies distribution. However, variations in the distribution patterns for individual species (especially within the species groups that characterize silt-clay environments) indicate that environmental conditions other than grain size and deposition rate affect their distribution. This is also suggested for the distribution of species within the recurrent mollusk associations identified by Hickman and Nesbitt (1980). Thus, it appears that by delineating station groups in NEG OA, we identified the largest discontinuities in an otherwise near continuum of species distributions (Stephenson 1973; Feder and Matheke 1980a).

Epifauna. Surveys in the northeastern Gulf during 1975 and 1979 yielded ~180 epifaunal species representing ten phyla (H.M. Feder and S.C. Jewett, University of Alaska, unpubl. OCSEAP data on file at NODC; Feder, Jewett, McGee, and Matheke 1981). Mollusks, arthropods, and echinoderms dominated both the species representation and the biomass. For this region, a general trend of decreasing epifaunal biomass was apparent from west to east at all depths (Table 12-10). Based upon the 1975 survey, epifaunal biomass from stations between 148° and 144°30'W and 144°30' and 140°W were 2.4 g/m² and 1.2 g/m², respectively (Table 12-10). Biomass values from the 1979 sampling were 2.6 g/m² between 144°30' and 140°W and 1.1 g/m² between 140° and 137°30'W. The high value of 2.6 g/m² between 144°30' and 140°W in 1979 was attributed to an unusually large catch of Dungeness crab (*Cancer magister*) outside of Icy Bay.

The highest biomass values occurred west of Kayak Island, specifically in the vicinities of Hinchinbrook Entrance off Prince William Sound and immediately west of Kayak Island. The substratum at these locations reflected a

depositional environment consisting mainly of silt and clay (Carlson *et al.* 1977). These regions were dominated at all depths by the predator/scavenger Tanner crab, *Chionoecetes bairdi* (Tables 12-10 through 12-12). Five stations outside Hinchinbrook Entrance yielded ~1.4 mt of mainly sub-adult and adult crabs in five hours of trawling. Crab biomass at these five stations collectively was 4.0 g/m², representing 86% of the total epifaunal biomass.

West of Kayak Island, in the vicinity of Kayak Trough and Middle Bank, Tanner crab accounted for 86% of the epifaunal biomass at eight selected stations (H.M. Feder and S.C. Jewett, University of Alaska, unpubl. data on file at NODC). Tanner crab biomass for these eight stations collectively was 4.1 g/m², with the highest value (6.0 g/m²) within the trough. The crab composition in this vicinity varied from station to station with no apparent pattern of size, sex, or maturity emerging for a particular depth or area. Other benthic organisms that exhibited high standing stocks near the west side of Kayak Island were the pink shrimp, *Pandalus borealis*, and the mud star, *Ctenodiscus crispatus* (Tables 12-10 and 12-11).

Long-term trends in the relative magnitude of Tanner crab within NEG OA can be shown by comparing the crab catch per unit of effort (CPUE in kg/h) for the 1961-1962 surveys by the IPHC and the 1973 to 1976 surveys by the NMFS (Ronholt *et al.* 1978). Although the population in some regions decreased while in others it increased, there was no marked change in the CPUE for Tanner crab within the Gulf of Alaska as a whole during the period from 1961 through 1976.

The shelf region south of Prince William Sound (148°-144°30'W) was the only region that showed a marked increase in the CPUE for Tanner crab during this period. In

Table 12-10.
Dominant fauna taken by trawl in NEGOA in 1975 and 1979.

DEPTH (m)	TOTAL STATIONS SAMPLED	AREA ^a SAMPLED (km ²)	TOTAL INVERTEBRATE BIOMASS (g/m ²)	DOMINANT TAXA	PERCENT OF AREA BIOMASS
148°-144°30'W 1975 ^b					
≤100	16	1.032	3.6	<i>Chionoecetes bairdi</i> <i>Pandalus borealis</i>	48.3 13.1
101-200	51	3.529	1.9	<i>Halocynthia helgendorfi igaboja</i> <i>Chionoecetes bairdi</i> <i>Ctenodiscus crispatus</i> <i>Pandalus borealis</i>	6.8 74.5 6.9 4.6
201-400	5	0.366	4.0	<i>Chionoecetes bairdi</i> <i>Ctenodiscus crispatus</i>	82.5 9.4
All depths	72	4.927	2.4	<i>Chionoecetes bairdi</i> <i>Pandalus borealis</i> <i>Ctenodiscus crispatus</i>	67.4 6.7 5.3
144°30'-140°W 1979 ^c					
≤100	3	0.102	6.9	<i>Cancer magister</i> <i>Pecten caurinus</i> <i>Pycnopodia helianthoides</i>	50.0 37.2 7.4
101-200	7	0.244	2.1	Cucumaridae <i>Strongylocentrotus droebachiensis</i> Porifera <i>Alloccentrotus fragilis</i>	3.8 44.3 26.4 8.9
201-400	6	0.183	0.9	Cucumaridae Porifera <i>Rossia pacifica</i> <i>Berryteuthis magister</i>	4.8 79.1 5.5 4.8
All depths	16	0.529	2.6	<i>Cancer magister</i> Porifera <i>Pecten caurinus</i> <i>Strongylocentrotus droebachiensis</i> Cucumaridae <i>Alloccentrotus fragilis</i>	25.3 19.3 18.8 16.6 3.8 3.4

^a Trawl opening width = 12.2 m.

^b 1975 trawl survey (H.M. Feder and S.C. Jewett, University of Alaska, unpubl. OCSEAP data on file with NODC).

^c 1979 trawl survey (Feder, Jewett, McGee, and Matheke 1981).

this region, increases were seen at all depth zones—on the inner shelf (0–100 m), on the outer shelf (101–200 m), and on the upper slope (201–400 m). Nearly 40% of the total estimated biomass of Tanner crab from the Gulf of Alaska shelf came from this region south of Prince William Sound.

In 1976, two new fishing districts were established by ADF&G for Tanner crab outside Prince William Sound. These districts were between Cape Fairfield (western entrance of the Sound) and Cape Suckling (west of Kayak Island). A north–south line from Hinchinbrook Entrance separated the two districts. The combined Tanner crab harvests from both districts increased from 351 mt in 1976–1977 to 2,509 mt in 1979–1980, when it peaked. Since that peak year, the harvest from both districts continued to fall to 439.5 mt in 1982–1983 (ADF&G 1985c). The 1983–1984 season brought a closure to the western district,

as well as to the Sound. Although the eastern district remained open in 1984, fishermen accepted the gloomy forecast and did not fish. Management biologists are unable to determine which specific factors are responsible for the population decline in this once-productive Tanner crab region although they suspect unfavorable environmental conditions (ADF&G 1985c).

In addition to the Tanner crab, the mud star was one of the most ubiquitous species on the shelf and was a dominant contributor to the biomass. It occurred mostly at depths greater than 100 m—in canyons and troughs as well as on banks and grounds. This non-selective deposit-feeding asteroid feeds on the organic material associated with the mud it ingests. It either dominated, or was second in total biomass in four canyons/troughs: Kayak, Icy, Yakutat, and Alsek. It was also very abundant at shallower depths in loca-

DEPTH (m)	TOTAL STATIONS SAMPLED	AREA ^a (km ²)	TOTAL INVERTEBRATE BIOMASS (g/m ²)	DOMINANT TAXA	PERCENT OF AREA BIOMASS
144°30'–140°W 1975 ^b					
≤ 100	17	1.118	1.2	<i>Chionoecetes bairdi</i> <i>Pycnopodia helianthoides</i> <i>Pecten caurinus</i>	39.1 24.0 19.4
101–200	29	2.017	0.7	<i>Ctenodiscus crispatus</i> <i>Chionoecetes bairdi</i> Cucumaridae <i>Lopholithodes foraminatus</i> <i>Pycnopodia helianthoides</i>	14.7 8.4 8.0 8.0 6.0
201–400	12	0.826	2.5	<i>Brisaster townsendi</i> <i>Ctenodiscus crispatus</i> <i>Alloccentrotus fragilis</i>	71.9 2.8 1.9
All depths	58	3.961	1.2	<i>Brisaster townsendi</i> <i>Chionoecetes bairdi</i> <i>Pycnopodia helianthoides</i> <i>Pecten caurinus</i> <i>Ctenodiscus crispatus</i>	29.8 13.8 8.6 5.9 5.8
140°–137°30'W 1979 ^c					
≤ 100	10	0.361	1.6	<i>Metridium senile</i> <i>Pecten caurinus</i> <i>Pycnopodia helianthoides</i>	47.7 31.3 7.9
101–200	12	0.451	1.1	<i>Chionoecetes bairdi</i> <i>Strongylocentrotus droebachiensis</i> <i>Alloccentrotus fragilis</i> <i>Fusitriton oregonensis</i>	34.5 32.8 5.8 3.1
201–400	4	0.122	0.3	<i>Brisaster townsendi</i> <i>Fusitriton oregonensis</i> <i>Ctenodiscus crispatus</i> <i>Alloccentrotus fragilis</i>	39.4 30.4 8.1 4.4
All depths	26	0.905	1.1	<i>Metridium senile</i> <i>Pecten caurinus</i> <i>Chionoecetes bairdi</i> <i>Strongylocentrotus droebachiensis</i> <i>Alloccentrotus fragilis</i> <i>Fusitriton oregonensis</i>	25.4 17.6 15.3 14.0 2.7 2.5

tions such as Cape Cleare Ground, Egg Island Trough, Middle Bank, and Icy Bank (Tables 12–10 and 12–12). Quantities of this small (< 5 cm diameter) sea star are presumed to be underestimated when sampled by trawls.

Although most of Tarr Bank was untrawlable, seven stations were sampled. Two stations along the northwest portion of the Bank exhibited extremely diverse macrofauna with 58 epifaunal taxa being identified in the 65- to 70-m depth range. Nearly two-thirds of the species were scavengers/predators; the remaining one-third were suspension feeders. The dominant taxa were Tanner crab, the ascidian *Halocynthia hilgendorfi igaboja*, and the green sea urchin, *Strongylocentrotus droebachiensis*. *Halocynthia* was attached to a substrate of small (~ 4 cm diameter), rounded rocks. Nearly 245 kg (4.5 g/m²) of this suspension-feeding organism were taken in one hour. In shallow subtidal regions *Strongylo-*

centrotus is characterized as a grazer; however, at greater depths it presumably feeds by browsing and scavenging. The Pacific halibut, *Hippoglossus stenolepis*, was the only abundant fish at the stations. Halibut averaged 18.5 kg per individual at these two stations—with 1,399 kg taken per hour. Stations on the eastern and southern portions of Tarr Bank were dominated by Tanner crab, pink shrimp, and the mud star.

The basket star *Gorgonocephalus caryi* was one of the species which dominated the epifaunal biomass at three banks/grounds. This species accounted for 1.5, 2.0, and 5.6% of the respective biomasses at Cape Cleare Ground, Middle Bank, and Icy Bank (Table 12–11). It resides in areas of rapid currents and relatively solid substrates, and feeds using a combination of predation, suspension feeding, and browsing (Patent 1970) (Table 12–12).

Table 12-11.
 Dominant fauna taken by trawl from the major physiographic regions of NEG OA in 1975^a and 1979^b.

AREA	DEPTH (m)	TOTAL STATIONS SAMPLED	AREA ^c SAMPLED (km ²)	AREA BIOMASS (g/m ²)	DOMINANT TAXA	PERCENT OF AREA BIOMASS
Cape Cleare Ground (1975)	101-197	21	1.490	1.4	<i>Chionoecetes bairdi</i>	68.5
					<i>Ctenodiscus crispatus</i>	8.7
					<i>Gorgonocephalus caryi</i>	1.5
					<i>Pandalus borealis</i>	1.3
					<i>Fusitriton oregonensis</i>	1.0
Egg Island Trough (1975)	101-132	10	0.705	2.8	<i>Chionoecetes bairdi</i>	87.8
					<i>Ctenodiscus crispatus</i>	4.1
					<i>Pandalus borealis</i>	3.9
					<i>Chionoecetes bairdi</i>	41.6
					<i>Halocynthia helgendorfi igaboja</i>	13.6
Tarr Bank (1975)	65-96	7	0.400	4.7	<i>Strongylocentrotus droebachiensis</i>	10.5
					<i>Pandalus borealis</i>	7.5
					<i>Ctenodiscus crispatus</i>	1.1
					<i>Chionoecetes bairdi</i>	75.7
					<i>Ctenodiscus crispatus</i>	7.7
Middle Bank (1975)	102-188	17	1.127	2.3	<i>Pandalus borealis</i>	7.3
					<i>Gorgonocephalus caryi</i>	2.0
					<i>Ophiura sarsi</i>	0.7
					<i>Chionoecetes bairdi</i>	86.2
					<i>Ctenodiscus crispatus</i>	9.2
Kayak Trough (1975)	202-222	2	0.142	5.8	<i>Neptunea lyrata</i>	1.5
					<i>Chionoecetes bairdi</i>	21.9
					<i>Pecten caurinus</i>	21.4
					<i>Lopholithodes foraminatus</i>	10.5
					<i>Pandalus borealis</i>	10.1
Kayak Bank (1975)	119-191	7	0.506	0.6	<i>Ctenodiscus crispatus</i>	6.9
					<i>Ophiura sarsi</i>	3.7
					<i>Alloccentrotus fragilis</i>	31.2
					<i>Brisaster townsendi</i>	15.6
					<i>Lithodes aequispina</i>	12.5
Bering Canyon (1975)	298-306	2	0.167	0.4	<i>Actiniidae</i>	8.6
					<i>Dipsacaster borealis</i>	1.3
					<i>Ctenodiscus crispatus</i>	26.3
					<i>Pycnopodia helianthodes</i>	11.1
					<i>Chionoecetes bairdi</i>	9.5
Icy Bank (1975)	113-182	20	1.360	0.6	<i>Gorgonocephalus caryi</i>	5.6
					<i>Ophiura sarsi</i>	4.2
					<i>Fusitriton oregonensis</i>	2.0
					<i>Lopholithodes foraminatus</i>	1.7
					<i>Ctenodiscus crispatus</i>	56.3
Icy Canyon (1975)	222-226	1	0.072	0.2	<i>Mediaster aequilis</i>	11.2
					<i>Pandalopsis dispar</i>	8.4
					<i>Brisaster townsendi</i>	83.9
					<i>Ctenodiscus crispatus</i>	2.8
					<i>Alloccentrotus fragilis</i>	1.2
Yakutat Canyon (1975)	209-312	9	0.623	2.8	<i>Rossia pacifica</i>	32.2
					<i>Berryteuthis magister</i>	28.3
					<i>Dipsacaster borealis</i>	9.3
					<i>Alloccentrotus fragilis</i>	4.3
					<i>Cucumaridae</i>	19.8
Outer Yakutat Canyon (1979)	284-351	5	0.163	0.2	<i>Lopholithodes foraminatus</i>	12.7
					<i>Alloccentrotus fragilis</i>	4.0
					<i>Chionoecetes bairdi</i>	3.2
					<i>Strongylocentrotus droebachiensis</i>	1.7
					<i>Fusitriton oregonensis</i>	1.6
Yakutat Bank (1975)	130-150	5	0.606	1.7	<i>Ctenodiscus crispatus</i>	1.0
					<i>Strongylocentrotus droebachiensis</i>	49.6
					<i>Chionoecetes bairdi</i>	22.1
					<i>Lopholithodes foraminatus</i>	7.4
					<i>Alloccentrotus fragilis</i>	7.4
Yakutat Bank (1979)	110-156	15	0.542	1.4	<i>Fusitriton oregonensis</i>	2.9
					<i>Strongylocentrotus droebachiensis</i>	39.5
					<i>Brisaster townsendi</i>	8.8
					<i>Fusitriton oregonensis</i>	8.1
					<i>Ctenodiscus crispatus</i>	8.1
Elsek Canyon (1979)	209-263	4	0.122	0.3	<i>Pandalopsis dispar</i>	3.4
					<i>Alloccentrotus fragilis</i>	2.9

AREA	DEPTH (m)	TOTAL STATIONS SAMPLED	AREA ^a SAMPLED (km ²)	AREA BIOMASS (g/m ²)	DOMINANT TAXA	PERCENT OF AREA BIOMASS
Fairweather Ground (1979)	113–166	3	0.095	0.3	<i>Alloctrotus fragilis</i>	45.0
					<i>Lopholithodes foraminatus</i>	16.2
					<i>Fusitriton oregonensis</i>	7.3
					<i>Rossia pacifica</i>	2.5

^a 1975 trawl survey (H.M. Feder and S.C. Jewett, University of Alaska, unpubl. OCSEAP data on file at NODC).

^b 1979 trawl survey (Feder, Jewett, McGee, and Matheke 1981).

^c Trawl opening width = 12.2 m.

The brittle star *Ophiura sarsi* is an organism not adequately sampled with large trawls. However, when concentrations are high, it is quite conspicuous, and trawl sampling allows a glimpse of their distribution and relative abundance. The area where they made up the greatest biomass was on Middle Bank, ~15 km west of the southern end of Kayak Island. This area yielded 11.3 kg per hour or 0.2 g/m² of this brittle star. This equates to a catch rate of ~2,000 individuals per hour. *Ophiura* is a deposit feeder/scavenger/predator (Kyte 1969), but may occasionally engulf sediment and detritus. It is preyed upon by a number of bottom-feeding species, among which the sunflower sea star, *Pycnopodia helianthoides*, and the flathead sole, *Hippoglossoides elassodon*, are predominant.

The broad region between Kayak Island and Lituya Bay generally displayed a low epifaunal biomass (Table 12–11). During 1975 and 1979, 58 and 42 stations, respectively, were sampled east of 144°30' West. Of these stations, only 14 yielded values exceeding 3 g/m². Three of these stations were in shallow waters (28–73 m) between Cape Yakataga and Yakutat Bay, six were within (and at the mouth of) Yakutat Canyon, three were on Yakutat Bank, and two were at shallow depths (62–64 m) nearshore between Dry and Lituya Bays.

Weathered scallops, *Pecten caurinus*, Tanner and Dungeness crabs, and sunflower sea stars were the dominant species at stations between Cape Yakataga and Yakutat Bay. A dense bed of scallops was found seaward of Icy Bay and landward of Icy Canyon. The scallop concentration here was 11.6 g/m² for a catch rate of nearly 1,100 individuals in a 30-minute tow. Other, less impressive scallop concentrations were noted off Cape Yakataga at 68 m, 10 km southeast of Dry Bay at 64 m, and 15 km south of Kayak Island at 130 meters.

Many large scallops in the Cape Yakataga/Yakutat Bay region were infected by the spionid polychaetes *Pygospio elegans* and *Polydora ciliata*. These polychaetes had burrowed into the upper valves, weakening them to the point where the valves were easily broken by trawling. Scallops in the Yakutat Bay vicinity were once the target of a major fishery; however, recent landings have been low. During 1984, only 33.6 mt were harvested in the Yakutat region (ADF&G 1985d).

Dungeness crab dominated in terms of both density and biomass at the mouth of Icy Bay in November 1979. At this

location (28 m) 833 crabs were obtained during a 30-minute tow. These crabs were mostly males weighing ~0.4 kg each. Waters on either side of Icy Bay have been the most important fishing areas for Dungeness crab in the Yakutat Bay area fishery. The value of this species to the fishermen in the Yakutat Bay fishery in 1984–1985 was about \$1 million for 346 mt (ADF&G 1985d). As a predator/scavenger, Dungeness crab takes an array of benthic prey, as has been demonstrated in Cook Inlet (Feder and Paul 1980).

The sunflower sea star is one of the largest sea stars in the Gulf of Alaska, often attaining weights to 0.5 kilograms. This species occurred mostly at shallower depths (<100 m), between Kayak Island and Dry Bay, although the depths between 113 and 182 m in Icy Bank were also important habitats (Tables 12–10 and 12–11). As a predator/scavenger, this sea star takes a variety of benthic prey (Paul and Feder 1975), but prefers clams, snails, brittle stars, and mud stars. Nearly 75% of the stations where *Pycnopodia* was found also contained *Ophiura sarsi* and/or the mud star. Other foods of lesser importance consumed by the sunflower sea star are the gastropods *Colus halli*, *Mitrella gouldi*, *Solariella obscura*, *Oenopota* sp., and *Natica clausa*, and the bivalves *Serripes groenlandicus* and *Clinocardium ciliatum*.

Stations examined on Yakutat Bank in 1979 were dominated by Tanner crab and the green sea urchin. The pooled concentration of sea urchins at two of the three high-biomass Yakutat Bank stations was 1,428 individuals/km, or 5.6 g/m².

Stations between Dry Bay and Lituya Bay were dominated by the anemone *Metridium senile*, as well as by scallops. Organic materials suspended in the water column in this turbulent shallow region are presumably the primary source of food for the suspension-feeding *Metridium*.

With the exception of Kayak Trough and Yakutat Canyon, epifaunal biomass at depths exceeding 200 m was considerably less than on adjacent banks and grounds (Table 12–11). In most cases, deposit feeders dominated these deep regions. However, stations in the Bering Canyon were dominated by the sea urchin *Alloctrotus fragilis*, which presumably feeds by a combination of browsing and scavenging. The greatest density of this species was only 37 individuals/km or 200 for each hour of trawling.

Trawl samples in Yakutat and Alsek Canyons, and to a lesser extent in Bering Canyon, were dominated by the heart urchin *Brisaster townsendi*. This species selects organic

Table 12-12.

Feeding methods of the biomass-dominant epifauna from NEGOA (1) and the Kodiak Shelf (2) (Barnes 1980; Feder and Jewett 1981a, b; Hyman 1955; Kozloff 1973; Kyte 1969; Morris, Abbott, and Haderlie 1980; Patent 1970; and Pearce and Thorson 1967).

TAXA	COMMON NAME	FEEDING CLASS	AREA OF DOMINANCE
Hydrozoa	hydroid	sessile SF	2
Porifera	sponge	sessile SF	1
Actiniidae	anemone	P/SF	1,2
<i>Metridium senile</i>	anemone	P/SF	1,2
<i>Ptilosarcus gurneyi</i>	sea pen	P/SF	2
<i>Stylatula gracile</i>	sea pen	SF	2
<i>Modiolus modiolus</i>	mussel	SF	2
<i>Pododesmus macroscimia</i>	jingle	SF	2
<i>Pecten caurinus</i>	weathervane scallop	mobile SF	1,2
<i>Neptunea lyrata</i>	snail	S/P	1,2
<i>Fusitriton oregonensis</i>	snail - Oregon Triton	P/S	1,2
Octopodidae	octopus	P/S	2
<i>Rossia pacifica</i>	squid	P/S	1
<i>Berryteuthis magister</i>	squid	P/S	1
<i>Pandalus borealis</i>	pink shrimp	P/S	1,2
<i>Pandalopsis dispar</i>	sidestripe shrimp	P/S	1
<i>Cancer magister</i>	Dungeness crab	P/S	1
<i>Chionoecetes bairdi</i>	Tanner (snow) crab	P/S	1,2
<i>Lithodes aequispina</i>	Golden (brown) King crab	P/S	1
<i>Lopholithodes foraminatus</i>	box crab	P/S	1
<i>Ophiura sarsi</i>	brittle star	P/B/DF	1
<i>Gorgonocephalus caryi</i>	basket star	P/SF/B	1,2
<i>Ctenodiscus crispatus</i>	mud star	non-selective DF	1
<i>Pycnopodia helianthoides</i>	sunflower seastar	P/S	1
<i>Mediaster aequilis</i>	vermillion star	P	1
<i>Dipsacaster borealis</i>	sea star	P?	1,2
<i>Echinarachnius parma</i>	sand dollar	DF/SF	2
<i>Strongylocentrotus droebachiensis</i>	green sea urchin	B/S	1
<i>Alloccentrotus fragilis</i>	sea urchin	B/S?	1
<i>Brisaster townsendi</i>	heart urchin	selective DF	1
Cucumaridae	sea cucumber	SF	1,2
<i>Halocynthia helgendorfi igaboja</i>	tunicate	SF	1,2

^a SF = suspension feeder; DF = deposit feeder; P = predator; S = scavenger; B = browser

material deposited either on or within the sediment in which it burrows. Because of its burrowing habit, sampling via trawl presumably underestimates their relative abundance. Nevertheless, they still accounted for 84, 40, and 16% of the biomass at stations in Yakutat, Alsek, and Bering Canyons, respectively (Table 12-8). Values as high as 7.5 g/m² or 12,340 individuals/h were obtained in Yakutat Canyon. Extensive bottom trawling in NEGOA during 1961 and 1962 revealed that *Brisaster* accounted for 50% of the total invertebrate catch by weight and mainly occurred in Yakutat, Alsek, and Bering Canyons (Hitz and Rathjen 1965).

Trawls taken from the outer Yakutat Canyon region contained the squids *Rossia pacifica* and *Berryteuthis magister*, two cephalopod species that are closely associated with the benthic substrate.

Embayments of the Northeast Gulf of Alaska

Yakutat Bay. The fine glacial sediments of Yakutat Bay (Fig. 12-1) were dominated by deposit-feeding polychaetes and bivalve mollusks, infaunal organisms characteristic of similar substrata elsewhere in the Gulf (Feder, Jewett, McGee, and Matheke 1981). Suspension-feeding species, such as cockles, scallops, and brachiopods were found in low numbers on the gravel-rock admixture in the mid- and

outer Bay. The fact that suspension feeders were found here suggests the presence of strong bottom currents in the outer Bay.

The area at the inner end of Yakutat Bay (mouth of Disenchantment Bay) was notable for the low abundance (32 individuals/m²) and biomass (1 g/m²) of its infauna. For stations in mid-Yakutat Bay, there was both an increased abundance (\bar{x} = 390 individuals/m²) and an increased biomass (\bar{x} = 62 g/m²). The highest infaunal values were recorded at the mouth of Yakutat Bay with a mean abundance of 520 individuals/m² and a biomass of 234 g/m².

Arthropods, echinoderms, and mollusks dominated the epifaunal species in terms of both abundance and biomass (H.M. Feder and S.C. Jewett, University of Alaska, unpubl. OCSEAP data on file at NODC). Arthropods contributed 13 species and made up 68.6% of the total biomass, echinoderms contributed seven species and constituted 16% of the biomass, while mollusks accounted for two species and 14.8% of the biomass. The biomass for all epifaunal species was 1.2 g/m². The dominant arthropod was the Dungeness crab, which contributed 88.1% of the arthropod biomass and 60.4% of the invertebrate biomass. The sunflower sea star and the weathervane scallop were the dominant echinoderm and mollusk species, respectively.

Prince William Sound.

Port Valdez and Valdez Arm. Feder, Mueller, Dick, and Hawkins (1973) and Feder and Matheke (1980b) described over 200 invertebrate taxa representing thirteen phyla from grab samples they took in Port Valdez (a turbid outwash fjord; the location of the marine terminal for the Trans-Alaska oil pipeline) and Valdez arm (Fig. 12-3). Polychaetous annelids were both dominant and widely distributed throughout the Port; mollusks were next in importance. Echinoderms (primarily ophiuroids) were the third most common group of organisms present. All other groups combined represented a minor component of the fauna. The abundance of infauna in Port Valdez ranged between 13 and 1,860 individuals/m², and the biomass (formalin wet weight) ranged from between 1 and 490 g/m².

Multivariate analysis of grab data in the Port separated sampling stations in the deep basin into two large groups—eastern and western—with a dividing line running between Gold Creek and a point to the east of Sawmill Creek (Feder and Matheke 1980b; Feder *et al.* 1983) (Fig. 12-4). Discrete communities such as those described by Petersen and Jensen (1911) and Thorson (1957) for the Baltic Sea were not observed in Port Valdez (Feder and Matheke 1980b).

Trawl surveys of the deep basin of Port Valdez made between 1972 and 1982 collected representatives of eight

invertebrate phyla (Feder *et al.* 1983). In general, crustaceans—primarily the shrimps *Pandalus borealis*, *Pandalopsis dispar*, and *Crangon communis*—dominated the bottom of both the eastern and the western stations. Juvenile Tanner crab, *Chionoecetes bairdi*, were sporadically abundant in Port Valdez, but adult crab were never common. The mud star, *Ctenodiscus crispatus*, was usually abundant in the catch at most trawl stations.

Both the pink shrimp (*P. borealis*) and the sidestripe shrimp (*P. dispar*) were uncommon in Port Valdez during 1972. They were more common in 1973, fairly abundant from 1977 to 1978, and were again reduced in numbers from 1980 to 1982. The common, small polychaetous annelids and crustaceans in the Port are important prey for *P. borealis* in other Alaskan waters (Rice *et al.* 1980; Carpenter 1983) and presumably represent common components of the diet of these crustaceans in Port Valdez. The increased numbers of pink shrimp in the Port from 1977 to 1978 may be related to the increased abundance of polychaetes present there during this period (Feder *et al.* 1983; Feder and Shaw 1986). The food of *P. dispar* is not known.

Other Fjords and Bays of Prince William Sound. Although no quantitative investigations of benthic fauna in Prince William Sound (other than for Port Valdez) are available, three qualitative surveys present useful information of

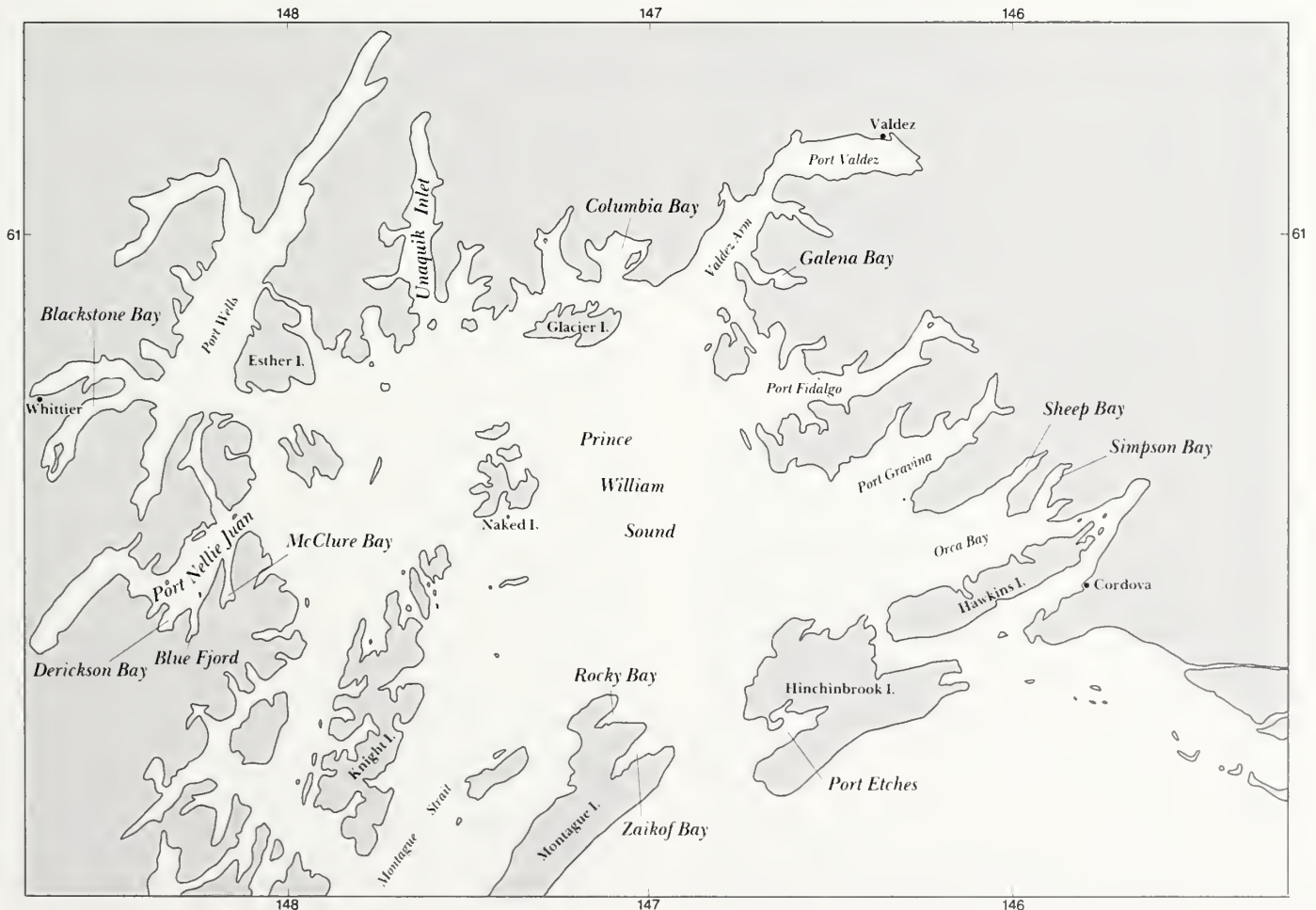


Figure 12-3. Map of Prince William Sound, Alaska, showing sampling sites for benthic biological studies.

fjords and embayments there (Hoskin 1977; Feder and Paul 1977; and Feder and Hoberg 1981).

Port Etches, an embayment of Hinchinbrook Island on the eastern side of Hinchinbrook Entrance (Fig. 12-3), was characterized by Hoberg (1986) as a deposit-feeding, mud-bottom infaunal assemblage. Many of the dominant infaunal mollusks present there (the protobranchs *Nucula tenuis*, *Nuculana fossa*, and *Yoldia* spp. and the gastropod *Mitrella gouldi*) were heavily preyed upon by the sunflower sea star (*Pycnopodia helianthoides*) (Paul and Feder 1975), Tanner crab, and bottomfishes (Feder and Hoberg 1981). The deposit-feeding polychaete *Sternaspis scutata* and the small suspension-feeding bivalve *Axinopsida serricata*—both characteristic of depositing environments of Prince William Sound—were also common here. The sandy bottom north of the entrance to the Port was dominated by suspension-feeding organisms (e.g., the sea pen, *Ptilosarcus gurneyi*, and the bivalve, *Glycymeris suboboleta*).

The epifauna of Port Etches was dominated by Arthropoda (Crustacea—22 species), Mollusca (8 species), and Echinodermata (4 species) (Feder and Hoberg 1981). The sunflower sea star accounted for 62% of the total biomass, and pink shrimp and Tanner crab made up 28 and 4% of the biomass, respectively. Mollusks only accounted for 0.2% of the total biomass. The total epifaunal biomass was 0.8 g/m².

The benthic environment of outer Rocky Bay, an embayment on the northwestern side of Hinchinbrook Entrance (Fig. 12-3), was dominated primarily by suspension/small-zooplankton feeders (Feder and Hoberg 1981; Hoberg 1986). The infauna included:

- sea pens (*Ptilosarcus gurneyi*)
- bivalves (*Astarte* sp., *Clinocardium* spp., and *Serripes groenlandicus*)
- amphipods (*Ampelisca hessleri*).

The epifauna included:

- alcyonarians (*Eunephthya rubiformis*)
- bryozoans
- brachiopods
- basket stars (*Gorgonocephalus caryi*)
- sea cucumbers (*Psolus chitinoideus* and *Bathylplotes* sp.)
- crinoids (*Heliogetra glacialis maxima*).

Infaunal deposit feeders such as the polychaete *Myriochele heeri* and the bivalves *N. tenuis* and *N. fossa* were most important within the inner Bay. Eighteen echinoderm species accounted for 87% of the total epifaunal biomass of Rocky Bay. Three species—*Bathylplotes* sp., *Ophiura sarsi*, and *Gorgonocephalus caryi*—made up 34, 26, and 16% of this biomass, respectively. Although there were 35 crustacean species and 24 mollusk species, they only accounted for 5.9 and 3.2%, respectively, of the total biomass. Ophiuroids (primarily the browsing/predator *O. sarsi*) were dominant prey for Tanner crab in Rocky Bay.

The benthos of outer Zaikof Bay (Fig. 12-3), on the southwestern side of Hinchinbrook Entrance, was characterized by some of the same infaunal suspension-feeding and scavenging species as Rocky Bay. Twelve species of echinoderms accounted for 50% of the total epifaunal biomass of Zaikof

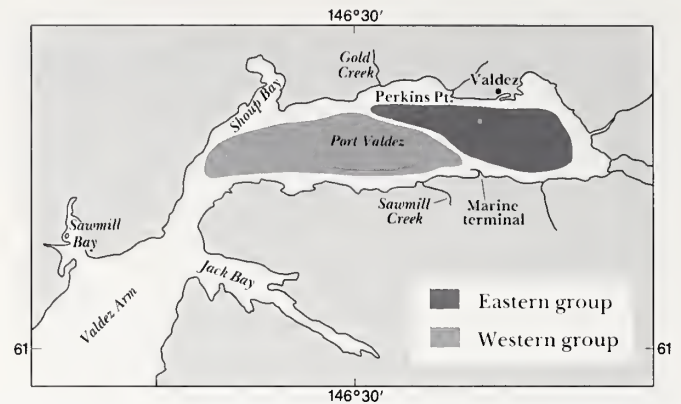


Figure 12-4. Two major station groups in Port Valdez, Alaska formed by cluster analysis of \ln -transformed infaunal abundance data. (Modified from Feder and Matheke 1980b.)

Bay. Two species, *P. helianthoides* and *G. caryi*, made up 31 and 15% of this biomass, respectively. Crustaceans accounted for 45% of the total biomass, lead by the sidestripe shrimp (24%), the pink shrimp (6%), and the Tanner crab (9%). The inner part of the Bay was dominated by deposit-feeding organisms. Deposit-feeding bivalves were more common as food for Tanner crab here than in Rocky Bay.

The bottom of outer Simpson Bay (southeastern Prince William Sound) (Fig. 12-3) is a gravely sand environment with fauna that is characteristic of areas with strong bottom currents. Organisms common here were sea pens, (*P. gurneyi*), cockles (*Clinocardium ciliatum* and *S. groenlandicus*), brachiopods (*Laqueus* sp.), and basket stars (*G. caryi*) (Feder and Paul 1977). The epifauna of the inner Bay was dominated by bottom-foraging crustaceans, suggesting the presence of a relatively rich infauna of polychaete worms, bivalve mollusks, and small crustaceans (see Paul, Feder, and Jewett 1979; Feder and Paul 1980; Rice 1980; Rice *et al.* 1980; and Feder and Hoberg 1981, for a listing of the food consumed by Alaskan crustaceans). Pink shrimp were abundant, sidestripe shrimp ranged from being common to abundant, and crangonid shrimps, Tanner crab, and Dungeness crab (*Cancer magister*) were all common.

The mud star *C. crispatus* was common on the soft bottom of inner Sheep Bay (adjacent to Simpson Bay; Fig. 12-3). The pink shrimp was abundant, and *Crangon* spp. and *Pagurus* spp. were also common epifauna in this Bay.

The mud star was also common on the bottom adjacent to Gravina Point and outer Port Gravina (an embayment northwest of Simpson Bay). The pink shrimp was the dominant epifaunal species here.

The benthos of the northern rocky entrance to Port Fidalgo, an embayment north of Port Gravina (Fig. 12-3), was dominated by suspension/zooplankton-feeding predators such as the crinoid, *H. glacialis maxima*, and the basket star (Schaefers, Smith, and Greenwood 1955; Feder and Paul 1977). The fauna of the muddy bottom of inner Port Fidalgo consisted of deposit-feeding organisms typical of the inner portions of embayments of eastern Prince William Sound (H.M. Feder, University of Alaska, unpubl. data).

The presence of suspension/zooplankton-feeding species (e.g., the infaunal bivalve *C. ciliatum* and the feather star *Heliogetra* sp.) in trawl samples from inner Galena Bay

(north of Port Fidalgo; Fig. 12-3) suggests the presence of strong bottom currents and associated particulate organic carbon. The pandalid shrimps *P. borealis*, *P. goniurus*, and *P. hyphantopus* were common in Galena Bay.

Columbia Bay, a tidewater-glacier fjord in the northern Sound (Fig. 12-3), contained walleye pollock (*Theragra chalcogramma*) that fed heavily upon both pelagic hyperiid amphipods (*Parathemisto libellula*) and pink shrimp. The presence of these amphipods in the Bay and the common occurrence of the suspension/zooplankton-feeding sea pen, *Ptilosarcus* sp., suggest that an influx of zooplankton from the Sound into the fjord is common. The presence of the mud star in 50% of the trawls also suggests that there is a flux of carbon to the bottom sufficient to support a deposit-feeding infaunal assemblage in Columbia Bay (Feder and Paul 1977).

Another tidewater-glacier fjord (Unaquik Inlet; Fig. 12-3) contained few infaunal organisms within the mud-gravel substrate inside the shallow (4 m) sill (H.M. Feder, University of Alaska, unpubl. data). However, large numbers of bottom-feeding pandalid shrimps were present outside the sill, suggesting the presence of a productive bottom there. Populations of deposit-feeding bivalve mollusks (*Nuculana* sp. and *Yoldia* sp.) and associated predatory snails (*Natica* spp.), along with large numbers of *C. crispatus* in the outer Inlet, all point to sufficient accumulations of carbon on the bottom to sustain deposit-feeding assemblages. Port Wells, a deep (400 m) tidewater-glacier fjord in the western Sound (Fig. 12-3), supported abundant populations of mud stars, protobranch bivalves, *Yoldia* spp., the heart urchin (*Brisaster townsendi*), and sea cucumbers (Synaptidae) on the bottom outside the sill (H.M. Feder, University of Alaska, unpubl. data).

The mud bottom of the deep (350 m) Blackstone Bay (southwest of Port Wells; Fig. 12-3) supported a deposit-feeding assemblage of species similar to that found in Port Valdez in the northern Sound (H.M. Feder, University of Alaska, unpubl. data). The stomachs and intestines of Tanner crab from Blackstone Bay were often full of mud, an occurrence noted in other areas of Prince William Sound (e.g., Port Valdez) whenever appropriate crab food items were uncommon (Paul, Feder, and Jewett 1979).

In the Port Nellie Juan area of western Prince William Sound, the macrobenthos of three contiguous fjords (Blue Fjord, Derickson Bay, and McClure Bay; Fig. 12-3) consisted primarily of deposit-feeding polychaetous annelids and bivalve mollusks (Hoskin 1977). Suspension feeders were more common in glacier-free McClure Bay ($\bar{x} = 15\%$) than in the more turbid Derickson Bay, a tidewater-glacier fjord ($\bar{x} = 6\%$) or Blue Fjord, a turbid outwash fjord ($\bar{x} = 9.5\%$). Biomass was highest in Derickson Bay ($\bar{x} = 19.9 \text{ g/m}^2$) with values decreasing somewhat from the head to the mouth of the fjord. The biomass was intermediate in Blue Fjord ($\bar{x} = 12.9 \text{ g/m}^2$), although a high value of 52 g/m^2 occurred behind the sill (the mean of the other stations within Blue Fjord was 3.1 g/m^2). The mean biomass in McClure Bay was 5.9 g/m^2 .

Resurrection Bay. A description of the physical/chemical environment of Resurrection Bay (Fig. 12-5), a turbid

outwash fjord with a deep (185 m) sill, is presented in Heggie *et al.* (1977). The benthic biology of this fjord is poorly known, but a qualitative survey of the benthos is available in Feder *et al.* (1979).

Crustaceans—in particular, shrimps (*Pandalus borealis*, *Pandalopsis dispar*, and *Crangon communis*), hermit crabs, and Tanner crabs (*Chionoecetes bairdi*)—dominated the epifauna throughout the Bay, but were more common inside the sill (Fig. 12-5). These species were particularly abundant directly behind the sill. The dominant infaunal taxa were deposit-feeding polychaetes and bivalve mollusks. The deep basin both within and outside the sill was characterized by the presence of the polychaete *Sternaspis scutata*, bivalve mollusks (Thyasiridae, *Nuculana fossa*), and the aplacophoran mollusk *Chaetoderma robusta*. The scaphopod mollusk *Dentalium* sp. and cumaceans occurred in low numbers in this region. Stations sampled by Feder *et al.* (1979) within the deep basin contained up to 20 taxa.

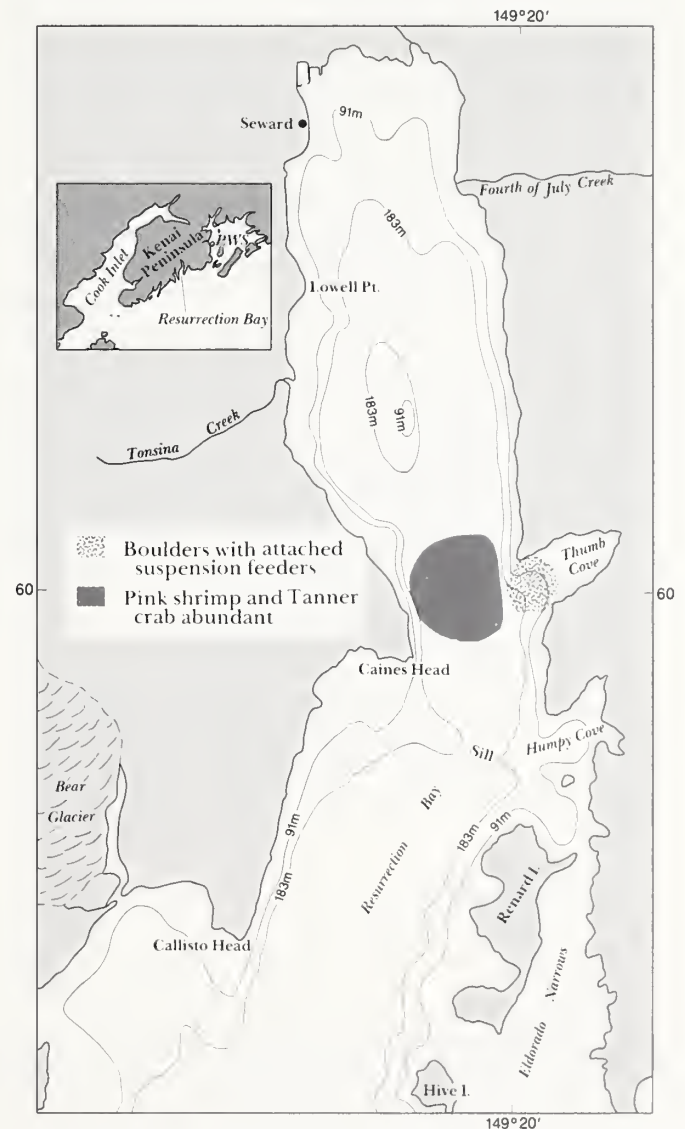


Figure 12-5. Resurrection Bay, Alaska. The dark gray area represents the region with the highest abundance values of pink shrimp (*Pandalus borealis*) and Tanner crab (*Chionoecetes bairdi*) as determined by Feder, Paul, and McDonald (1979).

Large numbers of two deposit-feeding taxa—the mud star and the heart urchin—occurred on the muddy bottom adjacent to Tonsina Creek on the western shore of the Bay. However, on the western side, inside the sill, the benthos was dominated by a variety of taxa (number of taxa at stations there ranged from 14 up to 21) typical of muddy substrates in Alaskan waters. These included:

- polychaetes (*Nephtys punctata*, *Sternaspis scutata*, *Terebellides stroemi*, *Spiophanes kroyeri*, and *Lumbrineris* sp.)
- bivalve mollusks (*Axinopsis serricata*, Thyasiridae, *Nuculana fossa*, and *Odontogena borealis*).

Similar taxa were found south of Caines Head (outside the sill), although up to 38 taxa were described here. In contrast, south of Callisto Head, only 10 taxa (primarily deposit feeders) occurred.

Along the eastern shore of Resurrection Bay, north of Fourth of July Creek, the bottom was dominated by deposit-feeding organisms (primarily the polychaete *S. scutata* and the bivalve *Macoma brota*). *Laminaria* spp. and other kelps were common here, and presumably supply detrital materials for these organisms. The small bivalve *A. serricata*, typical of muddy sediments in the Gulf, was also common in this region.

The fine mud of Thumb Cove—a small embayment on the eastern shore at mid-fjord—contained a rich infauna (36 taxa) dominated by the sipunculid *Golfingia vulgaris* and the polychaete *Myriochele heeri*. Also common were other deposit-feeding polychaetes, the sipunculid *Phascolion strombi*, and thyasirid bivalves. A relatively rich epifauna occurred on boulders protruding from the mud of outer Thumb Cove, suggesting that local eddy turbulence around these boulders makes particulate organic carbon available for the suspension feeders. Species present on the boulders within the Cove were solitary corals, serpulid polychaetes, ectoprocts, the brachiopod *Laqueus* sp., and the crinoid *Heliometra glacialis maxima* (H.M. Feder, University of Alaska, unpubl. data).

Aialik Bay. Carpenter (1983) examined infauna in Aialik Bay, a shallow-silled (6–10 m) tidewater-glacier fjord west of Resurrection Bay (Fig. 12-6). She described ~70 infaunal taxa, primarily annelids, mollusks, and arthropods. Twenty-one taxa occurred at 50% or more of the stations (Table 12-4). Nine taxa that occurred at all stations are:

- *Tharyx* sp.
- *Nephtys punctata*
- *Heteromastus filiformis*
- *Melinna cristata*
- *Nuculana* sp.
- *Lumbrineris* sp.
- *Myriochele oculata*
- *Terebellides stroemi*
- *Chaetoderma robusta*.

The first five of the above taxa occurred in high densities (732 individuals/m²) at one or more stations; the remaining taxa were present in low numbers. Six taxa constituted at least 10% of the wet weight at one or more stations (Table 12-5).



Figure 12-6. Aialik Bay, Alaska. The dark gray area represents the region investigated by Carpenter (1983).

Twenty-three taxa occurred at stations closest to the glacier. The number of taxa increased to 28 at stations inside the sill while 38 taxa occurred at a station outside the sill. The abundance of individuals increased from near the glacier to a maximum just inside the sill. The lowest abundance values occurred outside the sill. Biomass values varied from 19 to 48 g/m² at stations within the sill, and showed no pattern. The highest biomass value of 133 g/m² occurred outside the sill, mainly attributed to the presence of the heart urchin *Brisaster townsendi*, a species only found outside the sill. Dominance (Simpson Index) was highest near the glacier, where abundance values for *N. punctata* and *M. cristata* were also high. Diversity (Shannon Index) increased away from the glacier.

Lower Cook Inlet.

General. Lower Cook Inlet (south of Kalgin Island) (Fig. 12-7) is a tidally dominated estuary of the central Gulf of Alaska. It supports commercially harvested populations of Tanner, red king, and Dungeness crabs as well as shrimps

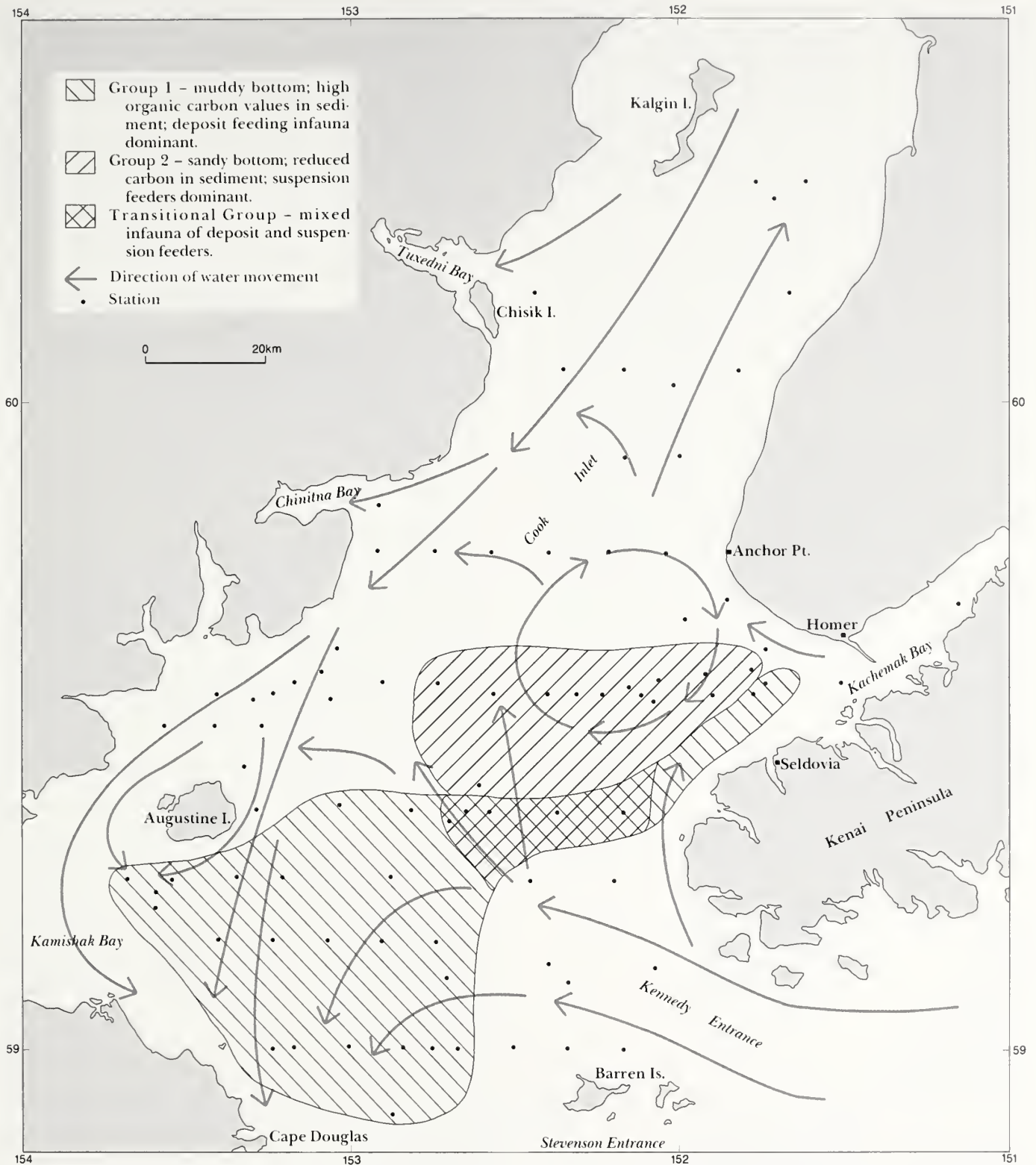


Figure 12-7. The two major infaunal station groups in lower Cook Inlet (Feder, Paul, Hoberg, and Jewett 1981), but modified to incorporate qualitative data derived from dredge samples (Feder 1978). Patterns of water movement within lower Cook Inlet are from Burbank (1977) and Muench *et al.* (1978).

(Pandalidae) (Ronholt *et al.* 1978). Primary production is high throughout the lower Inlet, and may exceed 7.8 g C/m²d in Kachemak and Kamishak Bays (Larrance, Tennant, Chester, and Ruffio 1977). During spring and summer, the eastern Inlet is characterized by clear, saline water entering from the Gulf via Kennedy Entrance. A gyre system acts to increase the residence time of water in outer Kachemak Bay and contributes to the early development of the large spring and summer plankton population found there (Burbank 1977; Larrance *et al.* 1977).

The western Inlet is greatly influenced by freshwater runoff and high concentrations of river-derived suspended matter carried there from the upper Inlet (Burbank 1977; Muench, Mofjeld, and Charnell 1978; Larrance *et al.* 1977; and Chester and Larrance 1981). These highly turbid waters restrict primary productivity in the western and northern portions of the Inlet, especially in early spring (Larrance *et al.* 1977).

The deeper waters of lower Cook Inlet are characterized by a relatively smooth bottom and strong tidal currents. The sediment is relatively coarse, gravel-to-boulder-bearing sand in the north grading to clean sand and then to muddy sand to the south (Bouma and Hampton 1976). The sediment of upper Kamishak Bay is a muddy sand grading to mud in the southern portion of the Bay. The sediments of inner Kachemak Bay are silts grading to muddy sand and rippled sand in the outer Bay (Driskell and Lees 1977). The bottom of the inshore waters of outer Kachemak Bay is characterized by shell debris, while the shallow subtidal area is a boulder/large-cobble facies (Driskell and Lees 1977).

Infaua. Subtidal invertebrates are rare in the turbid waters of upper Cook Inlet (north of Kalgin Island) (Rosen-

berg *et al.* 1969; Bakus *et al.* 1979; and H.M. Feder, University of Alaska, unpubl. data). However, in the relatively clear waters of lower Cook Inlet over 370 invertebrate taxa representing 11 phyla were described from grab samples taken at depths between 24 and 181 m (Feder, Paul, Hoberg, and Jewett 1981). Eighteen species occurred at 50% or more of the stations (Table 12-4), and 17 species constituted at least 10% of the wet weight at one or more stations (Table 12-5). Abundance values at sampling stations ranged between 150 and 3,988 individuals/m² and the biomass ranged from 21 to 731 g/m².

Cluster analysis of infaunal data (Feder, Paul, Hoberg, and Jewett 1981) identified two major station groups (Fig. 12-7). Group 1 consisted primarily of stations from southwestern Cook Inlet. Group 2 consisted of stations in the eastern part of the Inlet adjacent to Kachemak Bay. The two groups were distinguished by a number of differences, including (Tables 12-13 and 12-14):

- dominant taxa
- biomass
- abundance
- Shannon diversity
- species richness
- trophic group composition.

High biomass values within Station Group 2 were generally the result of large numbers of both the sand dollar, *Echinarachnius parma*, and two bivalve mollusks (*Tellina nuculoides* and *Glycymeris subobsoleta*).

Dredge sampling (Feder 1978) complemented and expanded data derived from grab samples (Feder, Paul, Hoberg, and Jewett 1981). Dredging made it possible to

Table 12-13.

Dominant taxa (no./m² and g/m²) and feeding classes in the groups from lower Cook Inlet determined by cluster analysis (Feder, Paul, Hoberg, and Jewett 1981). All samples collected by van Veen grab (see Fig. 12-7).

TAXA	PHYLUM ^a	FEEDING CLASS ^b	ABUNDANCE (No./m ²)	TAXA	PHYLUM ^a	FEEDING CLASS ^b	BIOMASS (g/m ²)
Group 1							
<i>Axinopsida serricata</i>	M	SF	352	<i>Echinarachnius parma</i>	E	SF	9.5
<i>Lumbrineris</i> sp.	A	DF/P	157	<i>Ptilosarcus gurneyi</i>	C	SF/P	8.9
<i>Nucula tenuis</i>	M	DF	86	<i>Macoma calcarea</i>	M	DF	7.8
<i>Magelona</i> sp.	A	DF	83	<i>Nuculana fossa</i>	M	DF	6.4
<i>Nuculana fossa</i>	M	DF	74	Alcyonacea	C	SF/P	5.8
<i>Macoma calcarea</i>	M	DF	67	<i>Macoma moesta</i>	M	DF	3.2
<i>Haploscoloplos elongatus</i>	A	DF	48	<i>Travisia brevis</i>	A	DF	2.7
<i>Lumbrineris zonata</i>	A	DF/P	40	<i>Nephtys ciliata</i>	A	DF/P	1.6
<i>Byblis gaimardi</i>	Ar	S	39	<i>Axinopsida serricata</i>	M	SF	1.4
<i>Eudorella emarginata</i>	Ar	DF	28				
Group 2							
<i>Tellina nuculoides</i>	M	SF/DF	263	<i>Echinarachnius parma</i>	E	SF	186
<i>Glycymeris subobsoleta</i>	M	SF	95	<i>Tellina nuculoides</i>	M	SF/DF	46
<i>Spiophanes bombyx</i>	A	DF/SF?	25	Ectoprocta	-	SF	16
<i>Echinarachnius parma</i>	E	SF	20	<i>Glycymeris subobsoleta</i>	M	SF	10
<i>Magelona</i> sp.	A	DF	16	<i>Astarte rollandi</i>	M	SF	3
<i>Ophelia limacina</i>	A	DF	13	<i>Alloctrotus fragilis</i>	E	S	3
<i>Glycera capitata</i>	A	P	11	<i>Ophelia limacina</i>	A	P?	1
<i>Paraphoxus</i> sp.	Ar	S	10	<i>Glycera capitata</i>	A	P	1

^a A = Annelida; M = Mollusca; Ar = Arthropoda; E = Echinodermata; C = Cnidaria.

^b DF = deposit feeder; SF = suspension feeder; P = predator; S = scavenger.

Table 12-14.

Distinguishing features of the two major infaunal groups determined by multivariate analysis for lower Cook Inlet (Feder, Paul, Hoberg, and Jewett 1981). (Refer to Fig. 12-7 for location of stations and groups.)

	GROUP 1	GROUP 2
Biomass (g/m ²)	74	283
Abundance (individuals/m ²)	1,743	616
Shannon Diversity	3.1	2.3
Species Richness	10.5	5.5
Deposit Feeders (%) ^a	58	38
Suspension Feeders (%) ^a	19	27

^a Percent of all individuals counted in samples.

examine regions not readily sampled with a grab. One such region is the rock/sand bottom immediately north of the Barren Islands and adjacent to Kennedy Entrance where fauna consisted primarily of suspension-feeding bivalve mollusks, brachiopods, bryozoans, and sand dollars. The fauna of the rock/cobble channel east of Kalgin Island and the rocky area adjacent to Tuxedni Bay and Chisik Island also consisted of bryozoans and brachiopods. The bottom immediately north of Augustine Island was identified as a deposit-feeding assemblage as a result of grab sampling, but dredge sampling revealed large numbers of the barnacle *Balanus rostratus* on pumice fragments.

Studies of Kachemak Bay by Driskell and Lees (1977) provide a descriptive overview of the bottom characteristics and associated infaunal species there. Several areas investigated by Driskell and Lees (1977) in the outer Bay overlap those considered by Feder, Paul, Hoberg, and Jewett 1981; results of both studies complement each other. Driskell and Lees (1977) identified five major subtidal geological facies within Kachemak Bay, consisting of four substrate types (rock, sand, silt, shell debris) (Fig. 12-8), and described their characteristic infaunal assemblages.

The northern shell debris assemblage was the richest—accounting for over 80% of the total species collected in Kachemak Bay. Mollusks and bryozoans dominated this assemblage. The southern shell-debris assemblage was dominated by mollusks with juvenile bivalves (mainly *G. subboSOLEta*) most common; polychaetes and bryozoans were of lesser importance. The rippled sand assemblage was also dominated by mollusks with the pinkneck clam *Spisula polynyma* most common; low numbers of other species of clams (e.g., *Tellina* spp.) were also present. In addition, adult sand dollars (*E. parma*) occurred throughout the area. The muddy-sand assemblage of the Bay was dominated by bivalve mollusks—*Axinopsida serricata*, *Nuculana fossa*, *Pandora grandis*, *Nucula tenuis*, *Psephidia lordi*, *S. polynyma*, and *Yoldia seminuda*. The sea pen *Phyllosarcus gurneyi* was also common. Juvenile sand dollars were concentrated in the northern portion of this assemblage. The silt assemblage of the Bay was impoverished—with polychaetes most abundant, followed closely by mollusks. The boulder/large-cobble facies is discussed in the epifaunal section of this chapter.

Bivalves are important trophic links in the benthic food webs that lead to Tanner, Dungeness, red king, and hermit crabs, as well as to flatfishes and other organisms in lower

Cook Inlet (Feder 1978; Paul, Feder, and Jewett 1979; Feder and Paul 1980; Rice 1980; and Feder, Paul, Hoberg, and Jewett 1981). Further, based on the benthic sampling of Driskell and Lees (1977), Feder (1978), and Feder and Paul (1980), it is clear that bivalve mollusks are common (76 species) and widely distributed throughout the Inlet. Deposit-feeding species dominated the fine sediments on the western side of the Inlet. Suspension-feeding species were more abundant in sandier areas of outer Kachemak Bay. Distribution, size, age, and mortality data for the six dominant bivalves in lower Cook Inlet are available in Feder, Paul, Hoberg, and Jewett (1981). These species include:

- *Nucula tenuis*
- *Nuculana fossa*
- *Macoma calcarea*
- *Glycymeris subboSOLEta*
- *Spisula polynyma*
- *Tellina nuculoides*.

Growth rates for each of these species were similar throughout the Inlet (Feder, Paul, Hoberg, and Jewett 1981).

The estimated mean infaunal production values for the two lower Cook Inlet station groups (Fig. 12-7) are: Group 1—6.6 g C/m²y, and Group 2—3.4 g C/m²y (H.M. Feder, University of Alaska, unpubl. data). The estimated value of benthic production for a station in outer Kachemak Bay is 2.5 g C/m²y; for two stations located beneath the gyre outside of Kachemak Bay, the estimated value is 6.3 g C/m²y (Knull and Williamson 1969; Burbank 1977); for a station immediately south of Augustine Island in Kamishak Bay, the estimated value is 9.9 g C/m²y; and for a station located within the Tanner crab nursery area in Stevenson Entrance, the estimated value is 10.1 g C/m²y (Feder, Paul, Hoberg, and Jewett 1981; Feder and Paul 1981).

Epifauna. Most of the shallow (<20 m) subtidal epifaunal investigations of Cook Inlet were conducted on rocky habitats in the lower portion of the Inlet—although some soft-bottom habitats have been examined there. The shallow subtidal assemblages of rocky substrates examined fall into

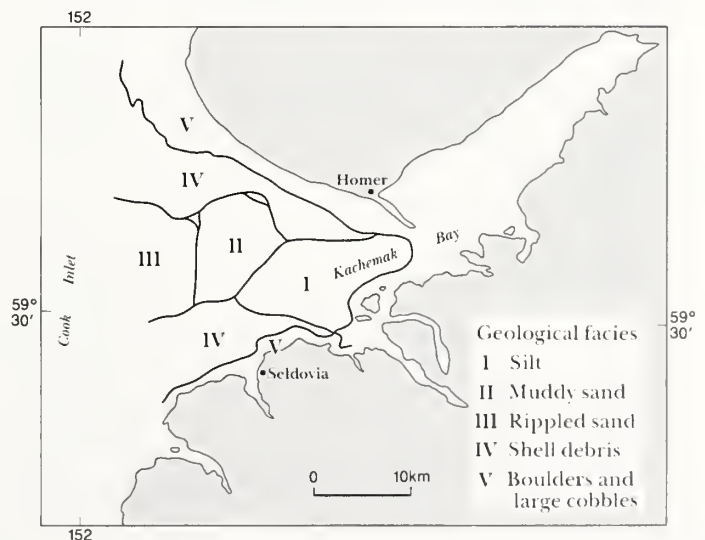


Figure 12-8. Geological facies in outer Kachemak Bay, lower Cook Inlet. (Modified from Driskell and Lees 1977.)

three geographically distinct groups: 1) southern Kachemak Bay, 2) northern Kachemak Bay, and 3) western Cook Inlet. The three assemblage groups are distinguished on the basis of the composition and structure of both macrophyte and epifaunal components. The dominant species from these areas are listed in Table 12–15, and a characterization of these three assemblages is summarized below (after Lees and Driskell 1981) (Fig. 12–9):

- 1) The southern Kachemak Bay assemblage has a lush, fairly dense kelp bed consisting of both a canopy and an understory. The epifaunal community exhibits low diversity and is poorly developed, although the predator/scavenger component is diverse with low density.
- 2) The northern Kachemak Bay assemblage is charac-

terized by a moderate kelp bed development that consists of a very spotty, thin canopy and a moderate understory, but with well-developed components of both sedentary and predator/scavenger invertebrates.

- 3) The western Cook Inlet assemblage exhibits little or no development of a kelp bed community. Sedentary invertebrates are well developed, and predator/scavenger epifauna are moderately developed.

Differences in the shallow subtidal rocky epifauna are most apparent between the east and west sides of the Inlet. Although many of the species found on the west side are also found on the east side, the absence of numerous eastern species in the west is most apparent. Further, there is an abundance of numerous species in the west that are more charac-

Table 12–15.

Dominant species in major rock bottom, shallow (<20 m) subtidal assemblages in lower Cook Inlet (Lees and Driskell 1981).

	SOUTHERN KACHEMAK BAY			NORTHERN SHELF OF KACHEMAK BAY			WEST SIDE OF COOK INLET		
	SELDOVIA POINT	BARBARA POINT	JAKALOF BAY	ARCHIMANRITOF SHOALS	BLUFF POINT	TROUBLESOME CREEK	KNOLL HEAD LAGOON	WHITE GULL ISLAND	BLACK REEF
Kelps									
Surface canopy									
<i>Nereocystis leutkeana</i>	A ^a (12) ^b	A	A	C(19)					
<i>Alaria fistulosa</i>	A(12)		A		C(12)	C			
Understory									
<i>Agarum cribrosum</i>	A(21)	A	A	C(13)	C(16)	C(14)	C(5)	C(3)	S(4)
<i>Alaria</i> spp. (not <i>fistulosa</i>)	Intertidal	Intertidal	Intertidal				A(2)	C(2)	S(2)
<i>Laminaria groenlandica</i>	A(20)	A	A	C(10)	C(12)	C(14)	C(4)	C(3)	S(2)
Maximum depth of kelps (m)	21	>14	12	13	16	15	5	3	4
Sedentary Invertebrates									
<i>Flustrella gigantea</i>	A	C	P	C	A	C	P		
<i>Microporina borealis</i>	C				C	S			
<i>Mycale</i> spp.	C			C	P	C	C	C	C
<i>Saxidomus giganteus</i>	C	P	A	C-A	S	A			
<i>Modiolus modiolus</i>			A	A	C	C	A	S	S
<i>Potamilla neglecta</i>			A	A			C	C	
<i>Halichondria panicea</i>	S				S	A	P	C	C
<i>Balanus rostratus</i>				C	C		S-C	C	C
<i>Dendrodoa pulchella</i>								A	A
<i>Costazia? surcularis</i>							C	A	A
<i>Metridium senile</i>	S		C		S	S		S	S
<i>Cucumaria miniata</i>			S	S	C	A		C	
<i>C. fallax</i>				S	C	A			
<i>Bidenkapia spitsbergensis</i>					P			C	C
<i>Dendrobeatia murrayana</i>				C	S			C	
Motile Invertebrates									
<i>Evasterias troschelii</i>	S		A		C	S			
<i>Dermasterias imbricata</i>			A			S			
<i>Pycnopodia helianthoides</i>	C	S	A			S			
<i>Orthasterias koehleri</i>	C	P	C			S			
<i>Henricia leviuscula</i>	C		C			S			P
<i>Leptasterias polaris acervata</i>				C	S	C	C	P	P
<i>Solaster stimpsoni</i>	S		C	S	S	S		P	
<i>Crossaster papposus</i>	C	P	C	C	C	S	C	P	P
<i>Henricia sanguinolenta</i>	S	P	A		C	C	C	C	P
<i>Fusitriton oregonensis</i>	C		A	C	C	C	C	S	P
<i>Neptunea</i> spp.				C	C	C	S	S	P
<i>Buccinum glaciale</i>				S	S	S	S	S	P
<i>Beringius kennicotti</i>				S	S		S	S	P
<i>Tonicella</i> spp.	C	P	C	C	C	C	C	S	P
<i>Strongylocentrotus droebachiensis</i>	C	C	A	A	C	A	S	S	P

^a A = Abundant; C = Common; S = Sparse; P = Present.

^b Parenthetic numbers represent maximum depth (m) of occurrence in this area.

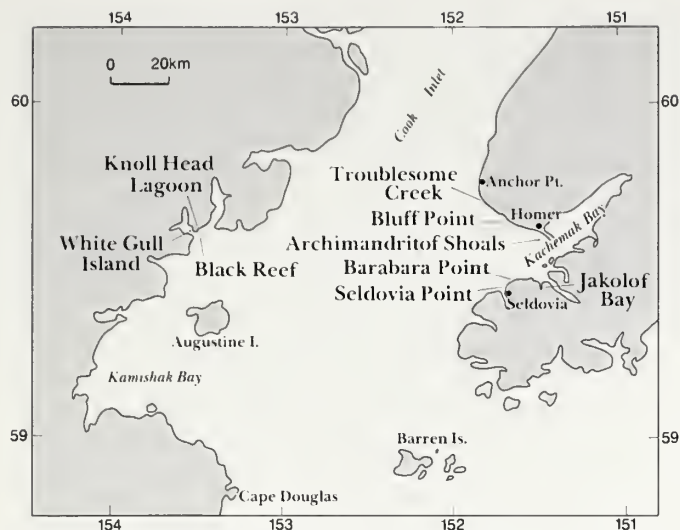


Figure 12-9. Areas in lower Cook Inlet in which shallow subtidal studies were made by Lees and Driskell (1981).

teristic of the Bering and Beaufort Seas. This fact is especially apparent when comparing bryozoan assemblages (Lees and Driskell 1981).

Benthic trawling conducted during various periods from 1976 to 1978 in deeper portions of the Inlet (25–181 m) yielded at least 287 invertebrate species from 46 stations (Table 12-16). Three or four species generally dominated at each station (Feder and Paul 1981). Twelve species accounted for nearly 84% of the total epifaunal biomass (Table 12-17). The dominant phyla—in numbers per m^2 —for combined data were Arthropoda (Crustacea) (91%), Mollusca (3.5%), and Echinodermata (3%). In terms of live weight, the dominant groups were Arthropoda (Crustacea) (74%), Echinodermata (17%), and Mollusca (6%) (Table 12-18). The important species were: 1) Tanner crab—accounting for 38.6% of the live weight and 1.1 g/m^2 , 2) humpy shrimp (*Pandalus goniurus*)—accounting for 20.7% of the weight and 0.6 g/m^2 , 3) red king crab—accounting for 7.2% of the weight and 0.2 g/m^2 , and 4) sea cucumber (*Cucumaria fallax*)—accounting for 4.8% of the weight and 0.1 g/m^2 (Table 12-17).

Within lower Cook Inlet the dominant organisms present reflected both the nature of the substratum and the bottom-current dynamics. In the inner portion of Kachemak Bay, where fine-grained sediments mainly prevail, omnivorous pandalid shrimps (pink, humpy, and coonstripe—*P. hypsinotus*), dominated both in terms of abundance (number/ m^2) and biomass (g/m^2) (Table 12-19). Toward the more dynamic outer Kachemak Bay, both the epifaunal density and the biomass were dominated by: 1) the grazing green sea urchin *Strongylocentrotus droebachiensis*, 2) the suspension-feeding sea cucumber *C. fallax*, and 3) the sand dollar *Echinarachnius parma*.

In Kamishak Bay, where the suspended sediment load tends to be greater than in Kachemak Bay, the omnivorous crangonid shrimps (mainly *Crangon dalli*) (Rice 1980) were the most numerous, while the scavenger/predator king and Tanner crabs dominated the biomass (Table 12-19).

Table 12-16. Number and percent of epifaunal species by phylum at depths >25 m in lower Cook Inlet (Feder and Paul 1981).

	NUMBER	PERCENT
Porifera	1	0.3
Cnidaria	9	3.1
Rhynchocoela	1	0.3
Annelida	19	6.6
Mollusca	94	32.8
Arthropoda	99	34.5
Ectoprocta	8	2.8
Brachiopoda	6	2.1
Echinodermata	47	16.4
Urochordata	3	1.0
Totals	287	100.0

In the central part of lower Cook Inlet where the bottom is sandy, the sand dollar and Tanner crab dominated both in terms of numbers and weight. In the outer portion of the Inlet where sediments are finer grained, Tanner crabs were most numerous and made the greatest contribution to the biomass. King crabs were also dominant in the biomass from this region (Table 12-19).

Stations in the vicinity of outer Kachemak Bay displayed the greatest epifaunal biomass, ranging from 6.2 to 14.5 g/m^2 . These relatively large biomass values can presumably be attributed to the high rate of primary productivity and the flux of much of this production to the bottom (Larrance and Chester 1979). The dominant epibenthic invertebrates in this region are capable of either using this organic carbon directly (e.g., *C. fallax* and *E. parma*) or indirectly—as in the case of large predators, such as the red king crab and the Tanner crab—by feeding on organisms that are suspension or detrital feeders.

Shellfish landed from lower Cook Inlet during the 1984–1985 season included Tanner and Dungeness crabs, five species of pandalid shrimps, scallops (*Pecten caurinus*), and octopus. The shellfish harvest for that season was valued at \$6.3 million (ADF&G 1985b).

Table 12-17. Biomass of the 12 dominant epifaunal species at depths >25 m in lower Cook Inlet (Feder and Paul 1981).

	BIOMASS (g/m^2)	PERCENT OF TOTAL BIOMASS
<i>Fusitriton oregonensis</i>	0.02	0.68
<i>Neptunea lyrata</i>	0.11	3.83
<i>Pandalus borealis</i>	0.02	0.84
<i>Pandalus goniurus</i>	0.60	20.72
<i>Paralithodes camtschatica</i>	0.21	7.20
<i>Hyas lyratus</i>	0.05	1.61
<i>Chionoecetes bairdi</i>	1.12	38.60
<i>Cancer magister</i>	0.03	1.21
<i>Evasterias troschelii</i>	0.04	1.40
<i>Echinarachnius parma</i>	0.02	0.70
<i>Strongylocentrotus droebachiensis</i>	0.07	2.29
<i>Cucumaria fallax</i>	0.14	4.85
Totals	2.43	83.91

Table 12-18.
Biomass of epifaunal phyla at depths >25 m in lower Cook Inlet (Feder and Paul 1981).

	BIOMASS (g/m ²)	PERCENT OF TOTAL BIOMASS
Porifera	0.026	0.91
Cnidaria	0.047	1.67
Rhynchozoela	<0.001	<0.01
Annelida	<0.001	0.02
Mollusca	0.071	5.87
Arthropoda	2.155	74.09
Ectoprocta	0.002	0.05
Brachiopoda	<0.001	0.02
Echinodermata	0.504	17.33
Urochordata	<0.001	0.03
Totals	2.909	100.00

Tanner crab were present throughout all regions of lower Cook Inlet (Feder and Paul 1981). Although adults were ubiquitous, juveniles were concentrated in the western and southwestern portions of the Inlet. In particular, the region between Cape Douglas and the Barren Islands, at depths of 150 to 170 m, is apparently a Tanner crab nursery area. Throughout various sampling periods, large concentrations of tiny crab (carapace widths ranging from 3–25 mm) were found there. These crab often occurred among a substrate of silty sand with scattered mats of sponge, hydroids, and polychaete tubes (mainly *Spiochaetopterus* sp.). As many as 414 of these small crab per kilometer were captured in a small (6.1 m) trawl in this region during October 1976. These juveniles were the dominant prey for three common demersal fishes—Pacific halibut (*Hippoglossus stenolepsis*), Pacific cod (*Gadus macrocephalus*), and great sculpin (*Myoxocephalus polyacanthocephalus*)—that were also common within the same nursery area. Nearly 63% of the 43 Pacific cod examined contained Tanner crab with as many as 12 crab found within a single cod stomach.

As a scavenger/predator, the Tanner crab feeds on a variety of prey organisms (Feder and Jewett 1981a; Jewett and Feder 1983). A food analysis of 428 Tanner crab, taken mainly from the western and southwestern portions of the Inlet, revealed that crab of different size, sex, and state of maturity consumed diverse but similar prey species (Paul, Feder, and Jewett 1979). The four major food items were: 1) small clams—44%, 2) hermit crabs—34% frequency of occurrence, 3) barnacles—18%, and 4) crangonid shrimps—9%. Occasionally, the crab preyed upon polychaetes, gastropods, amphipods, and ophiuroids. Stomach contents typically reflected prey species common to a given area. Furthermore, most of the prey species tended to use detrital or suspended material either directly or indirectly.

The Tanner crab is currently the target species found within the ADF&G Cook Inlet Shellfish Management Area. Historically, the Kamishak Bay and Barren Islands districts have produced most of the commercial Tanner crab; the Southern District, which includes both mid- and outer Kachemak Bay, has been of secondary importance. There has been a gradual decline in landings since the high of 3.5×10^3 mt during the 1973–1974 season. The 1983–1984 har-

vest was only 1.3×10^3 mt as of March 1985 (ADF&G 1985b). The crabbing fleet within the Southern District in the 1984–1985 season had doubled from recent years to ~80 vessels. Regardless of the increased effort during this season, the harvest trend is expected to continue in a downward direction for at least the next few years (S. Kyle, ADF&G, pers. comm., 1984).

Although the Dungeness crab was among the top twelve biomass-dominating epifauna captured in Cook Inlet trawl studies between 1976 and 1978, it only accounted for 1.2% of the epifaunal weight (Table 12-17). Furthermore, its distribution was generally confined to the Kachemak Bay area.

As a predator/scavenger, the Dungeness crab feeds on a number of benthic prey species. In 1977–1978, those crab over 50 mm in carapace width from Kachemak Bay primarily preyed on: 1) small bivalves—67% frequency of occurrence, 2) barnacles—11%, and 3) amphipods—6% (Feder and Paul 1980). For smaller crab (carapace widths 22 to 44 mm), the most frequent prey were: 1) Foraminifera—36% frequency of occurrence, 2) polychaetes—28%, 3) barnacles—28%, and 4) small bivalves—25%.

Dungeness crab have been harvested commercially in lower Cook Inlet since 1961. Annual catches have fluctuated markedly— from the smallest catch of 3.2 mt in 1967 to the largest catch of 968.6 mt in 1979. The average annual harvest from 1961 through 1984 was 283 mt, with most of the catch taken from near Kachemak Bay (ADF&G 1985b). The 1984 catch was nearly 364 mt, 75% of which came from the inner embayments of Kachemak Bay rather than from the Bluff

Table 12-19.
Dominant epifaunal invertebrates from deep (>25 m) regions in lower Cook Inlet (Feder and Paul 1981). The species are ranked in decreasing order of abundance and biomass.

REGION	ABUNDANCE	BIOMASS
Inner Kachemak Bay	<i>Pandalus borealis</i>	<i>Pandalus hypsinotus</i>
	<i>Pandalus goniurus</i>	<i>Pandalus borealis</i>
	<i>Pandalus hypsinotus</i>	<i>Pandalus goniurus</i>
Mid- Kachemak Bay	<i>Pandalus borealis</i>	<i>Chionoecetes bairdi</i>
	<i>Crangon dalli</i>	<i>Pandalus borealis</i>
	<i>Cucumaria fallax</i>	<i>Cancer magister</i>
Outer Kachemak Bay	<i>Strongylocentrotus droebachiensis</i>	<i>Cucumaria fallax</i>
	<i>Cucumaria fallax</i>	<i>Strongylocentrotus droebachiensis</i>
	<i>Echinarachnius parma</i>	<i>Echinarachnius parma</i>
Central Cook Inlet	<i>Echinarachnius parma</i>	<i>Chionoecetes bairdi</i>
	<i>Chionoecetes bairdi</i>	<i>Echinarachnius parma</i>
	Crangonidae	<i>Ptilosarcus gurneyi</i>
Outer Cook Inlet	<i>Chionoecetes bairdi</i>	<i>Chionoecetes bairdi</i>
	Crangonidae	<i>Paralithodes camtschatica</i>
	<i>Pandalus borealis</i>	<i>Neptunea lyrata</i>
Upper Kamishak Bay	<i>Crangon dalli</i>	<i>Chionoecetes bairdi</i>
	<i>Pandalus goniurus</i>	<i>Neptunea lyrata</i>
	<i>Chionoecetes bairdi</i>	<i>Paralithodes camtschatica</i>
Lower Kamishak Bay	Crangonidae	<i>Chionoecetes bairdi</i>
	<i>Chionoecetes bairdi</i>	<i>Paralithodes camtschatica</i>

Point area which has traditionally yielded large quantities. The majority of the harvest is normally taken from May through October. The ex-vessel value of the 1984 harvest was approximately \$1.08 million (ADF&G 1985b).

Although king crab only accounted for ~7% of the epifaunal biomass sampled during the Cook Inlet OCSEAP investigations (Table 12–17), the following account of the distribution, biomass, and relative abundance of this crab is appropriate because of its historic importance to Cook Inlet and adjacent Gulf of Alaska waters (ADF&G 1985 a,b,c,d).

King crab occurred in Kachemak and Kamishak Bays during all eight sampling months (March through August, October, and November). However, during October 1976 they also occurred within the Tanner crab nursery grounds of the outer Inlet. Over 95% of the king crab captured during all sampling periods were sexually mature individuals.

King crab within Kachemak and Kamishak Bays are apparently resident populations since adult crabs were found there in all periods. Crab of various sizes were often found in Kachemak Bay associated with remnants of macroalgae, hydroids, sponges, and bryozoans on the bottom. One station in outer Kachemak Bay yielded 28 juveniles with a biomass of 10.7 g/m² in March 1978. These crab were associated with the macroalgae, hydroids, and other taxa mentioned above.

Evidence of a major king crab nursery along the shallow (<27 m), rocky perimeter of outer Kachemak Bay from Diamond Gulch to Mutnaia Gulch is presented by Sundberg and Clausen (1977). Furthermore, Haynes (1977) reported that the concentration of glaucothoe larvae in the same general area, between Anchor Point and Bluff Point, implies that this area is especially important for the settling of king crab larvae.

King crab populations within Kamishak Bay were dominated by adults. The few juveniles taken were generally larger than those encountered in Kachemak Bay. Since a suitable habitat for king crab larval settlement was not observed and a resident adult population apparently exists there, suitable juvenile habitat presumably occurs nearby at shallower depths within the Bay. Many Kodiak Island regions that are shallow, rocky, and rich in epiphytic growth are ideal environments for king crab mating, spawning, egg-hatching, and juvenile-rearing activities (Jewett and Powell 1981).

The red king crab, like Tanner and Dungeness crabs, is a scavenger/predator capable of taking a variety of prey (Feder and Jewett 1981a; Jewett and Feder 1982). The food found in crabs from the Kachemak Bay region was dominated by the pinkneck clam *Spisula polynyma* (found in 38% of the crab stomachs). Barnacles were found in 14% of the crab stomachs, and the snail *Neptunea lyrata* was found in 11 percent. An additional 25 food categories were observed (Feder and Paul 1980; Feder, Paul, Hoberg, and Jewett 1981). The food of post-larval individuals (3–5 mm carapace length) from northwest Kachemak Bay consisted of: 1) unidentified crustaceans—45% frequency of occurrence, 2) polychaete worms—31%, 3) foraminiferans—27%, and the bryozoan *Flustrella* sp.—10%. Sediment was found in 93% of the tiny crab (Feder, McCumby, and Paul 1980).

Among the 20 food categories identified from the stomachs of Kamishak Bay king crab, the three most frequently observed prey were barnacles (81% frequency of occurrence), bivalves of the family Mytilidae (13%), and hermit crabs (12%) (Feder and Paul 1980).

Benthic samples from stations adjacent to Augustine Island often revealed the presence of volcanic bombs or pumice which resulted from the eruption of Augustine volcano in February 1976. Prior to the eruption, the bottom around the Island had little rocky substrate, and therefore, settling organisms such as barnacles were restricted primarily to biological substrates such as shells and crab carapaces. During the April and October 1976 surveys, pumice samples were examined for settling organisms, and no settlement was apparent. However, similar samples taken in November 1977 revealed that large numbers of barnacles (*Balanus* sp.), had settled on most of the volcanic bombs we examined (Feder 1978). Feder and Paul (1980) examined the stomach contents of potential barnacle predators taken in trawls during November 1977. Thirty-six king crab collected at a single station had full stomachs. All the crab had barnacles in their stomachs and 60% of these crab were feeding exclusively on barnacles. Judging from both the weights of the barnacle hard parts from within crab stomachs and from live specimens on the bombs, the average number of barnacles in each crab stomach was estimated as 11.2 (SD = 7.4).

Other organisms taken in the trawls from this region were the hermit crab *Pagurus ochotensis* and the Tanner crab, both of which were feeding on barnacles. Apparently, the substrate provided by the volcanic eruption on Augustine Island had an important effect on both the population densities of the barnacles and the food habits of the crabs.

The king crab fishery is the oldest commercial shellfish fishery in Cook Inlet. The earliest recorded commercial landings occurred in 1937 when crabs were canned at a Halibut Cove packing facility (ADF&G 1985b). From the late 1960s through 1976 the seasonal total catch ranged from 1.1– to 2.2 × 10³ mt. Since that time, catches have generally been decreasing. Since the 1982–1983 season, the Southern District (mid- and outer Kachemak Bay) has been closed. The 1983–1984 Cook Inlet king crab harvest of 87.7 mt was a record low and was 93% below the 16-year average of 1.3 × 10³ mt (ADF&G 1985b). The entire Cook Inlet management area was closed during 1984–1985, and the outlook for opening the fishery within the next several years is grim. Reasons that have been suggested for the declining population are the prevalence of 1) viruses, 2) microsporidians, 3) rhizocephalans, 4) egg predation by the nemertean worm *Carcinonemertes errans*, and 5) predation of larvae and juveniles by various fishes (Melteff 1985). All of these factors have been observed in Cook Inlet or adjacent waters.

Three numerically important species of pandalid shrimps (*P. borealis*, *P. gonivurus*, and *P. hypsinotus*) are also harvested commercially in lower Cook Inlet. The major trawl fishery has historically taken place in the Southern District which includes Kachemak Bay. Population-abundance-index surveys have been completed each year in Kachemak Bay since 1971 by ADF&G (1985b). Since the May 1979 index survey, the abundance index has been decreasing. After

completion of the May 1983 abundance–index survey in Kachemak Bay, the stock decreased to the point where a commercial fishery was not warranted. The fishery was reopened in January 1984. Information gathered from that winter fishery and the subsequent spring index survey indicated that continued harvest was warranted in the 1984–1985 season and ~682 mt were harvested with 79% of the harvest taken inside the Homer Spit. Species composition samples collected throughout that season were approximately: 75% *P. borealis*, 12% *Pandalopsis dispar*, 10% *P. goniurus*, and 3% *P. hypsinotus* (ADF&G 1985b).

Food samples taken from *P. borealis*, *P. hypsinotus*, and *P. goniurus* in lower Cook Inlet revealed that they are active predators of infaunal invertebrates as well as foragers that ingest detritus and sediment (Rice *et al.* 1980). Approximately 20 food categories were recorded for each of these shrimp species, with diatoms, polychaetes, bivalves, and crustaceans as the most frequently consumed food groups. Sediment was observed in at least 60% of each species.

Crangonid shrimps are not harvested commercially in lower Cook Inlet (or elsewhere in Alaska), but were abundant in trawl samples taken there. *Crangon dalli* was the dominant species taken (Feder and Paul 1981) (Table 12–19). These shrimps are food generalists, and Rice (1980) describes 60 categories of food for them in Cook Inlet. The most important food items were polychaetes, crustaceans, and bivalve mollusks. Most organisms used as food were deposit feeders, as evidenced by sediment and detrital material that was found in stomachs of all the feeding shrimp. The high occurrence of sediment in shrimp stomachs (typically more than 60% on a dry weight basis) and the types of food utilized by them suggest that these crustaceans rely heavily on the sediment/detrital system for food (Rice 1980).

Sediment ingestion is described as relatively important in *Crangon septemspinosa*, with sand representing 4% of the total volume of stomach contents (Wilcox and Jeffries 1974). In crangonids from Cook Inlet, inorganic sediment constituted over 56% of the stomach contents on a dry weight basis. A high percentage of sediment in stomach contents of pandalid shrimps and hermit crabs in lower Cook Inlet was also noted by Rice *et al.* (1980) and Feder, Paul, Hoberg, and Jewett (1981). Moriarity (1976) reported that the prawn *Metapenaeus* sp. ingests sediment and uses bacteria for food as part of its natural diet elsewhere. Preliminary experiments by Rice (1980) imply that *Crangon dalli* may also be able to assimilate the bacterial carbon that is associated with sediments. He suggests that, during low food levels, shrimp use the carbon that is associated with sediment (inclusive of microbial carbon) as a nutrient supplement.

In Cook Inlet, crangonids are an important food source for Tanner crab (Paul, Feder, and Jewett 1979) and bottom-feeding fishes (Feder, Paul, Hoberg, and Jewett 1981), including:

- starry flounder (*Platichthys stellatus*)
- halibut (*Hippoglossus stenolepis*)
- Pacific cod (*Gadus macrocephalus*)
- rock sole (*Lepidopsetta bilineata*)
- flathead sole (*Hippoglossoides elassodon*)
- walleye pollock (*Theragra chalcogramma*).

The Western Gulf of Alaska and Kodiak Island Regions

General Western Gulf Region—Infauna and Epifauna. The shelf of most of the western Gulf (*i.e.*, west of Cape Igvak) consists of slopes characterized by marked dissection and steepness—with many banks and reefs, numerous coarse, clastic, or rocky bottoms, and patchy bottom sediments. In contrast, the shelf adjacent to the Kodiak Archipelago consists of flat, relatively shallow banks cut by transverse troughs (Fig. 12–10). Unconsolidated sediments of the entire western shelf are distributed in relation to: 1) the physiography of the bottom and 2) local currents and related turbulence.

The banks are exposed to both wave and current action (particularly during winter storms) that continually resuspend bottom sediments and winnow out the finer sands, silts, and clays. Bottom materials such as sand, gravel, boulders, and broken shells are most characteristic of the banks. Other, less common features are fine sediments which accumulate in local depressions, and ridges that expose siltstones and silty sandstones. The deeper troughs commonly contain fine sands and muds made up in large part by volcanic ash (Bouma and Hampton 1976; Hampton *et al.*, Ch. 5, this volume).

The investigations of Semenov (1965) demonstrated that large areas of the bottom of the western Gulf were dominated by sessile suspension (filter) feeding infauna and epifauna (*e.g.*, sponges, sabellid and serpulid polychaetes, nesting clams (Saxicavidae), barnacles, and the brachiopod *Terebratulina unguicula*), with the biomass exceeding 3,000 g/m² in some regions. The biomass of this trophic group in the western Gulf was 112 g/m² (62% of the total biomass) (Table 12–2). Although sessile suspension feeders were common in the shallow sublittoral, they were most abundant at the shelf edge where valleys separate the broad plateaus from the coastal areas. Many of these plateaus form banks with complex relief and rock outcrops that are covered with coarse sediments—a substratum that is ideal for sessile suspension feeders. Separate patches of non-mobile filter feeders were encountered in the coastal regions such as Unimak Pass, southwest of the Shumagin and Trinity Islands, and east of Afognak Island.

Mobile suspension (filter) feeders (*e.g.*, the bivalve mollusks Pectinidae, Carditidae, Glycymeridae, Astartidae, *Serripes* sp., and *Cardium* sp., the amphipods *Ampelisca* spp., and the sand dollar *Echinarachnius parma*) also dominated in the western Gulf. They occurred mainly in two areas: 1) on the plateau-like surfaces of the shelf in areas with smooth relief and a predominance of sandy sediments and 2) on the sides of troughs and canyons where sand has accumulated. The organic level was low in these sediments. The biomass of this trophic group in the western Gulf was 26 g/m². This trophic group was also commonly found adjacent to the islands where coarse sands and broken shell occur.

Browsers and selective deposit-feeders—browsing detritus-feeders according to Semenov (1965) (*e.g.*, terebellid polychaetes and the bivalve mollusks *Nucula tenuis*, *Nuculana fossa*, *Yoldia* spp., and *Macoma* spp.)—were most common on bottoms which had a smooth relief and which were covered with fine-grained sand or muddy sediments at depths of from 52 to 158 meters. The organic carbon content

ens from 30 m at the entrance to 175 m in the innermost region. Approximately 1.9 km² of the bottom was trawled, with near-equal allocation at depths of less than 50 m, 50 to 100 m, and greater than 100 meters. A variety of substrate types yielded diverse assemblages of epifauna. Most of the species encountered were predator/scavengers, although low numbers of suspension feeders such as *Ptilosarcus gurneyi*, *Balanus* spp., and *Cucumaria* sp. occurred throughout the Bay.

Taxonomic analysis delineated 10 epifaunal phyla with 60 genera and 79 species. Two groups—Arthropoda (Crustacea) and Mollusca—dominated species representation, accounting for 34 and 22 species, respectively. The epifaunal biomass for all periods was 6.2 g/m² (Table 12-20), with the lowest biomass occurring in August (3.2 g/m²) and the highest biomass occurring in March (10.6 g/m²).

Five shrimp and two crab species accounted for 94.3% of the biomass (Table 12-20). Pink shrimp dominated the shrimps, yielding nearly 13% of the total biomass and averaging 9.9 kg/km. Abundant pink shrimp catches were obtained during June, July, and August from the middle and outer portions of the Bay. Although pink shrimp were not carrying eggs during June and July, in August aqua-colored eggs were either visible through the cephalothorax or were attached to the abdominal appendages. By the following March, eyes were visible in the developing embryos. Crangonid shrimps and other pandalid shrimps displayed similar timing for egg maturation.

King and Tanner crabs together accounted for nearly 75% of the biomass from Alitak Bay, with similar total weights for each species (Table 12-20). The king crab catch was 2.2 g/m², or 27.3 kg/km. Throughout the sampling period, king crab occurred mainly in the outer portion of the Bay and consisted primarily of egg-bearing females and juveniles of both sexes. Oviparous king crab were collected in the four sampling periods, and concentrations were so great in the outer Bay in March 1977 that sampling had to be discontinued at seven stations to avoid damaging the crab. The female-to-male ratio of mature king crab in the outer Bay was 7.4 to 1 for all periods.

Adult red king crab typically migrate into shallow waters to spawn from April through June. After they breed, they gradually migrate back to deeper water (Wallace, Pertuit, and Hvatum 1949; Powell 1964). The inshore waters of the Kodiak Island Archipelago provide a suitable environment for their molting, breeding, and feeding activities (Jewett and Powell 1981; Jewett and Feder 1982), although king crab are also known to breed on offshore banks (McMullen 1967a, b). Adult king crab were nearly absent from trawl catches on the Kodiak shelf in March 1978, and their absence presumably reflects their migration to shallow water for molting and mating.

Alitak Bay has traditionally been a major king crab mating area (Gray and Powell 1966; Kingsbury and James 1971), and until recently, the outer Bay and adjacent waters have produced substantial commercial quantities (ADF&G 1980).

Red king crab has been commercially harvested from the Kodiak Island area since 1960, and has dominated the commercial fisheries there for many of those years. The average catch for the years 1960 through 1983 was 1.1×10^4 mt, or 2.9×10^6 crab (ADF&G 1985a). The 1981-1982 harvest of 1.1×10^4 mt fell to 4.0×10^3 mt in 1982-1983, and by the 1983-1984 season, stocks were so low that the fishery was not opened. Furthermore, the fishery is expected to remain closed for the next several years in order for stocks to rebuild. ADF&G stock-assessment surveys in the latter years of the fishery had indicated that recruitment would be depressed for a few years, but not to the extent of an indefinite fishery closure (J. McCrary and G. Powell, ADF&G, pers. comm., 1984). Biologists are unable to identify definite reasons for the collapse. However, individuals closest to the fishery suspect an interaction of such factors as:

- physical/chemical changes in the environment
- increased predation by bottomfishes (Pacific cod and Pacific halibut)
- food competition with bottomfishes
- egg predation by a nemertean worm
- parasitism
- management problems.

Table 12-20.

Biomass of the major epifaunal taxa of Alitak and Ugak Bays. Sampling periods: June through August 1976; March 1977 (Feder and Jewett 1977).

TAXA	ALITAK BAY				UGAK BAY			
	BIOMASS (g/m ²)		% OF TOTAL BIOMASS		BIOMASS (g/m ²)		% OF TOTAL BIOMASS	
Porifera	0.022		0.35		0.044		1.24	
Cnidaria	0.006		0.10		0.022		0.62	
Mollusca	0.008		0.13		0.003		0.08	
Arthropoda (Crustacea only)	5.938		95.16		3.387		95.68	
<i>Pandalus borealis</i>		0.810		12.98		0.438		12.37
<i>P. goniurus</i>		0.138		2.21		0.125		3.53
<i>P. hypsinotus</i>		0.212		3.40		0.126		3.56
<i>Pandalopsis dispar</i>		0.025		0.40		0.001		0.03
<i>Eualis gaimardii belcheri</i>		0.042		0.67		0		0
<i>Paralithodes camtschatica</i>		2.237		35.85		1.285		36.30
<i>Chionoecetes bairdi</i>		2.423		38.83		1.361		38.45
Echinodermata	0.011		0.18		0.068		1.92	
Other	0.255		4.08		0.016		0.45	
Totals	6.240	5.887	100.00	94.34	3.540	3.336	100.00	94.24

The biomass of trawl-caught Tanner crab in Alitak Bay was 2.4 g/m² (Table 12-20), or 29.6 kg/km. Adult males were the main component of the population during summer months, although ovigerous females were also present. Adult males mainly occupied the deeper waters of the inner half of the Bay, and adult females were found mainly in shallower waters in the outer Bay. Females with eggs in the eyed stage were abundant during March, indicating that larval hatching was approaching. An adult population apparently resides in the Bay throughout the year, since adult males are commercially harvested during winter months.

The infaunal prey of king and Tanner crabs in Alitak Bay was dominated by clams—specifically, the selective deposit feeder *Nuculana fossa*. Unidentified decapods and fishes were also important prey (Table 12-21).

Alitak Bay and adjacent outside waters have historically yielded moderate catches of Tanner crab, Dungeness crab, and pink shrimp. The 1983-1984 Tanner crab harvest from this region produced 121 mt, or only 1.8% of the Kodiak Island catch. The Dungeness crab harvest for the 1984-1985 season was 46 mt, or 1.9% of the Kodiak Island harvest. Approximately 670 mt of pink shrimp were also harvested from Alitak Bay in June and July 1984. An additional 182 mt were taken from adjacent Olga Bay in June and July 1984 (ADF&G 1985a).

Ugak Bay. Ugak Bay lies along the eastern coast of Kodiak Island and extends nearly 30 km from the entrance to the head (Fig. 12-10). The benthic environment throughout Ugak Bay is characterized as mainly depositional, although suspension-feeding organisms such as barnacles, ectopods, brachiopods, and *Cucumaria* sp. occur in scattered locations. Soft substrata predominate at relatively uniform depths between 50 and 100 meters. The trawl surveys in Ugak Bay in 1976-1977 covered nearly 2.0 km² and yielded

epifaunal taxa similar to those from Alitak Bay, although the overall biomass from Ugak Bay (3.5 g/m²) was only about half that of Alitak Bay (Table 12-20). The reduced biomass was attributed to the fact that pink shrimp, king crab, and Tanner crab all had biomass values that were only half of their values in Alitak Bay. Catch composition of both crab species was similar to the catch composition from Alitak Bay.

Clams, including the deposit-feeding *Nuculana fossa*, were the dominant infaunal prey of king and Tanner crabs in Ugak Bay in 1978-1979. Other prey were unidentified decapods and fishes (Table 12-21).

Ugak and Alitak Bays also had similar shellfish harvests. In 1983-1984, 400 mt (6.1% of the Kodiak area harvest) of Tanner crab were harvested from the Ugak Bay district. The 1984-1985 Dungeness crab harvest was 473 mt, or 19.6 % of the island-wide catch (ADF&G 1985a).

Kiliuda Bay. Kiliuda Bay, which lies immediately south of Ugak Bay, extends ~22 km into the eastern coast of Kodiak Island (Fig. 12-10). Water depths are typically less than 100 meters. Substrate composition is similar to Alitak Bay, where mud and rock bottom occurs; however, soft bottoms are most prevalent in Kiliuda Bay.

The trawling activities of 1978-1979 occurred mainly in the outer half of Kiliuda Bay. Approximately 60% of the trawling occurred at depths less than 50 m and ~40% at 50- to 100-m depths. The epifaunal biomass of the Bay was 3.2 g/m², with nearly 94% of this value comprised of five species: 1) the anemone *Metridium senile*, 2) pink shrimp, 3) king crab, 4) Tanner crab, and 5) Dungeness crab (Table 12-22). Predators and scavengers dominated the biomass here. The suspension-feeding *M. senile* was mainly taken at 60-m depths along the south side of the outer Bay. Dungeness crab mainly occurred in shallower waters close to shore.

Table 12-21.

Dominant food of king and Tanner crabs from four bays of the Kodiak Island Archipelago. Prey are listed as percent frequency of occurrence (Feder and Jewett 1977; 1981b).

	ALITAK BAY		UGAK BAY		KILIUDA BAY		IZHUT BAY	
	K.C. ^a	T.C. ^b	K.C.	T.C.	K.C.	T.C.	K.C.	T.C.
	N ^c = 37	N = 34	N = 10	N = 36	N = 329	N = 142	N = 40	N = 417
Hydrozoa					5.2	3.5	10.0	11.7
Polychaeta		23.5		5.6	26.1	17.6		19.7
<i>Nucula tenuis</i>					19.8	5.6		9.6
<i>Nuculana fossa</i>	18.9	2.9	40.0	13.9	32.5	6.3	10.0	5.3
<i>Yoldia</i> sp.					4.6	3.5	2.5	
<i>Axinopsida serricata</i>					12.5	14.1	5.0	16.8
<i>Macoma</i> spp.					34.0	12.0		6.7
<i>Clinocardium ciliatum</i>					12.8		12.5	2.1
Unidentified Pelecypoda	10.8	26.5	30.0	27.8	16.1	14.1	5.0	15.3
Unidentified Gastropoda	13.5		10.0		22.2		2.5	2.4
<i>Balanus</i> spp.					21.3	8.4		
<i>Chionoecetes bairdi</i>					11.2	13.4		12.7
Unidentified Decapoda	13.5	23.5	10.0	25.0	21.3	39.4	15.0	13.0
Ophiuroidea					3.9	2.1	2.5	3.1
Pisces	18.9	8.8	20.0	5.6	7.6	21.1	65.0	28.1
Plant material	5.4	38.2	10.0	22.1	13.4	7.0	30.0	8.1
Sediment		55.9		27.8	20.0	40.8	12.5	51.8

^aK.C. = king crab

^bT.C. = Tanner crab

^cN = number of stomachs examined

Table 12-22.

Biomass of the major epifaunal taxa of Kiliuda and Izhut Bays. Sampling periods: April through August, November 1978; March 1979 (Feder and Jewett 1981b).

TAXA	KILIUDA BAY			IZHUT BAY		
	BIOMASS (g/m ²)	% OF TOTAL BIOMASS		BIOMASS (g/m ²)	% OF TOTAL BIOMASS	
Porifera	<0.001	0.01		0.023	0.61	
Cnidaria	0.185	5.74		0.037	0.96	
<i>Metridium senile</i>		0.175	5.43	0.033		0.84
Mollusca	0.063	1.95		0.054	1.39	
<i>Fusitriton oregonensis</i>		0.043	1.34	0.011		0.29
Arthropoda (Crustacea)	2.939	90.97		2.937	75.83	
<i>Pandalus borealis</i>		0.865	26.77	0.743		19.18
<i>Paralithodes camtschatica</i>		1.375	42.55	0.090		2.33
<i>Chionoecetes bairdi</i>		0.571	17.67	1.830		47.23
<i>Cancer magister</i>		0.071	2.20	0.150		3.88
Echinodermata	0.042	1.30		0.814	21.02	
<i>Pycnopodia helianthoides</i>		<0.001	0.02	0.698		18.03
Other	0.001	0.03		0.007	0.18	
Totals	3.231	3.101	100.00	3.872	3.555	100.00
			95.98			91.78

The infaunal prey most frequently consumed by king and Tanner crab from Kiliuda Bay included polychaete worms, gastropods, and bivalves (specifically the deposit feeders *Nuculana fossa*, *Nucula tenuis*, *Yoldia* spp., and *Macoma* spp., and the suspension feeder *Axinopsida serricata*) (Table 12-21). *Clinocardium ciliatum*, a suspension-feeding cockle, was also taken by king crab. Other important prey of both crab species were barnacles, Tanner crab, and fishes. The barnacle, *Balanus crenatus*, a suspension feeder, was mainly consumed at shallower depths in May, June, and July. Barnacles represent a major food source for recently molted king crab in shallow waters (Jewett and Feder 1982). No feeding data are available for Dungeness crab for Kiliuda Bay. However, feeding habits are presumably similar to those observed for this crab in lower Cook Inlet (Feder and Paul 1980).

As a commercial shellfish producer, Kiliuda Bay yielded 341 mt (5.2% of the Island-wide catch) of Tanner crab and 43 mt (1.8%) of Dungeness crab for the 1983-1984 season. Pink shrimp landings from Kiliuda Bay from 1974 and 1978 were between 2.7- and 4.0 × 10³ mt annually. However, no landings have been made there since 1978 (ADF&G 1985a).

Kiliuda, Ugak, and Alitak Bays resemble lower Cook Inlet in depth, substrate, water movement, epifauna, and commercial shellfishes. These embayments are characterized by a diverse benthic fauna with the epifauna generally dominated by commercial crabs and shrimps. Our data indicate that the common deposit- and suspension-feeding infauna present in these embayments are important components in the diet of the crustaceans there.

Izhut Bay. Izhut Bay is located north of Kodiak Island, along the southern shore of Afognak Island (Fig. 12-10). This Bay is the shortest and deepest of the four bays that we studied. It is nearly 15 km long with a 2.5-km-wide trough of deep water (>100 m) extending ~11 km into the Bay. The substrate of the trough is mainly composed of fine mud, with a sublayer of anoxic mud in the deeper regions of the outer bay. Mixed substrates prevail at shallower depths.

The trawl surveys of 1978-1979 covered 0.8 km² of the bottom of Izhut Bay. Because a small (6.1 m) trawl net was used most of the time, the shallower depths were sampled most intensively (i.e., 67% at <50 m, 25% at 50-100 m, and 7% at >100 m). The southeast portion of the Bay, near the entrance, was given the greatest attention. The overall epifaunal biomass was 3.8 g/m² (Table 12-22). Notable findings here were the presence of relatively few king crab and the abundance of sunflower sea stars. Important species, in decreasing order of biomass, were (Table 12-22):

- Tanner crab (*Chionoecetes bairdi*)
- pink shrimp (*Pandalus borealis*)
- sunflower sea star (*Pycnopodia helianthoides*)
- Dungeness crab (*Cancer magister*)
- red king crab (*Paralithodes camtschatica*).

Dominant infaunal prey taken by king crab at 180 m in outer Izhut Bay during June and July 1978 were the bivalves *Nuculana fossa* (deposit feeder), *Clinocardium ciliatum*, and *Axinopsida serricata* (suspension feeders), and brittle stars (browser/predator/deposit feeders) (Table 12-21). The mixed feeding habits of these prey organisms suggest that the bottom of Izhut Bay is not a strictly depositional environment—even though the depth and the substrate suggest that it should be.

The dominant prey taken by king crab from Izhut Bay in June and July 1978 were fishes—a prey of opportunity. This presumably resulted from intense surface feeding by sooty shearwaters, black-legged kittiwakes, and Steller sea lions, all of which were feeding on schooling fishes such as capelin (*Mallotus villosus*) and sand lance (*Ammodytes hexapterus*). These fishes may have fallen to the bottom after they were either injured or regurgitated by predators, and could then have been eaten by the crab.

Izhut Bay typically yields only small landings of commercially important shellfishes. Recent Tanner and Dungeness crab harvests were each less than 0.5% of the overall Kodiak district harvest (ADF&G 1985a).

The infaunal species consumed by Tanner crab in outer Izhut Bay consisted primarily of polychaetes and bivalves, including *Nucula tenuis*, *Axinopsida* spp., and *Macoma* spp. Other important prey were pandalid shrimps, juvenile Tanner crab, and fishes.

No feeding data are available for Dungeness crab for Izhut Bay. However, feeding habits are presumably similar to those observed for this crab in lower Cook Inlet (Feder and Paul 1980).

The sunflower sea star's food reflected the dynamic environment of the shallower depths. Dominant items included predatory snails (*Oenopota* sp., *Solariella* sp., *Mitrella gouldi*, and *Natica clausa*), bivalves (*Nuculana fossa*, *Psephidia lordi*, *Spisula polynyma*, *Clinocardium ciliatum*, and *Mya* spp.), and barnacles (*Balanus* spp.).

Portlock Bank. Although little is known of the epifauna of Portlock Bank, the dynamic character of the physical environment there indicates that suspension feeders and predator/scavengers should be dominant. An exploratory king crab trawl survey on Portlock Bank in the spring of 1966 revealed a king crab spawning ground on a substrate composed predominantly of rock and shell material (McMullen 1967b). In 1967, the ADF&G conducted an exploratory scallop survey covering most of Portlock Bank (P. Jackson, ADF&G, pers. comm.). Observations revealed that the southwestern portion of the Bank contained the greatest total biomass as well as the greatest epifauna species diversity. Common representatives were sea pens, king crab, scallops, sea cucumbers, and brittle stars. Kelp fragments (*Nereocystis*) were also common. Since the late 1960s, both scallops and king crab have been commercially harvested from the western portion of Portlock Bank (Ronholt *et al.* 1978; Science Applications, Inc. 1980).

In 1978, a trawl survey (Feder and Jewett 1981b) of a sandy station in the western edge of Portlock Bank revealed that the fauna was dominated by the sand dollar *Echinarachnius parma*, the sea pen *Ptilosarcus gurneyi*, and to a lesser extent by king crab (Table 12-23). The most abundant infaunal organisms collected by dredge from the same location were a mixture of deposit- and suspension-feeding organisms that included tube-dwelling amphipods, *E. parma*, a brittle star, and several clam species (Table 12-24). Grab sampling (Semenov 1965) demonstrated that both sessile and mobile suspension feeders such as sponges, bivalves (Glycymeridae, Astartidae, and Veneridae), barnacles, brachiopods, and *E. parma* were more common than deposit feeders on Portlock Bank. Furthermore, the biomass of sessile suspension feeders (mean of 600 g/m²) was about 12 times greater than the biomass of browsers and selective deposit feeders (mean of 48 g/m²) (Semenov 1965). The fact that both deposit and suspension feeders were present at the same dredge stations underscores the patchy distribution of faunal types.

Echinarachnius parma is occasionally taken as food by king crab (Jewett and Feder 1982). Crab that have recently preyed intensively on sand dollars often displayed external evidence of this feeding in the form of an obvious green stain along the crushing margin of the chelipeds. Subsequent examination of crab stomachs and gut contents have linked the green chelae to sand dollars with green tests.

The suspension-feeding sea pen, *P. gurneyi*, typically resided in sandy areas at depths between 10 and 100 m, where light-to-moderate currents prevail.

North Albatross Bank. North Albatross Bank is somewhat similar to Portlock Bank in terms of both substrate and fauna. However, the bottom depressions of Albatross Bank are covered by muddy sediments with an admixture of shell and pebbles. These sediments were occupied by large numbers of browsers and selective deposit feeders such as terebellid polychaetes, bivalves (*Macoma* spp.), and ophiuroids (Semenov 1965). Representatives of these two trophic groups had a combined mean biomass of 74 g/m². The most abundant infaunal organisms collected by dredge were of mixed feeding types with the brittle star (*Ophiopholis aculeata*) the dominant species (Table 12-24). A brittle star, presumably *O. aculeata*, dominated the food of the king crab that were collected here. The coarse substrata on all of Albatross Bank yielded an array of suspension-feeding macroinvertebrates that were dominated by sessile suspension feeders (mean of 766 g/m²) (Semenov 1965).

Those epifaunal species commonly encountered on this Bank during exploratory dredging for scallops in the 1960s were hydroids, scallops, sea stars, sea cucumbers, and brittle stars (P. Jackson, ADF&G, pers. comm.). The western portion of the bank is another offshore spawning ground for king crab (McMullen 1967a, b). Past fisheries for king crab and scallops have periodically been intense on this Bank (ADF&G 1980). Two stations where trawl surveys were conducted in 1978-1979 were found to be dominated by the mussel *Modiolus modiolus* and by a sea cucumber. These two species accounted for 67 and 22% of the biomass taken in the trawls, respectively.

Middle Albatross Bank. Little information is available concerning the epifauna of Middle Albatross Bank. Trawl surveys on this bank were only conducted at two sand-shell dominated stations (1978) off the eastern shore of Kodiak Island. The pooled epifaunal biomass of these two stations was 1.8 g/m² (Table 12-23). The sea anemone *Metridium* sp., king crab, and Tanner crab accounted for 45.4, 27.7, and 19.4% of the biomass, respectively. The western portion of Middle Albatross Bank has historically yielded commercial quantities of both of these crab species, although in recent years no king crab have been harvested. During the 1983-1984 fishing season, nearly 73 mt or 1.1% of all Tanner crab from the Kodiak district came from the waters of Middle Albatross Bank, outside of Ugak and Kiliuda Bays, and north Sitkalidak Strait (ADF&G 1985a). The suspension-feeding bivalve *Psephidia lordi* was the most numerous infaunal species taken by dredge in this region (Table 12-24).

South Albatross Bank. No benthic sampling was conducted on south Albatross Bank. Commercial Tanner crab production on south Albatross Bank was slightly less than on Middle Albatross Bank (ADF&G 1985a).

South Kodiak Island. The waters at the south end of Kodiak Island, west of Sitkinak Island, at depths shallower than 100 m have historically yielded high catches of king, Tanner, and Dungeness crabs. During the 1983-1984 season, nearly 42% (903 mt) of the Kodiak Dungeness crab catch came from waters surrounding the Trinity Islands (ADF&G 1984).

Table 12-23.

Dominant epifauna collected by trawl from some subtidal regions of the Kodiak Shelf (H.M. Feder and S.C. Jewett, University of Alaska, unpubl. OCSEAP data on file at NODC; Feder and Jewett 1981b).

AREA	DEPTH (m)	TOTAL STATIONS SAMPLED	AREA SAMPLED (km ²)	AREA BIOMASS (g/m ²)	DOMINANT TAXA	PERCENT OF AREA BIOMASS
W. Portlock Bank	64-73	1	0.020	8.1	<i>Echinarachnius parma</i>	46.1
					<i>Ptilosarcus gurneyi</i>	44.2
					<i>Paralithodes camtschatica</i>	7.3
N. Albatross Bank	69-93	2	0.045	6.8	<i>Modiolus modiolus</i>	67.0
					Holothuroidea	21.9
					<i>Halocynthia helgendorfi igaboja</i>	4.5
					<i>Pododesmus macroschisma</i>	3.9
					Hydrozoa	1.5
Middle Albatross Bank	46-59	2	0.062	1.8	<i>Metridium</i> sp.	45.4
					<i>Paralithodes camtschatica</i>	27.7
					<i>Chionoecetes bairdi</i>	19.4
					<i>Ptilosarcus gurneyi</i>	1.6
Inner Stevenson Trough	144-199	5	0.198	0.5	<i>Chionoecetes bairdi</i>	92.6
					<i>Paralithodes camtschatica</i>	4.2
					<i>Neptunea</i> spp.	1.9
Chiniak Trough	123-159	4	0.122	1.2	<i>Chionoecetes bairdi</i>	58.4
					<i>Gorgonocephalus caryi</i>	34.9
					<i>Stylatula gracile</i>	6.4
N.E. Kiliuda Trough	117-143	4	0.104	4.9	<i>Chionoecetes bairdi</i>	84.4
					<i>Paralithodes camtschatica</i>	12.8
					<i>Neptunea</i> spp.	0.6
W. Kiliuda Trough	101-157	7	0.245	2.0	<i>Paralithodes camtschatica</i>	54.6
					<i>Chionoecetes bairdi</i>	34.3
					Actiniidae	9.4
					<i>Gorgonocephalus caryi</i>	0.6
Albatross Gully	200-322	8	0.319	0.5	<i>Dipsacaster borealis</i>	31.4
					<i>Fusitriton oregonensis</i>	18.4
					<i>Chionoecetes bairdi</i>	17.9
					<i>Strongylocentrotus</i> sp.	13.0
					<i>Neptunea</i> sp.	8.4
Outer Izhut Bay	163-177	3	0.084	5.1	<i>Chionoecetes bairdi</i>	65.6
					<i>Pandalus borealis</i>	19.0
					<i>Paralithodes camtschatica</i>	11.0
Outer Marmot Bay	104-115	1	0.034	0.5	Octopodidae	47.0
					<i>Paralithodes camtschatica</i>	39.8
					<i>Pecten caurinus</i>	10.1

However, only 19% (464 mt) were taken there during the 1984-1985 season (ADF&G 1985a). High biomasses of mobile suspension-feeders—such as bivalve mollusks (*Pectinidae*, *Carditidae*, *Astartidae*, *Serripes* sp., and *Cardium* sp.) and amphipods (*Ampelisca* spp.)—occurred between Kodiak and Chirikof Islands (Semenov 1965). Most of the latter species serve as prey for crabs elsewhere on the shelf (Feder and Paul 1980; Jewett and Feder 1982, 1983).

Stevenson Trough. Five stations were trawled within inner Stevenson Trough during 1978 and 1979 (Feder and Jewett 1981b). The pooled biomass was low (0.5 g/m²) when compared with values obtained in troughs elsewhere near Kodiak (Table 12-23) and in the NEGOA region (Table 12-11). Tanner crab dominated, accounting for nearly 93% of the biomass (Table 12-23). The most recent catch statistics show that 161 mt (2.4%) of Tanner crab were taken from this trough during the 1983-1984 season (ADF&G 1985a). Unlike shallow banks which typically are characterized as a dynamic environment, troughs typically are depositional. The gray mud substrate and the associated infauna that are found in Stevenson Trough substantiate that it is mainly a

depositional environment, although the presence of suspension feeders suggests that particulate organic carbon must also be resuspended there (Table 12-24).

Chiniak Trough. Based on the substratum and the dominant faunal types, bottom-water movement in Chiniak Trough appears to be more dynamic than in other troughs. Stations sampled here had substrates of fine sand and cobble. The presence of the biomass-dominating suspension feeders *Stylatula gracile* (sea pen) and *Gorgonocephalus caryi* (basket star) further indicates that this is a dynamic region (Table 12-23). Both suspension- and deposit-feeding infauna were numerous here (Table 12-24). The Tanner crab was another important component of the epifaunal biomass of the Chiniak Trough. The 1983-1984 Tanner crab harvest from Chiniak Trough accounted for 2.8% (183 mt) of the Kodiak Island region harvest (ADF&G 1985a).

Kiliuda Trough. The benthos of the horseshoe-shaped Kiliuda Trough was examined extensively (Feder and Jewett 1981b) (Tables 12-23 and 12-24). This trough has historically yielded high commercial catches of king and Tanner crabs. The northeast and western portions of Kiliuda Trough were

Table 12-24.

Dominant infauna collected by pipe dredge from various subtidal regions of the Kodiak Shelf (H.M. Feder and S.C. Jewett, University of Alaska, unpubl. OCSEAP data on file at NODC; Feder and Jewett 1981b).

AREA	DEPTH (m)	NUMBER OF SAMPLES	SUBSTRATE	TAXON	FEEDING METHOD ^a	ABUNDANCE
W. Portlock Bank	64-73	1	sand	<i>Ampelisca</i> spp.	SF	10
				<i>Echinarachnius parma</i>	DF/SF	5
				<i>Macoma</i> sp.	DF	4
				<i>Ophiura sarsi</i>	P/B/DF	4
				<i>Astarte</i> spp.	SF	3
				<i>Cyclocardia</i> spp.	SF	3
W. Albatross Bank	69-84	2	sand-cobble	<i>Ophiopholis aculeata</i>	SF	12
				<i>Macoma obliqua</i>	DF	7
				<i>Oregonia gracilis</i>	P/S	7
				<i>Cancer oregonensis</i>	P/S	7
				<i>Golfingia vulgaris</i>	DF	3
				<i>Psephidia lordi</i>	SF	1,800
Middle Albatross Bank	46-57	2	sand-shell	<i>Olivella baetica</i>	P	85
				<i>Suavodrilgia kemnicotti</i>	P	75
				<i>Glycinde picta</i>	DF/P	30
				Gammaridae	SF	18
				<i>Psephidia lordi</i>	SF	26
				<i>Nuculana fossa</i>	DF	26
Inner Stevenson Trough	162-199	2	gray mud	<i>Axinopsida serricata</i>	DF/SF	23
				<i>Myriochele heeri</i>	DF	20
				<i>Yoldia</i> spp.	DF	16
				<i>Macoma</i> sp.	DF	8
				<i>Axinopsida serricata</i>	DF/SF	200
				<i>Macoma</i> sp.	DF	142
Chiniak Trough	123-159	3	fine sand-cobble	<i>Psephidia lordi</i>	SF	100
				<i>Nuculana fossa</i>	DF	40
				<i>Cucumaria calcigera</i>	SF	38
				<i>Nucula tenuis</i>	DF	25
				<i>Echiurus echiurus</i>	DF	807
				<i>Axinopsida serricata</i>	DF/SF	297
N.E. Kiliuda Trough	105-132	5	gray mud with anoxic sublayer	<i>Nucula tenuis</i>	DF	58
				<i>Yoldia</i> spp.	DF	45
				<i>Eudorella emarginata</i>	DF/B	27
				<i>Heteromastis filiformis</i>	DF	23
				<i>Nuculana fossa</i>	DF	20
				<i>Nephtys punctata</i>	DF/P	19
N.W. Kiliuda Trough (Entrance of S. Sitkalidak Strait)	128-145	3	gray mud with anoxic sublayer	<i>Axinopsida serricata</i>	DF/SF	615
				<i>Pinnixa occidentalis</i>	P/S	250
				<i>Echiurus echiurus</i>	DF	35
				<i>Macoma</i> spp.	DF	25
				<i>Haploscoloplos elongatus</i>	DF	19
				<i>Yoldia</i> spp.	DF	14
W. Kiliuda Trough (Horse's Head)	126-157	5	gray mud	<i>Axinopsida serricata</i>	DF/SF	807
				<i>Nucula tenuis</i>	DF	238
				<i>Macoma</i> spp.	DF	176
				<i>Eudorella emarginata</i>	DF/B	139
				<i>Nuculana fossa</i>	DF	125
				<i>Myriochele heeri</i>	DF	120
Outer Izhut Bay	163-177	3	gray mud with anoxic sublayer	<i>Pinnixa occidentalis</i>	P/S	79
				<i>Haploscoloplos elongatus</i>	DF	55
				<i>Yoldia</i> spp.	DF	44
				<i>Echiurus echiurus</i>	DF	31
				<i>Axinopsida serricata</i>	DF/SF	42
				<i>Nephtys punctata</i>	DF/P	13
Outer Alitak Bay	54-69	4	gray mud	<i>Heteromastis filiformis</i>	DF	10
				<i>Macoma</i> spp.	DF	6
				<i>Yoldia</i> spp.	DF	4
				<i>Pinnixa occidentalis</i>	P/S	4
				<i>Psephidia lordi</i>	SF	3
				<i>Axinopsida serricata</i>	DF/SF	870
				<i>Nuculana tenuis</i>	DF	420
				<i>Yoldia</i> spp.	DF	82
				<i>Macoma</i> spp.	DF	81
				<i>Nuculana</i> spp.	DF	61
				<i>Tysanoessa inermis</i>		40
				<i>Heteromastis filiformis</i>	DF	29
				<i>Rhynchocoela</i>	P	22

^a DF = deposit feeder; SF = suspension feeder; B = browser; P = predator; S = scavenger.

dominated by both Tanner and king crab in 1978–1979. Statistics for the 1983–1984 season show that 445 mt (21.9%) of Tanner crab were harvested in the Trough. Stocks of king crab were so low for the 1983–1984 season that the fishery was not opened (ADF&G 1985a). Prior to the collapse of the king crab fishery in 1983, the Horse's Head region of the western portion of the Trough was a big producer of king crab (ADF&G 1980). Water movement at depth within Kiliuda Trough is apparently minimal, giving way to a predominance of deposit feeders such as polychaete and echiurid worms, along with bivalves (Table 12–24).

The food of king crab taken from the Horse's Head region was extremely diverse. As many as 73 taxa were found in crab from here; 25 taxa were found in a single crab stomach. Deposit-feeding clams were the most important prey, although Tanner crab and fish were also important. A sediment sublayer of black anoxic mud was characteristic at the northeast portion of the trough, as well as in the vicinity of the west end of Sitkalidak Island (Fig. 12–10). King crab from the northwest Kiliuda Trough area mainly consumed the pea crab (*Pinnixa occidentalis*) and fishes. The pea crab was also abundant in dredge samples from the same location (Table 12–24).

Albatross Gully. Albatross Gully also received comparatively extensive trawl-survey coverage. In March 1978, eight stations were sampled in this deep region (200–322 m), yielding a combined biomass of 0.5 g/m². Dominant epifauna were the sea star *Dipsacaster borealis* (31.4% of the biomass), the snail *Fusitriton oregonensis* (18.4%), Tanner crab (17.9%), and a maroon sea urchin *Strongylocentrotus* sp. (13%) (Table 12–3). A small portion of the 1983–1984 Tanner crab catch (20 mt; 0.3%) came from this deep region (ADF&G 1985a).

Shelikof Strait. Exploratory trawling throughout Shelikof Strait during the summer of 1961 revealed consistently high catches (>100 kg/h) of benthic invertebrates (Ronholt *et al.* 1978). Tanner crab catches typically exceeded 100 kg/h from at least 40 m to the bottom (>200 m). King crab catches were mainly between 0.6 and 25 kg/h at all depths. During the 1983–1984 Tanner crab season 1,524 mt (23.1% of the Kodiak district catch) of crab were harvested from the Shelikof Strait region (ADF&G 1985a). All areas of the Strait were big producers, except the area along the Alaska Peninsula at the south end of the Strait.

Shrimp-catch statistics indicate that the southern, and particularly the northeast portions of the Strait have traditionally been important areas for pink shrimp (Ronholt *et al.* 1978; ADF&G 1985a). The 1984–1985 shrimp harvest of 212 mt from waters adjacent to the mainland was considerably lower than in previous years. The shallow waters on both sides of the Strait are also productive Dungeness crab grounds. The 1984–1985 fishing season yielded 590 mt (24.5% of the Kodiak district catch) of Dungeness crab from the Shelikof Strait district (ADF&G 1985a).

In the basin west of Kodiak Island at the entrance to Shelikof Strait, the slopes were occupied by browsing and selective deposit-feeding infauna. Non-selective deposit feeders such as malidanid polychaetes were abundant west of Kodiak Island in the trough at the entrance to, and within, Shelikof Strait (Semenov 1965). Many of the infaunal taxa

found on the slope and in the trough were organisms that were used as food by crabs and shrimps elsewhere in the Kodiak region (Feder and Jewett 1981b; Jewett and Feder 1982, 1983).

Aleutian Islands Region—Infauna and Epifauna. The bottom adjacent to the Aleutian Islands—from the Near Islands to Unimak Pass—was examined by Shevtsov (1964b); most of the data were from Near Strait and adjacent to Buldir Island, Amchitka, and Amukta Passes. The substrata in these regions are mostly bedrock outcrops and coarsely fragmented sediments infrequently interspersed with sand bottoms. The bottom fauna was dominated by sessile suspension feeders. The biomass of this trophic group (primarily sponges, barnacles—*Balanus rostratus*, and bryozoans) in Near Strait was 400 g/m², representing 96% of the total biomass of the area.

In Buldir Pass, the sessile suspension feeders were primarily sponges, sea anemones, sabellid polychaetes, bivalves (Saxicavidae, *Pododesmus macroschisma*), and bryozoans. Their biomass was over 1.0 kg/m²—representing 98% of the total biomass of the area. In Amukta Pass, the biomass consisted mainly of sponges, hydroids, bryozoans, and ascidians and was 400 g/m², or 96% of the total biomass of the area. Selective deposit feeders were dominant at the entrance to all of the straits, although they occurred more frequently at depths of 1,000 m where the rocky, pebbly, or gravelly bottoms were replaced by sand and muddy sand.

On the Pacific side of Buldir Island, ophiuroids and eunicid and onuphid polychaetes composed up to 78% of the total biomass of 450 g/m². On the Pacific side of Amukta Pass, the biomass of the ophiuroids *Amphiura psilopora* and *Ophiura* spp. made up 3 g/m², or 50% of the total biomass of the area; on the Bering Sea side, the polychaete *Lysippe labiata* and ophiuroids made up 6 g/m², or 47% of the total biomass. Motile suspension feeders in the straits of the Aleutians accounted for 27% of the total biomass of the region. Non-selective consumers were uncommon in the area, and their biomass never exceeded 1.0 g/m².

Factors Affecting Distribution and Composition of the Fauna

Shelf of the Northeast Gulf of Alaska

There are a number of major discontinuities in the faunal distribution within the northeast Gulf of Alaska (NEGOA). These discontinuities are related, in part, to differences in the sediment-size distribution that are controlled by factors such as water movement and the deposition of glacially derived fine sediments (Carlson *et al.* 1977; Feely and Cline 1977; Hickman and Nesbitt 1980; and Molnia and Carlson 1980). The sediments that enter the NEGOA are transported westward except near Kayak Island where they are deflected to the southwest and trapped in a counterclockwise gyre west of the Island (Burbank 1977; Sharma, Wright, Burns, and Burbank 1974; Galt 1976; and Royer 1983). This results in high sedimentation rates and a high suspended-sediment load throughout much of the

shelf area west of Cape Spencer (Feely and Cline 1977; Molnia and Carlson 1980). However, on both topographic highs and shallow inshore waters on the shelf (62–130 m), scouring by strong bottom currents and frequent winter storm waves prevent sediment accumulation (Carlson *et al.* 1977; Molnia and Carlson 1980). This turbulence also creates ideal feeding conditions for suspension feeders such as bryozoans, brachiopods, and scallops. The westward transport of particulates by the Alaska Coastal Current and the Alaskan Stream also inhibits the accumulation of sediment within some regions of the shelf, including the shelf break. Sediment deposition within Hinchinbrook Entrance (especially at the mouths of Rocky and Zaikof Bays to the west of the entrance) is limited by currents of up to 50 cm/s that move in and out of Prince William Sound (T. Royer, University of Alaska, pers. comm.).

The infauna of the Inshore Group (IG) (Feder and Matheke 1980a) (Fig. 12–2), where the sediments are fine (at least 30% silt and clay) and the sedimentation rates are high, consisted primarily of motile deposit-feeding organisms which were widely distributed throughout the region. The fauna of the Hinchinbrook Entrance Group (HEG), where sediments were ~28% sand mixed with silt and clay, was also dominated by deposit-feeding organisms. However, abundance, biomass, species richness, and diversity of the fauna was greater in the Hinchinbrook Entrance Group than the Inside Group (Table 12–6). This resulted from the presence and increase in abundance of many species in the HEG which were absent or rare in the IG.

High epifaunal biomass values—resulting primarily from the Tanner crab—occurred in the vicinity of Hinchinbrook Entrance and to the west of Kayak Island. A frontal system formed by water moving into Prince William Sound along the eastern side of Hinchinbrook Entrance probably concentrates nutrients along the front, thereby stimulating production both in the water column and on the bottom (T. Royer, University of Alaska, pers. comm.). The high infaunal biomass of 417 g/m² in the HEG (Feder and Matheke 1980a) represented a food resource capable of supporting the large numbers of Tanner crab found there. The clockwise gyre west of Kayak Island (Galt 1976; Royer 1983), extends vertically from the surface to the bottom. When the gyre is coupled with nutrients supplied by the Copper River, the productivity of the area is presumably enhanced.

Greater numbers of sessile and suspension-feeding infaunal organisms occurred as the sediment changed from the silt and clay found in the IG to the sand and gravel mixed with silt and clay found in the Shelf Break Group (SBG) and the Tarr Bank Group (TBG) (Feder and Matheke 1980a). The diversity and species richness of the fauna in the SBG and the TBG were the highest found in the Northeast Gulf (Table 12–6). Although there are several possible explanations for the increase in diversity in the SBG and the TBG areas, the most obvious one is the increase in environmental heterogeneity provided by the presence of sand and gravel. Among the common organisms found in the TBG and the SBG were brachiopods, bryozoans, and other organisms that require a solid substrate.

The smaller numbers of suspension-feeding organisms found in muddy sediments (noted elsewhere by Davis 1925;

Jones 1950; Sanders 1956, 1958; Thorson 1957; and McNulty, Work, and Moore 1962) may be partly responsible for the reduced diversity of the infauna of the Inshore Group. The activities of deposit-feeding organisms often make an area unsuitable for suspension feeders by creating an easily resuspended, unstable sediment-water interface which clogs the suspension feeders' gills and either buries or inhibits the settling of their larvae (Rhoads and Young 1970). Further, unstable sediment may also exclude suspension feeders by requiring them to expend excessive energy in order to maintain contact with overlying waters (Myers 1977). Throughout much of the NEG OA shelf, the poorly consolidated fine deposits are easily resuspended (Feely and Cline 1977), and this condition tends to exclude suspension-feeding organisms (Rhoads and Young 1970; Rhoads 1974).

Jumars and Fauchald (1977) postulated that sessile species may also be excluded from regions with disturbed sediments or high sedimentation rates. They suggest that both burial and the rapid alteration of the local sediment characteristics give an advantage to motile individuals. They further suggest that the relative abundance of sessile organisms would decrease as the flux of organic material to the substrate decreased. They also state that in areas with a limited food supply, "the foraging radius required for adequate nutrition exceeds the reach of most sessile individuals." Since much of the sediment deposited in the NEG OA is of glacial origin, it might be expected that the sediments would be low in organic carbon. For example, the relatively low carbon values in the outwash deltaic complex formed by glacier streams in Port Valdez indicate that glacially derived sediments contain low concentrations of organic carbon (Sharma and Burbank 1973). Thus, there is a reduced abundance of sessile organisms in those NEG OA areas that have a high rate of deposition of glacially derived sediments (*e.g.*, the Inshore Group of Feder and Matheke 1980a). This may be due, in part, to the relatively low organic carbon values in the sediment.

Port Valdez

The only identifiable difference in the environmental conditions between the deep basin in eastern and western Port Valdez appears to be an increased sediment flux to the bottom in the eastern region (Feder and Matheke 1980b; Feder *et al.* 1983). The geographical boundary between the eastern and western station groups (Fig. 12–4) closely coincides with significant differences in sediment flux to the bottom on either side of that boundary (Feder and Matheke 1980b). Throughout most of Port Valdez, sedimentation rates are relatively high, resulting in poorly consolidated, easily resuspended fine sediments (Sharma and Burbank 1973). As suggested previously for NEG OA, these conditions tend to exclude suspension-feeding organisms.

Areas adjacent to stream or river outflows and within the Valdez Narrows were the only ones in which more than 20% of the fauna was composed of suspension feeders. *Axinopsida serricata*, a small suspension-feeding bivalve adapted to muddy environments, accounted for most of the suspension-feeding organisms in the former regions. The Narrows

are subject to relatively high current speeds, conditions conducive to suspension feeding.

The sporadic presence of large numbers of juvenile Tanner crab coupled with a relative scarcity of adults indicates that food resources are insufficient to support older individuals. Studies of both the infauna and the food habits of Tanner crab within Port Valdez suggest that prey—such as large polychaetes, clams, hermit crabs, and barnacles normally available to adult crab elsewhere in Alaskan waters (Paul, Feder, and Jewett 1979; Jewett and Feder 1983)—are not readily available to them here. Thus, although juvenile crab have sufficient small prey available to them (*e.g.*, small polychaetes), they must either migrate out of the Port as they become larger, or fail to survive.

Other Fjords and Bays of Prince William Sound

The benthos of Port Etches (Fig. 12-3) exists in a depositional environment. This is a result of the heavy sediment load from the Copper River that is carried into Hinchinbrook Entrance by the Alaska Coastal Current, and subsequently deflected into the Port. The depositional nature of the Port is reflected by the presence of a mud bottom dominated by deposit-feeding infaunal species (Hoberg 1986).

The relatively high abundance and biomass values recorded for suspension-feeding species at the entrances to Rocky and Zaikof Bays (Feder and Hoberg 1981) (Fig. 12-3) suggest a dynamic environment in which detrital material and zooplankters remain in suspension within the water column. A current that flows southward on the western side of Hinchinbrook Entrance across the entrances to the two Bays (T. Royer, University of Alaska, pers. comm.) presumably brings particulate organic carbon (POC) from Prince William Sound into Hinchinbrook Entrance. This current also provides the turbulence required to keep POC suspended in the water column where it would be available for suspension feeders. The current also deflects the sediment-laden water away from the bay entrances.

The heads of bays on the eastern side of Prince William Sound (Fig. 12-3) are characterized by mud bottoms enriched by terrestrial and marine detrital materials. All the inner bays examined were characterized by deposit-feeding infauna (Feder and Paul 1977). However, the mouths of these bays are more dynamic, and the benthos was always dominated by suspension-feeding species. Fjords on the western side of the Sound uniformly demonstrated low infaunal abundance and biomass values within the sill, but showed an increase in these values for the benthic fauna in the more dynamic environment outside the sill.

In the Port Nellie Juan area of western Prince William Sound (Fig. 12-3), three contiguous fjords appear to be in separate phases of glacial retreat (Hoskin 1977). Derickson Bay is dominated by icebergs that are calved from the tidewater Nellie Juan Glacier. Blue Fjord is influenced both by meltwater and by the sediment that is derived from the terrestrial Ultramarine Glacier. In contrast, McClure Bay is no longer influenced by glacial processes and has clear water. The bottom fauna varied in these three fjords, reflecting differing sedimentation rates in each area. Biomass was highest

in the glacier-influenced Derickson Bay, but suspension feeders were uncommon. Biomass was lowest in glacier-free McClure Bay, but suspension feeders were more common.

Resurrection Bay

The fine sediments inside the sill of Resurrection Bay are similar to those described for Port Valdez in Prince William Sound. (Both of these bodies of water are turbid outwash fjords; Sharma and Burbank 1973; Heggie *et al.* 1977.) Deposit-feeding species dominate the infauna in both fjords, and suspension feeders are uncommon (Feder *et al.* 1979; Feder and Matheke 1980b). The movement of zooplankton into the fjord may be enhanced by the Bay's proximity to the open Gulf and the presence of its deep sill (R.T. Cooney, University of Alaska, pers. comm.). The continued flux to the bottom of organic carbon, derived from entrained zooplankters and detritus from the shore and local streams, presumably enriches the bottom. The presence of both an abundant epibenthic fauna on rocks and boulders within Thumb Cove and relatively large numbers of large deposit-feeders throughout Resurrection Bay suggest that this fjord is more productive than Port Valdez. However, the reduced number of benthic taxa behind Callisto Head, an area directly affected by the turbid waters derived from Bear Glacier, is similar to observations made within the turbid waters at the heads of Port Valdez and Aialik Bay (Carpenter 1983).

Aialik Bay

The characteristics of the sediment and the composition of benthic organisms near Aialik Glacier (a tide-water-glacier fjord; Fig. 12-6) demonstrate the effects of the high sediment load that comes from glacial meltwater (Carpenter 1983). Both the high sedimentation rate (Post 1980) and the low primary productivity (Goering, Shiels, and Patton 1973) associated with glacial sediment plumes are presumably responsible for the low nitrogen and organic carbon content of the sediment in fjords. The low organic content of the sediment near Aialik Glacier (Carpenter 1983) appeared to be one of the limiting factors for infaunal organisms. However, a few taxa were common close to the glacier. These taxa included: 1) the polychaetes *Melinna cristata* and *Nephtys punctata* and 2) the bivalve mollusks *Axinopsida viridis* and *Nuculana* sp.

Although the number of taxa and the abundance of infaunal organisms tend to be reduced in turbid outwash fjords as compared with tidewater-glacier fjords, many of the same taxa occur in both, as in Blue Fjord and Derickson Bay (Hoskin 1977), Resurrection Bay (Feder *et al.* 1979), and Port Valdez (Feder *et al.* 1983). The biomass of the infaunal benthic organisms in Aialik Bay was higher than the biomass in turbid-outwash fjords (Hoskin 1977; Feder *et al.* 1983), but it was only one tenth of the benthic biomass observed either on the NEOGA shelf (Feder and Matheke 1980a) or in Cook Inlet (Feder, Paul, Hoberg, and Jewett 1981).

The abundance and the diversity of benthic organisms were higher immediately behind the sill than outside. This

suggests that conditions were more favorable and stable inside and close to the sill than in other regions of the inner fjord. Since most of the suspended sediment load is deposited near the glacier (Post 1980), the stress on benthic organisms resulting from high sedimentation rates is reduced near the sill. Further, the bottom directly behind the sill is a relatively stable environment that undergoes deepwater renewal at least once a year (Muench and Heggie 1978), and probably receives both organic debris and zooplanktonic organisms with the incoming water at flood tide. Terrestrial debris probably also accumulates in the deep basin behind the sill. Pearson (1975) suggests that even a moderate increase in the flux of organic carbon to the bottom will result in greater numbers of benthic organisms. Both the increased abundance and the diversity of the benthic organisms in the deep, stable basin adjacent to the sill within Aialik Bay presumably result from an accumulation of organic material there.

Lower Cook Inlet

The distribution of the infauna and epifauna within lower Cook Inlet (Fig. 12-7) generally reflects the current patterns as well as the type of bottom sediment present. The dynamics of the Inlet's benthic system is far more complex than that observed for the outer Gulf shelf, but the limited infaunal sampling within the Inlet makes it difficult to assess benthic relationships there.

There is a large clockwise gyre in the western half of outer Kachemak Bay and a smaller counterclockwise gyre in the eastern half of the Bay (Knull and Williamson 1969; Burbank 1977). Knull and Williamson (1969) estimated a flushing time for Kachemak Bay of 27 days. The relatively long residence time of water in Kachemak Bay may be a controlling factor in the development of the extended phytoplankton blooms (7.8 g C/m² for May–August) in the Bay. The prolonged period of primary productivity here is unlike most North Pacific areas where phytoplankton production is characterized by a short spring bloom followed by nutrient-limited summer production.

The total amount of carbon contributed to the bottom over the period of May to August was 60 g C/m² in Kachemak Bay and 17 g C/m² in the central Inlet (Larrance and Chester 1979). Although phytoplankton production was reduced in Kamishak Bay, a flux of 40 g C/m² of organic material to the bottom of this Bay was reported for the same period (Larrance and Chester 1979). Allochthonous carbon derived from both algal and terrestrial detrital materials also contributes to the total carbon input to the bottom of both bays and the entrance to the Inlet. The contribution of benthic marine algae to detrital reserves is highest in Kachemak Bay. A greater proportion of detrital material that accumulates on the bottom in Kamishak Bay is probably terrigenous in origin (Lees and Driskell 1981).

The infauna of Station Group 1 (Feder, Paul, Hoberg, and Jewett 1981) (Fig. 12-7) typically occurred in sandy silt, in gravelly mud, or in gravelly-muddy sand (Bouma and Hampton 1976; Hampton *et al.*, Ch. 5, this volume). Kamishak and Kachemak Bays, and the Stevenson Entrance region, are described as areas of sediment accumulation.

The highest levels of total organic carbon, lipid concentrations, and microbial activity in the sediment of the Inlet are reported here (Chester and Larrance 1981; Atlas *et al.* 1983; and Atlas and Griffiths, Ch. 8, this volume). Most of the bottom occupied by Station Group 1 is within the area identified by these investigators as an enriched depositional environment. The fauna of this group consisted primarily of deposit feeders (58.4%), presumably responding to high levels of organic carbon within the sediment. Suspension feeders represented only 19.3% of the organisms present.

The bottom within the area of Station Group 2 (Feder, Paul, Hoberg, and Jewett 1981) (Fig. 12-7) is subject to strong currents, and the sediment consists of sand, silty sand, and sandy gravel. The infauna of this station group consisted of a higher percentage of suspension feeders and a lower percentage of deposit feeders (38.3%). Water passing through Kachemak Bay contains high levels of POC derived from a variety of sources, including the high phytoplankton production, streams, estuaries, tidal flats, and algae on rocky shores (Lees and Driskell 1981; Chester and Larrance 1981). These organically rich waters move rapidly across the northern part of Kachemak Bay where they are entrained by the large gyre at the mouth—making POC available to benthic suspension feeders. Both the high abundance and biomass of suspension-feeding clams (*Tellina nukuloides* and *Glycymeris subobsoleta*), and sand dollar (*Echinarachnius parma*) within the Group 2 area reflects the abundance of a rich food source in the waters over the bottom (Table 12-13). The rich, rocky epifaunal assemblages on the bottom of the eastern region of the Inlet north of Kachemak Bay (Feder, Paul, Hoberg, and Jewett 1981; Feder and Paul 1981) apparently reflect the northward movement of this water mass along the coast (Muench *et al.* 1978).

Western Gulf of Alaska and the Aleutians

The shelf of the western-region of the Gulf (including the Kodiak region) and the area near the Aleutian passes are characterized by a benthos that is dominated by filter-feeding organisms (Semenov 1965). This dominance results from favorable bottom relief and from storm-induced vertical mixing that prevent sediment accumulation. Particulate organic carbon remains suspended in the water column in this turbulent region, making it available for the abundant suspension-feeding fauna. The gravelly and rocky habitats that serve as attachment sites for these animals are characteristic of the area. Although there is relatively little sedimentation in the western Gulf, fine sediment, with associated carbon, accumulates in troughs and canyons along the shelf margin. Non-selective deposit feeders occur in higher numbers at these sites. The presence of commercially important shellfishes and bottomfishes in some troughs reflects the relative abundance of food benthos in these areas.

Discussion

The shelf of the Gulf of Alaska is a complex and dynamic geologic environment where each major region is influenced by a unique set of variables (see Hampton *et al.*, Ch. 5,

this volume). Nevertheless, the shelf can be divided into three broad areas (eastern, north-central, and western) based on: 1) bottom topography, 2) sediment characteristics, 3) the amount of available organic carbon, and 4) trophic composition of the bottom fauna (Semenov 1965). A summary of these and other characterizing features of the shelf regions is included in Table 12-25.

The eastern area, extending south of Cape Spencer, is characterized by strong tidal currents and a low organic content in the sediment (Semenov 1965). The outer shelf of this area is dominated by deposit-feeding infauna. The mean biomass is 23 g/m² (Table 12-2), apparently reflecting a reduced carbon flux to the bottom. The northcentral area (NEGOA) receives large quantities of fine sediment from both glaciers and rivers. These sediments cover the bottom and obliterate most of the differences between the sediment

of the troughs and banks. Sediments are also muddy on both the seaward edge of the shelf and the upper portion of the slope of the NEGOA. This area has two particular characteristics: 1) low-water mobility with reduced particulate organic carbon (POC) in the water column, and 2) a relatively high organic carbon content within the sediment (Semenov 1965). Deposit feeders dominate the infauna here. An increase in both the abundance and the biomass of suspension-feeding macrofauna occurs on Tarr and Yakutat Banks. The mean biomass of the northcentral area was reported as 64 g/m² by Semenov (1965) and as 118 g/m² by Feder and Matheke (1980a).

The western area is characterized by a series of banks cut by transverse troughs with a bottom dominated by sand, gravel, and rocky outcrops. Sediment accumulates in the depressions and the troughs. However, sediment influx into

Table 12-25.

Summary of the general features of regions of the Gulf of Alaska considered in this chapter.

	EASTERN SHELF	NORTHERN SHELF	WESTERN GULF	ALEUTIAN PASSES
Water mobility	High	Low	High	High
Suspended sediment load	Low	High	Low	Low
Particulate organic carbon (POC)	Low	Low	High	High
Terrestrial carbon input	-	Low	Low	Low
Bottom topography	Variable	Relatively wide shelf with several banks or grounds bisected by submarine canyons or troughs	Relatively narrow shelf with slopes of marked dissection and steepness; many banks and reefs	Rocky bottom prevalent
Substrate type	Mixed	Mainly muddy except on banks	Sand, gravel, rocky outcrops; fine sediment in troughs and depressions	Sand, gravel, rock
Organic content of sediment	Low ^a	Variable: Low to relatively high ^a	Low	Probably low
Infaunal biomass (g/m ²) (van Veen grab)	23 ^a	\bar{x} = 64 ^a , 118 ^b	\bar{x} = 180 ^a	-
Mobile epifaunal biomass (g/m ²) (trawl)	Low	Variable: low to high depending on shelf location; 0.2-5.8 ^c	Variable: low to high depending on shelf location; high in some troughs; 0.5-8.1 ^c	Probably low
Total benthic production (microflora, meiofauna, macrofauna) (g C/m ² y)	-	13.7 ^d	-	-
Macrofaunal production (infauna and epifauna) available to apex predators	-	4.7 ^d	-	-
Dominant infaunal trophic groups	Deposit feeders	Deposit feeders; suspension feeders on banks	Suspension feeders; deposit feeders in troughs	Suspension feeders
Dominant mobile epifauna	-	Tanner crab; occasionally Dungeness crab	Commercial crabs; pandalid shrimps	-

^a Semenov (1965).

^b Feder and Matheke (1980a).

^c This chapter, Table 12-11.

^d Estimated, this chapter.

^e This chapter, Table 12-23.

^f This chapter, lower Cook Inlet section.

^g Feder and Paul (1981).

^h H.M. Feder (University of Alaska, unpubl. data), infaunal data only.

ⁱ Carpenter (1983), tidewater-glacier fjord.

^j This chapter, Port Valdez, turbid outwash fjord.

^k Feder and Jewett (in press).

^l Hoberg (1986).

this area is low because no large rivers drain onto the shelf. In the Aleutian passes, the bottom is mainly rocky. The water column over much of the relatively shallow western shelf and the Aleutian passes is generally characterized by storm-induced vertical mixing that suspends POC; consequently, filter-feeding bottom fauna dominate the bottom here. Semenov (1965) reported a macrofaunal biomass of 180 g/m² for the area.

In the NEGOA, relatively low macrofaunal production (2.2 g/m²y) has been estimated for the soft-bottom areas that make up a major portion of the shelf (see the Inshore Group: Fig. 12-2, Table 12-9). As suggested by Cooney (1986), the seasonal presence of large oceanic copepods (*Neocalanus cristatus*, *N. plumchrus*, and *Eucalanus bungii*) on both the eastern and central shelf should channel most of the primary production into a pelagic rather than a benthic food

web, so that low benthic production values should be expected. Similarly, in the southeastern Bering Sea, the seasonal movement of oceanic copepods onto the outer shelf domain supports a pelagic food web used by squid and walleye pollock (*Theragra chalcogramma*) (Iverson, Coachman, Cooney, English, Goering, Hunt, Macaulay, McRoy, Reeburgh, and Whitlege 1979; Cooney and Coyle 1982). Infaunal production for the latter region was calculated as only 2.8 g C/m²y, as opposed to the middle-shelf domain where reduced numbers of grazers in early spring result in a high flux of POC to the bottom and an infaunal production estimate of 28 g C/m²y (H.M. Feder, unpubl. data in Walsh and McRoy 1986). The dominant fishes of the NEGOA shelf are also pelagic species—mainly the arrowtooth flounder (*Atheresthes stomias*) and the walleye pollock. These two species make up over half of the total standing stock of commer-

	LOWER COOK INLET	FJORDS	BAYS
Water mobility	High	Low	Tidally flushed
Suspended sediment load	Generally high	High	Intermediate
Particulate organic carbon (POC)	High	Relatively low	Relatively low
Terrestrial carbon input	Low to high	Generally low	Relatively high
Bottom topography	Relatively smooth bottom	Relatively smooth bottom; steep sides	Relatively smooth with some rock projections and gravel adjacent to streams
Substrate type	Coarse in the north grading to muddy sand to the south; bays mainly muddy	Muddy; gravelly adjacent to rivers	Mud
Organic content of sediment	Variable depending on location	Generally low	Probably relatively high ^l
Infaunal biomass (g/m ²) (van Veen grab)	\bar{x} = 74: Station Group 1 ^l ; \bar{x} = 283: Station Group 2	14-48 ⁱ ; 1-490 ^j	May be relatively high ^l 6-617
Mobile epifaunal biomass (g/m ²)(trawl)	Variable: low to high depending on location; 0.1-14.5 ^s	Variable; depending on fjord	-
Total benthic production (microflora, meiofauna, macrofauna)(g C/m ² y)	-	-	-
Macrofaunal production (infauna and epifauna) available to apex predators	2.5-10.0 ^h	0.3-1.7 ^k	-
Dominant infaunal trophic groups	Deposit feeders: Station Group 1; Increased percentage suspension feeders: Station Group 2	Deposit feeders	Deposit feeders
Dominant mobile epifauna	-	Variable; low to high densities of crabs and shrimps	Tanner crab; pandalid shrimps

cially important invertebrates and fishes there (Ronholt *et al.* 1976, 1978).

Although the bottom-feeding Tanner crab (*Chionoecetes bairdi*) constitutes 12.5% of the total standing stock of organisms available to the commercial fishery for the NEGOA, the only areas identified as commercially productive are in shallow waters off either the Kenai Peninsula or Yakutat Bay (Ronholt *et al.* 1978). Tanner crab forage widely over the shelf, feeding on common small polychaetes, mollusks, and crustaceans. They were relatively abundant in the vicinity of Kayak Trough and Middle Bank where organic material and the associated deposit-feeding infauna probably accumulate in the sediment beneath the gyre off the west end of Kayak Island (Galt 1976; Royer 1983).

A relatively high macrofaunal production value (9.3 g C/m²y) is estimated for the relatively shallow Tarr Bank where the hard bottom and increased vertical mixing results in a diverse assemblage of both suspension and deposit feeders. The areas within and adjacent to the Bank were dominated by Tanner crab that were presumably taking advantage of the rich benthic fauna there. This crab was also common on Yakutat Bank. Macrofaunal production is also relatively high (4.6 g C/m²y) within Hinchinbrook Entrance (Feder and Matheke 1980a). This region is characterized by suspension-feeding species that feed on the POC suspended in the water column by strong tidal currents.

A total production of 13.7 g C/m²y can be estimated for the benthos of the NEGOA shelf (H.M. Feder, University of Alaska, unpubl. data) (Table 12-9). This value is based on the assumption that the microfloral and meiofaunal production of 9.0 g C/m²y is double the production of the macrofauna (Schwinghammer 1981; Parsons, Ch. 18, this volume) and that the epifaunal production is 0.24 g C/m²y (H.M. Feder and S.C. Jewett, University of Alaska, unpubl. data). Others have assumed that the macrofauna consumes most of the microorganisms in the sediment (Mills 1980; Reise 1979; and Parsons, Ch. 18, this volume), and the microorganisms are then shunted through the macrofauna as an additional carbon source. Thus, only 4.5 g C/m²y of benthic production (*i.e.*, macrofauna + mobile epifauna) (Table 12-9) is available to apex predators (*e.g.*, sea stars, crabs, and bottomfishes). By using a transfer efficiency of 10% (Parsons, Ch. 18, this volume), it is estimated that the macrobenthos requires 45 g C/m²y and the microflora/meiobenthos requires 90 g C/m²y. If it is assumed that primary production on the shelf is ~300 g C/m²y (Parsons, Ch. 18, this volume), then at least 160 g C/m²y could be available to the grazing community in the water column.

Cooney (Ch. 10, this volume) estimates the zooplankton production on the NEGOA shelf to be up to 32 g C/m²y. If a conversion efficiency of 20% (Cooney, Ch. 10, this volume) is applied, zooplankton on the shelf would require 160 g C/m²y of the available primary production. Thus, the benthic production values estimated for the shelf seem to be reasonable—given the calculated carbon requirement for the zooplankton on the NEGOA shelf.

The composition of the benthic fauna in the bays and fjords of Prince William Sound reflects, in general, the seasonal sediment loads in the water column and the type of bottom. Thus, the fjords of the western Sound—which are

impacted by glacial silts—are characterized by a depauperate fauna in contrast to the higher abundance and biomass found in the bays of the eastern Sound. The mobile epifaunal components of the bays and fjords are variable, and appear to reflect both the type and the abundance of infaunal food organisms. For example, Port Etches (within Hinchinbrook Entrance) has a relatively high infaunal biomass and contains large numbers of the protobranch clam *Nuculana fossa*. This clam is a food resource for Tanner crab and the sunflower star *Pycnopodia helianthoides*, as well as for several species of bottomfishes in the Port (Paul and Feder 1975; Feder and Hoberg 1981; and Paul, Feder, and Jewett 1979). In contrast, Port Valdez with its low infaunal biomass (Feder and Matheke 1980b) is unable to support large populations of benthic predators such as pandalid shrimps, crabs, and demersal fishes (Feder *et al.* 1983). In general, the low infaunal standing stocks characteristic of most of the bays and fjords in the Sound suggest that benthic production values should also be low. However, a low but constant supply of carbon from terrestrial and marine sources generally maintains small populations of deposit-feeding organisms, but occasionally sustains high densities of pandalid shrimps, Tanner crab, and blue king crab (*Paralithodes platypus*) (Feder and Paul 1977; also see the general discussion on Norwegian fjords in Sargent, Hopkins, Seiring, and Youngson 1983). The high annual primary productivity of 185 g C/m²y that is estimated for the Sound and its embayments and fjords (Goering *et al.* 1973) suggests that grazing communities may dominate the water column, and that most of the energy flow occurs in pelagic food chains—as it does in Norway's Balsfjord (Sargent *et al.* 1983).

The large populations of bottom-feeding crabs and pandalid shrimps in lower Cook Inlet require substantial amounts of food (Paul, Feder, and Jewett 1979; Feder, McCumby, and Paul 1980; and Rice *et al.* 1980). Although Kachemak Bay (on the eastern side of the Inlet) has a high rate of primary productivity, has abundant shrimp and crab larvae (English 1979), and has a high flux of POC to the bottom, the infaunal biomass and production estimates are relatively modest—52 g/m² and 2.5 g C/m²y (Feder, Paul, Hoberg, and Jewett 1981; H.M. Feder, University of Alaska, unpubl. data). Most of the POC flux to the bottom appears to be flushed out of the Bay by strong tidal currents and then entrained by the gyre at the entrance to the Bay (Fig. 12-7). It is beneath this gyre that the highest infaunal biomass and production values are found (400 g/m²; 6.3 g C/m²y). Crabs are common here, and they feed on the abundant juvenile clams that inhabit the sediment (Feder, Paul, Hoberg, and Jewett 1981). The highest epifaunal biomass (8.1 g/m²) within lower Cook Inlet is also reported for this area.

For Kamishak Bay (in the western side of the Inlet), a four-month (spring/summer) POC flux of 40 g C/m² has been reported for an area south of Augustine Island (Larance and Chester 1979). Water moving through the Bay forms an eddy behind the Island (Burbank 1977), and the increased residence time of the primarily terrigenous POC within this eddy contributes to the high infaunal production (9.9 g C/m²y) which occurs there. Tanner and king crabs, and yellowfin sole (*Limanda aspera*) are common in Kamishak Bay, and feed on this highly productive infauna.

A high benthic production value (10 g C/m²y) was also calculated for the Stevenson Entrance area. This is a region where sediment is deposited, carbon accumulates, and there is an abundant food benthos (infaunal biomass of 163 g/m²) that supports bottom-feeding organisms. This area serves as a nursery for juvenile Tanner crab (Feder and Paul 1981; Paul 1982) and supports a significant fishery for adult Tanner crab. Accumulations of carbon and associated food benthos in Shelikof Strait support commercially important stocks of Tanner crab as well.

The calculations of benthic production in lower Cook Inlet discussed above were based on conservative productivity-to-biomass (P/B) values for bivalves (0.5–0.7), a dominant component of the infauna. However, clam populations in lower Cook Inlet consisted mainly of young individuals as a result of the intense predation pressure on the larger, older clams (Feder, Paul, Hoberg, and Jewett 1981). Consequently, a higher P/B value (e.g., 2.0; Robertson 1979) might be more appropriate for production calculations in the Inlet (see Robertson 1979 for discussion). Thus, by applying a P/B value of 2.0 (rather than 0.5–0.7) for all the bivalves, infaunal production values in the Inlet become 4.2 to 12.5 g C/m²y (compared with the 2.5–10 g C/m²y noted above). The highest production estimate (i.e., 12.5 g C/m²y) approaches the value obtained for the benthos of the highly productive middle shelf of the southeastern Bering Sea. In that area, there is a substantial carbon flux to the bottom due to ungrazed phytoplankton (Iverson *et al.* 1979; Cooney and Coyle 1982; and H.M. Feder, University of Alaska, unpubl. data). Also, by using the higher P/B value for Cook Inlet bivalves, a high value of 13.4 g C/m²y is calculated for Stevenson Entrance—the region identified as a Tanner crab nursery area.

The relatively high biomass (180 g/m²) reported for the western area of the Gulf is attributed to an increase in non-mobile filter feeders (62% of the total biomass; 112 g/m²) associated with the predominantly hard bottom of the region (Semenov 1965) (Table 12–2). However, the fine sediments that settled in depressions on the banks and in the troughs contained deposit-feeding species, composing 15% of the total biomass (30 g/m²) of the shelf. These areas generally supported large populations of Tanner, red king, and Dungeness crabs. Carbon production values for the sedimented regions on banks and troughs of the western area are unavailable, but are probably as high or higher than those calculated for the physically similar Hinchinbrook Entrance/Tarr Bank region of the central Gulf shelf—between 4 and 9 g C/m²y.

The POC of the sediment bottom of the western Gulf has multiple origins: 1) westward transportation onto the Kodiak Shelf of zooplankton and juvenile fishes both by the Alaska Coastal Current (also known as the Kenai Current) and by the Alaskan Stream (Royer 1981, 1983; Royer *et al.* 1979; Cooney 1986), 2) detrital input from lower Cook Inlet that is transported primarily into Shelikof Strait, and 3) terrigenous and marine detritus from the coastal regions of the Alaska Peninsula and the Kodiak Archipelago. POC from these sources accumulates in the troughs on the shelf, in Shelikof Strait, and is further concentrated by eddies in the Alaska Coastal Current south of Kodiak Island.

The accumulation of organic carbon on the bottom and the associated increase in deposit-feeding infauna are especially important in Kiliuda Trough (Fig. 12–10) which has historically yielded large commercial catches of red king and Tanner crabs. An enhanced sediment input and the associated carbon flux to the bottom within Shelikof Strait also result in an increase in food benthos. These factors contribute to the high standing stocks of commercially important crustaceans which are found there.

The bays of the Alaska Peninsula and the Kodiak Archipelago are presumably also enriched by the POC transported by the adjacent Alaska Coastal Current (Royer 1981; Cooney 1986) as well as from local marine and terrigenous sources. These bays are traditionally used by shrimps and crabs for reproduction and feeding, and the seasonally enhanced populations of these crustaceans have made many of the bays important fishing grounds (Feder and Jewett 1981b).

The relatively low infaunal standing stocks in Aialik Bay and other steep-sided tidewater-glacier fjords of the Gulf suggest that there is a reduced flux of organic carbon to the bottom to support the benthos. However, resident populations of marine birds and mammals feed heavily on euphausiids, pandalid shrimps, and mid-water fishes in most of these fjords, implying that there is high productivity in the water column. Nevertheless, the heavy sediment loads combined with low salinity of the near-surface waters of glaciated fjords in late spring and summer act to limit the vertical zone that can support primary productivity to the upper one meter (Goering *et al.* 1973). Cooney (Ch. 10, this volume; pers. comm.) suggests that oceanically derived zooplankton, advected from the Gulf shelf into the fjords, may represent a major carbon source that can sustain water-column consumer populations there. Diel vertical migration of pandalid shrimps (Barr 1970; Percy 1970; and Beardsley 1973) places them in a position to be carried over the sill by tidal currents and into the inner fjord where they accumulate (Carpenter 1983). An increased abundance and diversity of infauna behind the sill in some fjords (Hoskin 1977; Carpenter 1983) probably represents an accumulation of this advected organic material into the relatively stable basin (Muench and Heggie 1978).

As discussed above, each broad area of the shelf and its contiguous embayments and fjords is characterized by a relatively distinctive fauna related to the local physical features and organic input. However, localized 'hot spots'—regions with enhanced benthic standing stocks—can be identified within these areas. Examples of some of these enriched benthic regions that have been discussed in this chapter include:

- the Kayak Island gyre
- Tarr Bank
- Hinchinbrook Entrance and adjacent bays
- the gyre west of Kachemak Bay
- Kamishak Bay
- Portlock Bank
- Shelikof Strait
- the embayments of the Kodiak Archipelago
- Kiliuda Trough.

Carbon input to these enriched regions has variable origins depending on the location of the 'hot spot', but the high benthic standing stocks can usually be related to the autochthonous and allochthonous detrital material characteristic of the region.

Perhaps one unifying feature of these benthically enriched areas is their proximity to the Alaska Coastal Current with its entrained POC (Royer 1981; Cooney 1986). It can be assumed that there is a continuous fallout of POC as the Alaska Coastal Current moves westward along the Gulf shelf and that any diversion of this current—whether by coastal features such as points, capes, islands, or entrances to embayments or by bottom such as banks or reefs—will cause local eddying, turbulence, or vertical mixing. This should increase the water's residence time over local areas and result in a higher POC flux to the bottom. We suggest that the Alaska Coastal Current and the physiographic and oceanographic features of the Gulf combine to concentrate POC, and offer a possible mechanism to explain why some local regions can assume importance for their large populations of commercially important benthic species.

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ABSTRACT

The nearshore fishes in the Gulf of Alaska have been studied mainly in the areas near Kodiak, lower Cook Inlet, and Prince William Sound. These studies have been in response to potential oil development and, in southeastern Alaska, in response to a developing rockfish fishery. Several types of sampling gear were employed to determine the species compositions and the relative abundances of fish in various habitats, such as rocky/kelp, epipelagic, intertidal beaches, subtidal shelves, and the deeper bottoms of bays. However, each type of gear was—to some extent—selective, and some species were undoubtedly under-represented in the catches.

Greenlings, cottids, and flatfishes (yellowfin sole [*Limanda aspera*] and rock sole [*Lepidopsetta bilineata*]) were the prominent large fish that were found near shore in the bays, whereas greenlings, cottids, and rockfishes were more prominent along the exposed coast. Pacific sand lance (*Ammodytes hexapterus*), capelin (*Mallotus villosus*), and juveniles of many species were the prominent forage fishes. The nearshore zone serves as an important spawning and/or rearing area for several commercially important species such as the Pacific salmon (*Oncorhynchus* spp.), Pacific herring (*Clupea harengus pallasii*), walleye pollock (*Theragra chalcogramma*), and flatfishes. The densities of several of the larval fishes were much higher in the bays than they were in the off-shore waters of the shelf.

The typical forage fishes and juveniles of all species fed predominantly on zooplankton and small epibenthic crustaceans, whereas larger fish consumed mainly polychaetes, crab, shrimp, and small fishes. Most of the organisms eaten were not commercially important. However, two species, yellowfin sole and yellow Irish lord (*Hemilepidotus jordani*), consumed significant quantities of Tanner crab (*Chionoecetes bairdi*) and Pacific cod (*Gadus macrocephalus*); three species—walleye pollock, flathead sole (*Hippoglossoides elassodon*), and yellow Irish lord—consumed large quantities of pandalid shrimp.

Research on nearshore fish is needed in other areas of the Gulf, and there is a special need to determine the magnitude of interannual variations at specific locations if we are to accurately evaluate environmental or fishery impacts in the future.

Introduction

Because marine research is relatively expensive, our knowledge of the fish communities in the Gulf of Alaska has been largely dictated by the need to understand potential environmental or fishery crises. Prior to the 1970s, studies were largely confined to either single commercially important species such as salmon, halibut, or herring, or to off-shore bottom fishes (Ronholt, Shippen, and Brown 1979).

Research on nearshore fish communities consisted largely of taxonomic studies and the compilation of both checklists and geographic distributions (Wilimovsky 1954; Hubbard and Reeder 1965; and Quast and Hall 1972). However, with the initiation of the Outer Continental Shelf Environmental Assessment Program (OCSEAP) in 1974, and the State of Alaska's interest in the inshore groundfish resources soon thereafter, research funding was provided in order to investigate the ichthyofauna of this previously undescribed zone.

The nearshore zone, in contrast to the open offshore waters in the Gulf of Alaska, is especially vulnerable to environmental impacts from human activities. The nearshore zone for this chapter is defined as the intertidal and subtidal waters to a depth of about 30 m and the deeper waters of bays or estuaries within less than 5 km of the shoreline. Exploration for and potential development of petroleum resources in lower Cook Inlet, off the eastern coast of Kodiak Island, and in the northeastern Gulf of Alaska, prompted the United States government to fund research projects on the nearshore fish communities in these areas. Surveys of inshore fishes in the southeastern Gulf of Alaska were initiated in anticipation of a new domestic commercial fishery. The results of these widely separated studies form the primary basis for our discussion of the nearshore fishes of the Gulf of Alaska.

Nearshore fish research in the southeastern Gulf has been concentrated either on single species such as walleye pollock (Clausen 1983) and Pacific herring (Blankenbeckler 1980; Carlson 1980), or on limited assemblages (e.g., bottomfish and rockfish) (Haldorson and Rosenthal 1983). The nearshore fish communities in the northeastern Gulf have likewise received relatively little study (Rogers, Wangerin, Garrison, and Rogers 1983). Although Rosenthal (1983) reported the results of a survey in Prince William Sound (which we will review), nearshore research in the central and western Gulf of Alaska has been sparse and has been directed toward single species such as salmon (Tyler 1972). The only exception is in lower Cook Inlet and along the eastern coast of Kodiak Island.

Intensive fish sampling was conducted in lower Cook Inlet in 1978 by both the Alaska Department of Fish and Game (ADF&G) and by Dames and Moore (Blackburn, Anderson, Hamilton, and Starr 1983; Dames and Moore 1983). The ADF&G and the Fisheries Research Institute (FRI) conducted a similar study in 1976 within three bays (Alitak, Kaiugnak, and Ugak) on Kodiak Island (Fig. 13-1) (Blackburn 1979; Harris and Hartt 1977). However, the most extensive nearshore fish survey was conducted in 1978-1979 in four Kodiak Archipelago bays (Kaiugnak, Kiliuda, Kalsin, and Izhut). This survey by ADF&G, FRI, and the National Marine Fisheries Service (NMFS) employed six types of gear and was conducted during seven months of the year. Over 1,000 sets or hauls were made and 14,000 fish stomachs were examined to determine seasonal compositions and food habits of the nearshore fish communities (Blackburn and Jackson 1980; Rogers, Rabin, Rogers, Garrison, and Wangerin 1979). In addition, larval fish were sampled concurrently using four different types of gear in the bays and offshore waters (Dunn, Kendall, Wolotira, Bowerman, Dey, Matarese, and Munk 1981; Kendall, Dunn, Matarese, Rogers, and Garrison 1981).

The shallow-water fish assemblages of the northeastern Gulf of Alaska and Prince William Sound (Fig. 13-2) were examined during 1977 through 1979 (Rosenthal 1983). Additional baseline observations were made in the summer of 1980 (Rosenthal, Lees, and Maiero 1982). These studies were designed to provide detailed descriptions and ecological analyses of nearshore fish assemblages. Important food-web links and dietary trends among the conspicuous species

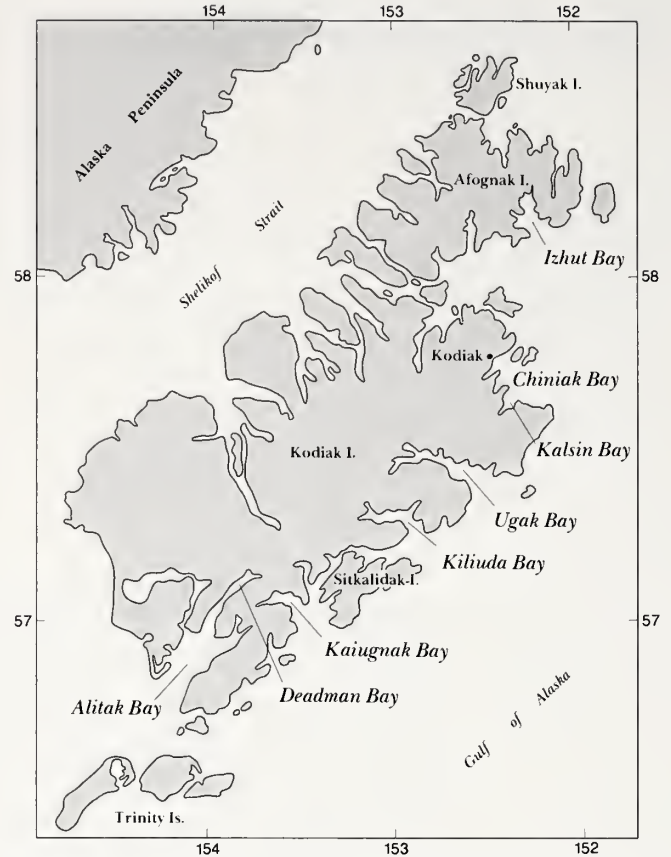


Figure 13-1. Bays of the Kodiak Archipelago in which nearshore fish surveys were conducted.

of fish were also described as part of these investigations. Morrison (Alaska Department of Fish and Game, unpubl. data) surveyed rockfish and lingcod (*Ophiodon elongatus*) stocks along the outer Kenai Peninsula during 1982-1983. The ADF&G field studies were in response to a developing small-boat fishery for rockfish in this area.

Resource assessment studies of both inshore and shallow offshore bottomfish in southeastern Alaska were conducted during 1980 to 1983 in anticipation of an expanding domestic fishery for rockfish and lingcod. The need for baseline information on these multispecies assemblages was recognized and research was directed by ADF&G (Rosenthal, Field, and Myer 1981; Rosenthal, Haldorson, Field, O'Connell, LaRiviere, Underwood, and Murphy 1982; and Haldorson and Rosenthal 1983).

Most of the shallow exposed waters of the Gulf of Alaska remain in a relatively pristine state; therefore, a unique situation was presented to the various investigative teams in that they were able to survey fish populations before human influence and heavy commercial exploitation disrupted natural population dynamics.

Sampling Methods

In order to obtain a broad description of the nearshore fish communities, several types of gear were used because each has unique properties regarding both where and how it samples the fishes. Passive gear—such as a set gill-net,



Figure 13-2. Shallow-water study sites in Prince William Sound.

trammel net, or hook and line—depends on the fishes' activity as well as their size and shape, and it is relatively ineffective in capturing small or sedentary fish. Active gear—such as trawls and tow nets—is not so dependent on the activity of the fish, but its effectiveness is dependent on mesh size and the size of the net opening. Seines are probably the least selective gear since they catch fish by surrounding them; however, they can only be used either in shallow or surface waters and in areas where there are few obstructions.

The main gear types employed in the Kodiak bays are illustrated in Figure 13-3. Not shown are a mid-water trawl used only in the summer of 1976 and a surface gill net used only in the late spring and summer of 1978. Catches were sorted by species and weighed. Lengths were measured and stomachs collected from selected species (usually the more

abundant species). Stomach contents were identified, enumerated, and weighed in the laboratory. Catch statistics and stomach contents were grouped by fish length for the purpose of analysis; the lengths were broken into categories of 30–150 mm, 151–300 mm, and over 300 mm. Fish less than 150 mm were predominantly juveniles (*i.e.*, young-of-the-year or yearlings).

Larval fish (typically <20 mm in length) were sampled by four gear types (Fig. 13-4). A neuston net sampled the surface layer, an epibenthic sled sampled fish near the bottom, and a Tucker trawl sampled discrete mid-water depths. The bongo net, which sampled from near bottom to the surface, was the most effective gear because it caught by far the greatest number of larval fish and eggs.

Blackburn *et al.* (1983) sampled the nearshore fishes in lower Cook Inlet using a beach seine, a try net, a tow net, a

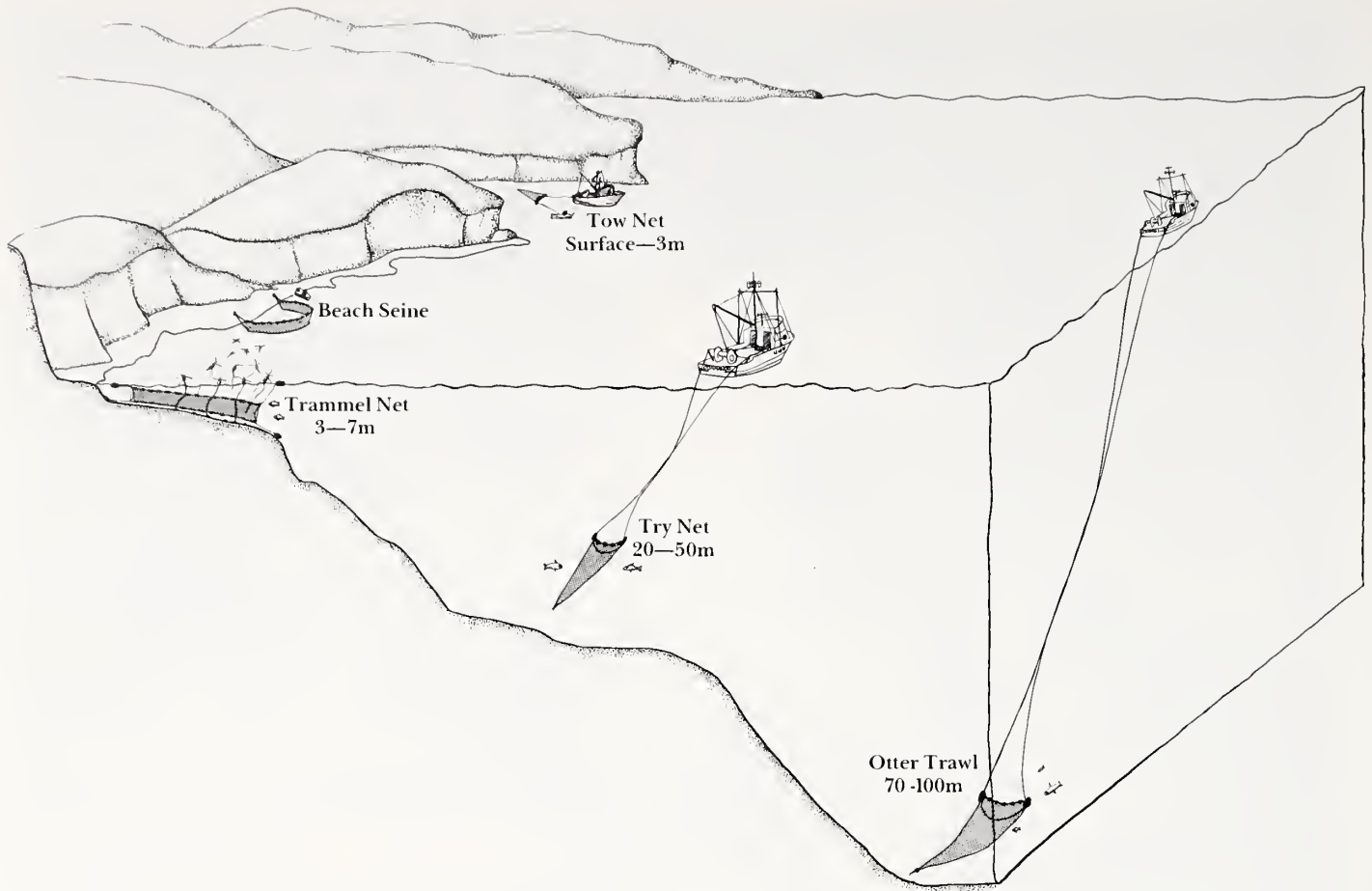


Figure 13-3. Sampling gear employed in the nearshore zone of Kodiak Island bays.

gill net, and a trammel net. Dames and Moore (1983) also made SCUBA observations near shore in Kamishak and Kachemak Bays.

Rosenthal (1983) studied fish communities from 2 to 39 m below MLLW at four primary sites in outer Prince William Sound. Gill nets, hook and line, and SCUBA were the main sampling techniques. Divers covered nearly 1.3×10^4 m², gathering fish density and distribution information along random or haphazardly placed transects. They also covered nearly 6×10^3 m² along fixed transects.

The primary gear used in Southeast Alaska by Rosenthal, Field, and Myer (1981) was automatic jigging machines rigged with monofilament line, weights, and between 5- and 10-hook strings attached to synthetic rubber lures. The jig gear was fished vertically from the bottom to near the surface. Diver/biologists were also used to conduct counts, observe behavior, and to collect fish that were located in depths up to ~30 meters. In the period from 1980 to 1982, 201 diver transects—each measuring 30 m \times 2 m—were studied, for a total coverage of 12,060 square meters.

Fish collected from Prince William Sound and southeastern Alaska were sorted according to species, and individual fish were measured and weighed to the nearest gram. Two general methods were used to describe the food habits: 1) divers made direct observations of fish feeding, or 2) stomachs which had been removed from selected species were

examined either while they were fresh or after they were preserved.

Results

Occurrence of Species

Based on a summary of the early fish collections that were made in Alaska, Quast and Hall (1972) suggested that the range of numerous species would be extended by future research. Peden and Wilson (1976) subsequently surveyed the inshore waters of northern British Columbia and captured 120 species of fish. Their results extended the geographic ranges of 20% of these species.

The nearshore sampling conducted in the Gulf of Alaska during 1976 through 1982 resulted in the collection of 153 species of fish from 33 families (Table 13-1). Included in the samples were four species and three families represented only by larval fish. Cottids (sculpins) were most numerous and constituted 25% of the 149 species (excluding larvae), while the rockfishes (largely from Prince William Sound and southeastern Alaska) constituted 12% of the species. About 21% of the fishes collected in the inshore Gulf waters were either previously unreported there or their occurrence extended their known range in the Gulf (Rosenthal and Haldorson, in press). Notably, the Bering wolffish (*Anarichas*

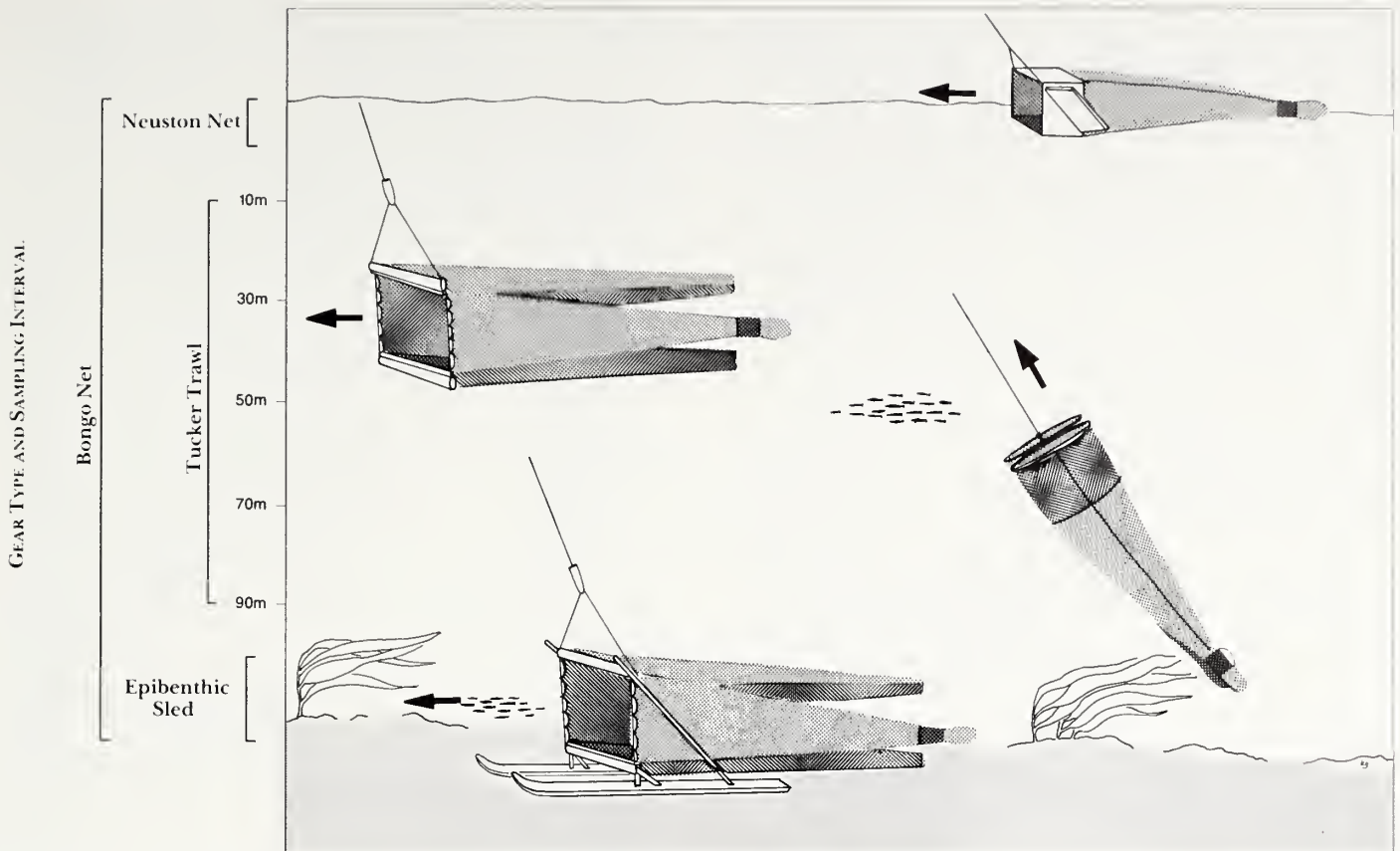


Figure 13-4. Ichthyoplankton sampling gear employed in Kodiak Island bays.

orientalis) and leatherfin lump sucker (*Eumicrotremus derjugini*) were caught in Cook Inlet (Blackburn *et al.* 1983), and the Bering poacher (*Ocella dodecaedron*) was caught at Kodiak (Harris and Hartt 1977). These species had previously been reported as occurring along the North American coast only from the Bering Sea or from the Arctic Ocean.

Several of the species caught inshore were uncommon in the catches and were atypical of nearshore fishes. In the following section, we emphasize the relative abundance of the more common species in each of the four nearshore regions of the Gulf.

Kodiak Archipelago.

Adult and Juvenile Abundance. Blackburn (1979) made 240 otter trawls in both Ugak and Alitak Bays during the period from June to September 1976 and during March 1977. The preponderant species he recorded were yellowfin sole, great sculpin, flathead sole, yellow Irish lord, Pacific halibut (*Hippoglossus stenolepis*), Pacific cod, walleye pollock, starry flounder (*Platichthys stellatus*), and *Gymnocanthus* spp. The catch composition was similar throughout the area with the exception of Deadman Bay, which had more eelpouts, snailfish, stout eelblenny (*Lumpenus medius*), and longsnout prickleback (*Lumpenella longirostris*) than any other site. Deadman Bay also had fewer of all other species except flathead sole, great sculpin, and capelin. There were two trends that emerged: 1) there were fewer species toward the heads of the bays, and 2) the fish were larger at greater

depths. In the winter, most species moved to deeper water and no species moved into shallower water, although some species apparently moved into the bays.

Comparisons of the otter trawl catches in Ugak and Alitak Bays with catches from the continental shelf and slope near Kodiak (Ronholt, Shippen, and Brown 1979) indicated the uniqueness of the bays. Rockfish were more common on the shelf and the slope than they were in bays. Yellowfin sole constituted 58% of all the flounder in the bays but was only incidental on the shelf. Arrowtooth flounder (*Atherestes stomias*) ranked sixth among flounders in the bays, but was the most abundant flatfish on the shelf. However, in shelf areas of less than 100 m, rock sole was the most common flounder—but it only ranked fifth among flounders in Ugak and Alitak Bays. Starry flounder was the fourth most abundant species in the bays—due primarily to high winter catches—but it was incidental offshore. However, winter studies were not conducted offshore, so the two are difficult to compare.

Most species were more abundant on the shelf than they were in the bays, with abundance generally decreasing toward the heads of bays. Fish size increased with increasing depth, indicating that the shallow areas—which are the most vulnerable to environmental impacts—are important as nursery sites.

The nearshore and pelagic fish of Ugak, Kaiugnak, and Alitak Bays on both the east and the south coasts of Kodiak Island were sampled during four cruises that took place from late May to mid-September 1976 (Harris and Hartt

Table 13-1.

List of fishes collected in the nearshore waters of the Gulf of Alaska from Kodiak (K), Cook Inlet (C), Prince William Sound (P), and Southeast Alaska (S) between 1976 and 1982.

Petromyzontidae			Scorpaenidae		
<i>Lampetra japonica</i>	Arctic lamprey	C	<i>Sebastes alutus</i>	Pacific ocean perch	K
Lamnidae			<i>S. auriculatus</i>	Brown rockfish	P
<i>Lamna ditropis</i>	Salmon shark	PS	<i>S. brevispinis</i>	Silvergray rockfish	PS
Squalidae			<i>S. caurimus</i>	Copper rockfish	CPS
<i>Squalus acanthias</i>	Spiny dogfish	KC	<i>S. ciliatus</i>	Dusky rockfish	KCPS
Rajidae			<i>S. crameri</i>	Darkblotched rockfish	K
<i>Raja binoculata</i>	Big skate	KCS	<i>S. emphaeus</i>	Puget Sound rockfish	PS
<i>R. kincaidii</i>	Black skate	C	<i>S. entomelas</i>	Widow rockfish	S
<i>R. rhina</i>	Longnose skate	KCS	<i>S. flavidus</i>	Yellowtail rockfish	PS
Clupeidae			<i>S. maliger</i>	Quillback rockfish	PS
<i>Clupea harengus pallasii</i>	Pacific herring	KCPS	<i>S. melanops</i>	Black rockfish	KCPS
Salmonidae			<i>S. miniatus</i>	Vermilion rockfish	S
<i>Coregonus laurettae</i>	Bering cisco	C	<i>S. mystinus</i>	Blue rockfish	S
<i>Oncorhynchus gorbuscha</i>	Pink salmon	KCPS	<i>S. nebulosus</i>	China rockfish	PS
<i>O. keta</i>	Chum salmon	KC	<i>S. nigrocinctus</i>	Tiger rockfish	KPS
<i>O. kisutch</i>	Coho salmon	KCPS	<i>S. pinniger</i>	Canary rockfish	S
<i>O. nerka</i>	Sockeye salmon	KCPS	<i>S. proriger</i>	Redstripe rockfish	S
<i>O. tshawytscha</i>	Chinook salmon	CS	<i>S. ruberrimus</i>	Yelloweye rockfish	PS
<i>Salmo gairdnerii</i>	Steelhead	S	Anoplopomatidae		
<i>Salvelinus malma</i>	Dolly Varden	KCS	<i>Anoplopoma fimbria</i>	Sablefish	KS
Osmeridae			Hexagrammidae		
<i>Hypomesus pretiosus</i>	Surf smelt	KC	<i>Hexagrammos decagrammus</i>	Kelp greenling	KCPS
<i>Mallotus villosus</i>	Capelin	KC	<i>H. lagocephalus</i>	Rock greenling	KCPS
<i>Spirinchus thaleichthys</i>	Longfin smelt	C	<i>H. octogrammus</i>	Masked greenling	KCPS
<i>Thaleichthys pacificus</i>	Eulachon	KC	<i>H. stelleri</i>	Whitespotted greenling	KCPS
Bathylagidae			<i>H. superciliosus</i>	Terpug	K
<i>Leuroglossus schmidti</i>	Northern smoothtongue	*	<i>Pleurogrammus monopterygius</i>	Atka mackerel	K
Myctophidae			<i>Ophiodon elongatus</i>	Lingcod	KCPS
<i>Stenobrachius leucopsarus</i>	Northern lampfish	*	Cottidae		
Gadidae			<i>Artedius fenestralis</i>	Padded sculpin	KCPS
<i>Eleginus gracilis</i>	Saffron cod	C	<i>A. harringtoni</i>	Scalyhead sculpin	CPS
<i>Gadus macrocephalus</i>	Pacific cod	KCPS	<i>A. lateralis</i>	Smoothhead sculpin	CP
<i>Microgadus proximus</i>	Pacific tomcod	KCPS	<i>A. notospilotus</i>	Bonyhead sculpin	CP
<i>Theragra chalcogramma</i>	Walleye pollock	KCPS	<i>Blepsias bilobus</i>	Crested sculpin	KP
Zoarcidae			<i>B. cirrhosus</i>	Silverspotted sculpin	KCP
<i>Bothrocara pusillum</i>	Alaska eelpout	K	<i>Clinocottus acuticeps</i>	Sharpnose sculpin	KCP
<i>Lycodes brevipes</i>	Shortfin eelpout	KC	<i>Dasycottus setiger</i>	Spinyhead sculpin	KC
<i>L. palearis</i>	Wattled eelpout	KC	<i>Enophrys bison</i>	Buffalo sculpin	KPS
Gasterosteidae			<i>E. diceraus</i>	Antlered sculpin	KC
<i>Gasterosteus aculeatus</i>	Threespine stickleback	CP	<i>Gilbertidia sigalutes</i>	Soft sculpin	KC
Syngnathidae			<i>Gymnocanthus galeatus</i>	Armorhead sculpin	KC
<i>Syngnathus griseolineatus</i>	Bay pipefish	S	<i>G. pistilliger</i>	Threaded sculpin	KC
Aulorhynchidae			<i>Hemilepidotus hemilepidotus</i>	Red Irish lord	KCPS
<i>Aulorhynchus flavidus</i>	Tubesnout	KCPS	<i>H. jordani</i>	Yellow Irish lord	KCP
Embiotocidae			<i>H. spinosus</i>	Brown Irish lord	CP
<i>Cymatogaster aggregata</i>	Shiner perch	S	<i>Hemitripterus bolini</i>	Bigmouth sculpin	KCP
Trichodontidae			<i>Icelinus borealis</i>	Northern sculpin	KC
<i>Trichodon trichodon</i>	Pacific sandfish	KC	<i>Icelus spiniger</i>	Thorny sculpin	KC
Bathymasteridae			<i>Jordania zonope</i>	Longfin sculpin	PS
<i>Bathymaster caeruleofasciatus</i>	Alaskan ronquil	KCPS	<i>Leptocottus armatus</i>	Pacific staghorn sculpin	KCPS
<i>B. leurolepis</i>	Smallmouth ronquil	CP	<i>Malacocottus kincaidi</i>	Blackfin sculpin	C
<i>B. signatus</i>	Searcher	KCPS	<i>Myoxocephalus jaok</i>	Plain sculpin	KC
<i>Ronquilus jordani</i>	Northern ronquil	KCPS	<i>M. niger</i>	Warthead sculpin	K
			<i>M. polyacanthocephalus</i>	Great sculpin	KCP
			<i>M. scorpius</i>	Shorthorn sculpin	KP
			<i>Nautichthys oculoasciatus</i>	Sailfin sculpin	KPS
			<i>N. pribilovius</i>	Eyeshade sculpin	KC
			<i>Oligocottus maculosus</i>	Tidepool sculpin	KCP
			<i>Psychrolutes paradoxus</i>	Tadpole sculpin	KC
			<i>Radulimus asprellus</i>	Slim sculpin	K
			<i>Rhamphocottus richardsonii</i>	Grunt sculpin	CPS
			<i>Scorpaenichthys marmoratus</i>	Cabazon	S
			<i>Synchirus gilli</i>	Manacled sculpin	K
			<i>Triglops forficata</i>	Scissortail sculpin	KC
			<i>T. macellus</i>	Roughspine sculpin	K
			<i>T. pingelii</i>	Ribbed sculpin	KCP

Stichaeidae			Agonidae		
<i>Anoplarchus purpurescens</i>	High cockscomb	KCP	<i>Agonopsis emmelane</i>	Northern spearnose poacher	C
<i>Chirolophis nugator</i>	Mosshead warbonnet	PS	<i>Agonus acipenserinus</i>	Sturgeon poacher	KCP
<i>C. decoratus</i>	Decorated warbonnet	S	<i>Anoplagonus inermis</i>	Smooth alligatorfish	KCP
<i>Lumpenella longirostris</i>	Longsnout prickleback	K	<i>Aspidophoroides bartoni</i>	Aleutian alligatorfish	C
<i>Lumpenus maculatus</i>	Daubed shanny	KC	<i>Asterotheca alascana</i>	Grey starsnout	C
<i>L. medius</i>	Stout eelblenny	K	<i>Hypsagonus quadricornis</i>	Fourhorn poacher	C
<i>L. sagitta</i>	Snake prickleback	KCPS	<i>Ocella dodecaedron</i>	Bering poacher	KC
<i>Poroclinus rothrocki</i>	Whitebarred prickleback	K	<i>Pallasina barbata</i>	Tubenose poacher	KC
<i>Stichaeus punctatus</i>	Arctic shanny	KCP	<i>Sarritor frenatus</i>	Sawback poacher	C
<i>Xiphister mucosus</i>	Rock prickleback	S	Cyclopteridae		
Pholididae			<i>Aptocyclus ventricosus</i>	Smooth lumpsucker	KP
<i>Apodichthys flavidus</i>	Penpoint gunnel	KPS	<i>Eumicrotremus derjugini</i>	Leatherfin lumpsucker	C
<i>Pholis clemensi</i>	Longfin gunnel	K	<i>E. orbis</i>	Pacific spiny lumpsucker	CP
<i>P. laeta</i>	Crescent gunnel	KCPS	<i>Liparis callyodon</i>	Spotted snailfish	KC
Anarhichadidae			<i>L. cyclopus</i>	Ribbon snailfish	KC
<i>Anarichas orientalis</i>	Bering wolffish	KC	<i>L. dennyi</i>	Marbled snailfish	KCP
<i>Anarrhichthys ocellatus</i>	Wolf-eel	KCPS	<i>L. florum</i>	Tidepool snailfish	C
Ptilichthyidae			<i>L. fucensis</i>	Slipskin snailfish	KC
<i>Ptilichthys goodei</i>	Quillfish	*	<i>L. mucosus</i>	Slimy snailfish	K
Cryptacanthodidae			<i>L. pulchellus</i>	Showy snailfish	C
<i>Delolepis gigantea</i>	Giant wrymouth	C	<i>L. rutteri</i>	Ringtail snailfish	C
<i>Lyconectes aleutensis</i>	Dwarf wrymouth	*	Pleuronectidae		
Zaproridae			<i>Atheresthes stomias</i>	Arrowtooth flounder	KCP
<i>Zaprora silenus</i>	Prowfish	KCPS	<i>Glyptocephalus zachirus</i>	Rex sole	KC
Ammodytidae			<i>Hippoglossoides elassodon</i>	Flathead sole	KCP
<i>Ammodytes hexapterus</i>	Pacific sand lance	KCPS	<i>Hippoglossus stenolepis</i>	Pacific halibut	KCPS
Gobiidae			<i>Isopsetta isolepis</i>	Butter sole	KC
<i>Coryphopterus nicholsii</i>	Blackeye goby	S	<i>Lepidopsetta bilineata</i>	Rock sole	KCPS
			<i>Limanda aspera</i>	Yellowfin sole	KCP
			<i>Microstomus pacificus</i>	Dover sole	KCP
			<i>Parophrys vetulus</i>	English sole	KCP
			<i>Pleuronectes quadrituberculatus</i>	Alaska plaice	KC
			<i>Platichthys stellatus</i>	Starry flounder	KCPS
			<i>Psettichthys melanostictus</i>	Sand sole	KC

* Collected only as larval fish from Kodiak.

1977). The survey objectives were to determine the species composition, distribution, and relative abundance for the common species, along with determining the age-class composition and the food habits for the key species.

The estuarine bays proved to be nursery areas. Juvenile fish were found both near shore and in the pelagic habitats of the bays. During the study, 70 species were caught, with more species found in the subtidal zone than in either the intertidal or the pelagic zones. Large numbers of capelin and young-of-the-year Pacific sandfish (*Trichodon trichodon*) were encountered in the pelagic zone, with both species exhibiting a diel migration. Few adults were found in the study area.

Other abundant pelagic species were young-of-the-year sand lance and juvenile salmon (mainly pink salmon [*Oncorhynchus gorbuscha*]). Both pink and chum salmon (*Oncorhynchus keta*) moved from nearshore to pelagic habitats in early summer and left the bays by mid-September. Greenlings were prominent in the rocky/kelp habitats and flatfishes were prominent in the subtidal smooth-bottomed habitats.

Of the four bays surveyed in 1978 and 1979 (Blackburn and Jackson 1980), one (Kaiugnak) had also been sampled in 1976. Although the station locations were not identical for both surveys, this dual sampling provided some comparison of the interannual variation in relative abundance. However, between 1976 and 1978, there was a marked change in seasonal water temperatures in the nearshore region of

Kodiak Island (Table 13-2). Water temperatures during 1976 were comparable to the average for 1950 through 1976, whereas water temperatures in 1978 were significantly warmer during winter and spring months, although they were comparable to averages for the recent warmer years

Table 13-2.

A comparison of monthly mean sea surface temperatures (C) in 1976 and in 1978 and 1979 with recent and earlier historical means and ranges for Womens Bay (Kodiak).

MONTH	JUNE 1950- OCT. 1976		1976	NOV. 1976- DEC. 1985		1978	1979
	MEAN	RANGE	MEAN	MEAN	RANGE	MEAN	MEAN
Jan	0.8	-1.7,3.0	2.4	4.1	2.3,5.1	4.0	5.0
Feb	1.0	-0.8,3.1	2.4	3.6	1.8,5.4	4.2	3.1
Mar	1.6	-0.5,4.3	2.8	4.2	2.3,6.0	4.7	4.5*
Apr	3.6	2.1,5.0	3.9	5.5	3.1,6.9	5.9*	6.9
May	6.3	4.2,7.8	6.0*	7.6	5.9,8.8	7.2*	8.8
Jun	8.5	6.4,10.3	8.7*	10.3	8.6,11.7	10.3*	10.6
Jul	11.0	8.7,13.7	11.1*	12.1	10.1,13.7	11.8*	13.2
Aug	11.9	9.8,13.4	11.8*	12.9	11.4,14.4	13.2*	14.4
Sep	9.9	8.1,11.4	11.0*	11.1	9.6,12.1	11.5	12.1
Oct	6.9	5.2,8.4	8.2	8.0	6.7,9.1	8.8	9.1
Nov	4.0	0.4,5.8	6.1	5.8	4.1,7.3	6.2*	7.3
Dec	1.7	-0.6,3.8	5.7	4.2	2.9,5.7	5.4	4.2

* Months in which sampling was conducted in Kodiak bays.

Data source: U.S. Department of Commerce, NOAA/NOS, Rockville, MD 20852.

(1976–1985). This is important because temperature probably affects the distribution and availability of fish.

The snake prickleback (*Lumpenus sagitta*) was the most abundant fish that was caught using try nets in Kaiugnak Bay in 1976, yet it was absent in try net hauls in 1978. Instead, yellowfin sole was the most abundant species that year. Capelin were most abundant in tow net catches in 1976, whereas they were not caught at all in Kaiugnak Bay during 1978—and the Pacific sand lance was the most abundant species. Pacific sandfish was the third most abundant species in the 1976 beach seine catches that were made in Kaiugnak Bay, but they were also not captured there during 1978. Only the species' compositions in trammel-net catches were similar in 1976 and 1978. These catches were dominated by both masked and rock greenling (*Hexagrammos lagocephalus*) that were generally larger and older than the highly variable, small, and mostly pelagic forage fishes.

The geometric means of the catches made during 1978 and 1979 for the four bays—Izhut, Kalsin (within the larger Chiniak Bay), Kiliuda, and Kaiugnak—depict the seasonal changes in relative abundance of the five most common species (Table 13–3). Catches were combined for April (1978) and March (1979) to represent the cold temperatures of winter; they were combined for May and June (rising spring temperatures), and for July and August (summer tem-

peratures), with catches for November representing fall with its declining temperatures.

The nearshore fishes were relatively scarce in late winter and were apparently the most abundant in the summer. The seasonal changes in the deeper waters (sampled by otter trawls) were not so pronounced. The gill net catches are not given because they were obtained mainly during the summer and the sampling effort was relatively low. Pacific herring was most abundant in the gill net catches, whereas it was either scarce or absent from catches taken by the other gear. More adult salmon were caught by gill nets than by any other gear. The abundance of salmon in the Kodiak region was well established from historical fishery records, and areas of salmon concentrations (*e.g.*, stream mouths) were purposely avoided.

Twenty-two families and 101 species of fish were identified in the catches taken from the Kodiak Archipelago bays. Many species were apparently not very abundant. However, if other gear such as SCUBA or hook-and-line had been employed, or if the sampling had been conducted outside the bays on exposed headlands, a somewhat different view as to the most abundant nearshore fishes at Kodiak might have emerged.

The trend apparent from otter trawl catches, showing that body size decreased from offshore to inshore, appeared

Table 13–3.

Seasonal abundances of the five most abundant fish species by gear type in four bays along the southeastern coastline of the Kodiak Archipelago, 1978–1979.

GEAR TYPE (UNIT OF EFFORT)	NUMBER PER UNIT EFFORT				BIOMASS PER UNIT EFFORT			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Species								
Beach seine (haul)						(grams)		
Pink salmon	3	69	6	0	1	37	2,202	0
Dolly Varden	+	+	1	+	3	78	118	40
Pacific sand lance	+	9	154	2	+	33	299	13
Masked greenling	1	1	4	1	9	46	78	26
Great sculpin	1	3	5	3	7	124	52	152
Trammel net (2 h set)						(grams)		
Rock greenling	2	13	28	5	474	6,716	9,952	2,139
Masked greenling	1	8	48	3	20	895	6,498	818
Whitespotted greenling	+	2	5	2	2	335	1,291	82
Great sculpin	+	1	1	1	126	255	249	860
Rock sole	1	3	2	1	117	674	61	78
Tow net (10 min haul)						(grams)		
Pink salmon	+	3	2	0	+	1	7	0
Chum salmon	+	4	+	0	+	5	+	0
Capelin	+	1	+	1	1	2	+	+
Pacific sand lance	+	+	52	+	1	+	81	+
Threespine stickleback	+	+	+	0	1	1	+	0
Try net (10 min haul)						(grams)		
Great sculpin	+	1	2	1	12	102	849	177
<i>Gymnocanthus</i> sp.	2	4	7	4	48	236	323	61
Rock sole	6	18	34	29	241	1,061	1,834	1,370
Yellowfin sole	1	19	39	12	13	1,187	3,576	626
Flathead sole	1	4	9	2	3	47	227	15
Otter trawl (20 min haul)						(kilograms)		
Walleye pollock	210	75	190	517	0.4	3.2	26.2	22.7
Great sculpin	15	64	39	30	17.4	70.7	40.4	41.6
Rock sole	309	397	154	115	43.5	102.6	39.0	30.9
Yellowfin sole	236	349	300	756	36.7	77.2	77.8	150.4
Flathead sole	98	405	557	479	3.9	41.7	94.8	23.5

to continue into the nearshore zone. However, the trend was partially obscured by gear selectivity. The average body weights (by season) and the composition (by length intervals) were averaged over the seasons and then examined for two particular species that were caught in four types of gear (Table 13-4). The trammel net was obviously ineffective in capturing juvenile fish, and the smaller *Myoxocephalus* juveniles were more difficult to identify; otherwise, great sculpins—some *Myoxocephalus* spp., but predominantly *M. polyacanthocephalus*—were smaller, and a higher proportion of juveniles was present in the intertidal and subtidal waters than in deeper waters.

Rock sole were smaller in the winter and generally smaller nearshore than they were in deeper water. However, there was a higher proportion of juveniles in the subtidal (try net) than in the shallower beach areas. The nearshore zone does appear to be especially important as a rearing area for juvenile fish.

Ichthyoplankton. Nearshore surveys of both fish larvae and eggs within the Gulf were mainly conducted in the east-coast bays of the Kodiak Archipelago. More extensive surveys were conducted offshore over the continental shelf and slope at about 90 stations from 40 to 2,000 m deep (Dunn *et al.* 1981). We compared the results of the inshore (bays) surveys and the offshore surveys with regard to the most abundant taxa and their densities (number per 100 m²) in order to determine the uniqueness, if any, of the nearshore ich-

thyofauna. Offshore, five cruises were conducted that spanned the four seasons; inshore, ten cruises were conducted during four seasons. To choose the most abundant taxa for discussion, catches during four inshore cruises were examined—these cruises taking place during: 6 to 16 March, 29 March to 8 April, 21 to 29 July, and 3 to 13 November.

Inshore, 110 taxa were captured compared with the ~60 taxa that were captured offshore. The numbers and the diversity of the ichthyoplankton were greater in the spring and summer than they were in the fall and winter, and inshore catches were generally larger than offshore catches. Thirty taxa were abundant enough to allow their distributions to be described. Seven of the most abundant are discussed here: larvae of four species (Pacific sand lance, sand sole [*Psettichthys melanostictus*], stout eelblenny, and walleye pollock); two larval groups (smelt and great sculpins); and flatfish eggs.

The smelt larvae were identified only to the familial level in the bays because of their small size; however, most were probably capelin. Capelin were identified in the offshore samples. Smelt larvae were found year-round and constituted about 90% of all larval fish in the bays. They were caught more frequently in bongo nets than neuston nets at both offshore and inshore sampling sites. The average density of smelt larvae reached 13,480/100 m² in the bays during late August. They were somewhat more abundant in Izhut Bay than in the other bays. Their offshore density averaged only 11/100 m² during the period of 19 June to 9 July, with densities tending to be higher closer to shore.

More smelt larvae were captured in neuston tows during the night than during the day. Smelt larvae were at their most abundant densities at 10, 30, and 50 m during both day and night. However, high densities also occurred at the remaining sample depths of 70 and 90 meters. Smelt larvae were also the most abundant taxon in epibenthic sled samples that were taken close to the sea floor.

Walleye pollock larvae were collected mostly in the spring. Inshore, the highest abundances occurred during the period from 21 April to 1 May (76/100 m²). Offshore, the highest abundance of larvae occurred during the spring cruise from 28 March to 20 April (7/100 m² larvae). The highest abundances occurred in Chiniak Bay and the lowest occurred in Kaiugnak Bay.

At least four species of great sculpins occur in the northeast Pacific: *Myoxocephalus jaok*, the plain sculpin, *M. scorpius*, the shorthorn sculpin, *M. niger*, the warthead sculpin, and *M. polyacanthocephalus*, the great sculpin. Two types were recognized in the ichthyoplankton, one of which (Type A) resembled a larval great sculpin which was very abundant in Kodiak bays. The other (Type B) could not be identified. Both types occurred primarily during the spring when densities of both A and B reached 102/100 m² during the period from 21 April to 1 May. Their densities were highest at 10 m during the day, but highest at 30, 50, and 70 m during the night.

Pacific sand lance larvae were captured primarily by bongo nets, with the larvae occurring from early March (186/100 m²) to mid-June (2/100 m²). Pacific sand lance densities were highest during 29 March through 8 April (343/100 m²). There were no differences in abundance among the

Table 13-4.
Comparisons of the body sizes of fish caught by different gear types in four Kodiak Archipelago bays, 1978-1979.

COMPOSITION OF CATCH BY BODY WEIGHT		MEAN BODY WEIGHT (g)			
SPECIES	GEAR TYPE	Winter	Spring	Summer	Autumn
Great sculpin					
	Beach seine	9	48	11	53
	Trammel net	419	425	311	955
	Try net	62	146	404	161
	Otter trawl	1,163	1,104	1,032	1,400
Rock sole					
	Beach seine	19	74	88	59
	Trammel net	130	250	34	87
	Try net	44	57	54	47
	Otter trawl	141	259	253	268

COMPOSITION OF CATCH (%) BY BODY LENGTH		LENGTH INTERVAL (mm)		
SPECIES	GEAR TYPE	≤150	151-300	>300
Great sculpin				
	Beach seine	81	12	7
	Trammel net	0	23	77
	Try net	27	22	51
	Otter trawl	4	6	90
Rock sole				
	Beach seine	36	50	14
	Trammel net	3	56	40
	Try net	73	21	6
	Otter trawl	5	64	31

bays; however, mean catches were larger inshore than offshore.

In Izhut Bay, highest densities of Pacific sand lance larvae occurred at 10 and 30 m during the day, whereas at night, the major abundances were at 30, 50, 70, and 90 meters. Densities were also highest in Kiliuda Bay during the day, but at night, the major concentrations were at 10, 30, 50, and 70 meters.

Stout eelblenny larvae were taken inshore during the winter, the spring, and the summer. The largest numbers occurred during late March to early April (31/100 m²) and the largest catches came from Kiliuda Bay. The smallest catches were in Izhut Bay and no larval stout eelblenny were collected in surface samples. They were apparently distributed over 10- to 90-m depths during both day and night. Offshore catches were negligible.

Unidentified flatfish eggs most likely came from five species: starry flounder, sand sole, English sole (*Parophrys vetulus*), yellowfin sole, or butter sole (*Isopsetta isolepis*). Inshore, the largest catches occurred in both mid-July (1,752/100 m²) and early August (1,816/100 m²). The highest mean catch of eggs was in Kiliuda Bay.

Sand sole larvae were caught both in the bays and offshore. Catches in bays occurred from late May to late August. The largest catches were in late July (44/100 m²). Abundances did not differ significantly among the bays. Offshore, sand sole larvae were caught only during the summer, and then only at 41% of the stations. Catch densities averaged 18/100 m². Larval sand sole in both Izhut and Kiliuda Bays were concentrated at 10- and 30-m depths during the day. At night, high concentrations occurred at both 30 and 50 m—although larvae were also caught at 70 and 90 meters.

The high abundance of sand sole larvae was somewhat surprising because adults and juveniles were relatively scarce inshore. However, rock sole, which were the most abundant flatfish in the bays, were represented by large numbers of larvae in the spring (21 April to 1 May—338/100 m²). The high catches of larval capelin and Pacific sand lance were expected because of the high abundance of the older fish inshore.

Lower Cook Inlet. Twenty-five families (105 species) were collected from lower Cook Inlet. The most important species by numbers in the beach seine catches were Pacific sand lance, juvenile chum salmon, Dolly Varden (*Salvelinus malma*), juvenile pink salmon, Pacific herring, longfin smelt (*Spirinchus thaleichthys*), whitespotted greenling (*Hexagrammos stelleri*), Pacific staghorn sculpin (*Leptocottus armatus*), and *Myoxocephalus* spp. (mainly the great sculpin).

The most important species by weight in the trawl catches were yellowfin sole, butter sole, flathead sole, Pacific halibut, rock sole, arrowtooth flounder, *Myoxocephalus* spp., and walleye pollock juveniles. Numerically predominant species in the tow net were the Pacific sand lance, Pacific herring, whitespotted greenling, capelin, as well as juvenile pink, sockeye, chum, and chinook salmon. Numerically important species caught in the gill net were adult herring, chum salmon, Dolly Varden, and Bering cisco (*Coregonus laurettae*). Numerically predominant species taken by trammel

net included adult Pacific herring, whitespotted greenling, sturgeon poacher (*Agonus acipenserinus*), yellowfin sole, masked greenling (*Hexagrammos octogrammus*), and the Pacific staghorn sculpin.

The composition of the ichthyofauna was different at each location. SCUBA surveys in Kamishak and Kachemak Bays revealed that non-schooling species were prominent at each rocky site. Sculpin, greenling, and ronquil were representatives of the major families that were observed. Only the greenling were common over rock habitats in Kamishak Bay. Alaskan ronquil (*Bathymaster caeruleofasciatus*) and kelp greenling were the most important demersal fishes in Kachemak Bay, but black rockfish (*Sebastes melanops*) and dusky rockfish (*S. ciliatus*) were the most numerous schooling fishes found over the rocky substrate. Whitespotted greenling and masked greenling were the main demersal fishes found in Kamishak Bay. Over soft substrates, flatfish predominated in both bays. In the summer, the important species found on a sand beach were Pacific sand lance, Pacific staghorn sculpin, English sole, rock sole, sturgeon poacher, and Dolly Varden. During the winter, only Pacific sand lance, Pacific staghorn sculpin, and surf smelt (*Hypomesus pretiosus*) were present.

Prince William Sound. Overall, 72 species from 18 fish families were identified in Prince William Sound. Of these, 14 species were found in areas that extended their known range. Species richness was generally the highest in exposed and semi-exposed habitats that were dominated by rocks and profuse algal growth. Within these habitats, rockfish and greenling usually dominated—both in terms of numbers and weight. The kelp greenling was the most important species in terms of its frequency of occurrence and its relative abundance. Black rockfish, dusky rockfish, Alaskan ronquil, and whitespotted greenling were also important.

In the eelgrass meadows, whitespotted greenling and Pacific tomcod (*Microgadus proximus*) were the preponderant species. Other important species in these habitats were starry flounder, tubesnout (*Aulorhynchus flavidus*), and juvenile yellowtail rockfish (*Sebastes flavidus*). There was a positive correlation between the fish biomass and the bottom relief, suggesting that biomass was lower in these low relief areas than it was in the rocky, high-relief sites.

There were marked seasonal changes in the species richness, the densities, and the spatial distribution of the fish communities. Summer density peaks were followed by strong winter declines at both the protected and the exposed sites. These were marked by bathymetric shifts as the fish moved farther offshore or into deeper waters. For example, at Zaikof Point in the southern entrance to Prince William Sound, there was a total of 15 species of reef fish sighted during the summer (August) 1978 survey (Rosenthal 1983). Fish density averaged 2,200 fish/ha in fixed (300 m²) transects, and 1,812 fish/ha in randomly (800 m²) placed transects. However, when the same area and depth strata were revisited in early April 1979, fish density had sharply declined to only 400 fish/ha in the fixed transects and 197 fish/ha in random transects. In addition, only seven species of fish were sighted in the entire subtidal study area. Most of the population was recorded well below the 10-m isobath.

Species richness and abundance remained low through May, but steadily increased over summer until August (1979), when a total of 16 species was recorded. Density estimates in both the fixed and random transect bands during August were 1,833 and 1,667 fish/ha, respectively. The differences in the species composition, species richness, and the abundance between summer and winter were significant ($P = 0.05$).

Southeastern Alaska. Fifty-one fish species were regularly observed in the rocky environment of the outer coast of southeastern Alaska between 1980 and 1982 (Rosenthal, Haldorson, Field, O'Connell, LaRiviere, Underwood, and Murphy 1982). There were 12,060 m² of sea floor that were examined by SCUBA divers in four different depth strata. The rockfish family (Scorpaenidae) was represented by 12 species—six species that were regularly sighted in the shallow water zone and six others that were present but less frequently encountered (Table 13-5). Overall, the most important species in terms of frequency of occurrence was the black rockfish.

Another prominent species in this nearshore assemblage was the Puget Sound rockfish (*Sebastes emphaeus*), which ranked first in relative abundance. Dusky and yellowtail rockfishes were also relatively abundant. Many more species inhabit this shallow water zone; however, the field team was concerned only with species that frequent the exposed, high-energy rocky reef environment of the southeastern Gulf.

The bathymetric patterns that relate to distribution and growth were studied for relatively unexploited populations of rockfish that inhabit the southeastern Gulf (Rosenthal, Haldorson, Field, O'Connell, La Riviere, Underwood, and Murphy 1982; Field 1984). Shallow-water bottomfish were categorized along various depth gradients starting at the shore and extending to the 50-fm (~91-m) depth contour.

Table 13-5.

Frequency of occurrence on transects and relative abundance (average number per transect) of most commonly observed bottomfish on diver transects sampled during 1980, 1981, and 1982 in southeastern Alaska.

SPECIES	FREQUENCY OF OCCURRENCE (%)			RELATIVE ABUNDANCE (% OF TOTAL FISH)		
	1980	1981	1982	1980	1981	1982
Puget Sound rockfish	31.6	31.8	77.8	31.8	33.5	45.2
Black rockfish	68.4	75.6	94.4	28.2	31.2	18.0
Dusky rockfish	57.1	43.3	72.2	23.1	11.2	7.9
Yellowtail rockfish	31.1	44.3	83.3	4.9	8.8	18.7
China rockfish	40.7	59.2	77.8	4.0	6.1	4.2
Quillback rockfish	33.9	27.9	33.3	5.4	5.4	2.7
Copper rockfish	14.1	20.9	16.7	1.2	1.4	0.7
Yelloweye rockfish	1.1	8.5	22.2	0.1	0.3	0.4
Canary rockfish	0	3.0	0	0	0.3	0
Tiger rockfish	1.1	6.5	22.2	0.1	0.3	0.6
Silvergray rockfish	7.3	3.0	16.7	0.4	0.2	0.7
Widow rockfish	0	1.0	0	0	0.1	0
Lingcod	11.3	28.4	44.4	0.7	1.2	0.8
Total transects	177	201	18			
Total fish				3,340	6,238	962

Populations were structured by depth, distance from shore, and type of underlying habitat.

Small, immature fish were usually found near shore. However, as depth increased, the size of the fish increased in a statistically significant fashion. Three species—black, yellowtail, and dusky rockfishes—exhibited a clear pattern of increasing size and age with increasing depth, and there was an absence of small or young fish in the deeper water (Table 13-6).

Larger, mature fish were found either farther offshore or at greater depths than the immature members of the same species or population. Also, most of the fish collected in the deeper portions of the southeastern Gulf were much older than their counterparts in the nearshore zone (Fig. 13-5).

Ecologically, three distinct zones became apparent during summer studies of rocky substrates (Fig. 13-6). The first zone was shallow, level, or rocky and extended from the low intertidal down to ~6 m (20 ft). This zone was dominated by low-statured kelps. Rock greenling, sculpins (*Artedius* spp.), and juvenile kelp greenling were common in this zone.

The second zone was made up of kelp forests with canopies that floated on the sea surface. Juvenile black, dusky, and yellowtail rockfishes inhabit these three-dimensional kelp forests. Other schooling fishes such as the tubesnout, herring, and Pacific tomcod were repeatedly observed in these stands of vegetation. Adult kelp greenling dominated the underlying sea floor that was overlain with fleshy algae and encrusting macroinvertebrates such as sponges and tunicates. These kelp forests occurred to depths of ~18 m on the exposed rocky outer coast.

The third zone consisted of boulder fields inhabited primarily by both sea urchins (*Strongylocentrotus* spp.) and crustose coralline algae. Sedentary reef-dwelling fishes such as the Alaskan ronquil, red Irish lord, and the longfin sculpin were closely associated with the rocky substrate. Various rockfish species frequently schooled above the rock pavement and boulder patches or hid within the interstices of the reef. Lingcod were also common in the deeper zones.

Boulder fields and rocky reefs occasionally extend to depths of 100 m in the southeastern Gulf of Alaska. Many of the bottomfish that were collected or observed in the shallow-depth strata were either juveniles or subadults, as larger, sexually mature fish were typically found at depths beyond 30 m—the lower limit for safe diver observations in these northern waters.

Food Habits

About 950 stomachs from 18 fish species were examined by Harris and Hartt (1977) from samples collected in three Kodiak bays during 1976. Pelagic fish such as juvenile pink salmon, greenlings, and capelin consumed pelagic foods such as calanoid copepods, nauplii, euphausiids, and fish eggs. Juvenile pink and chum salmon caught in the intertidal zone had epibenthic diets, including harpacticoid copepods and gammarid amphipods. Pacific sand lance captured in intertidal areas had consumed mostly pelagic foods such as calanoid copepods, crab zoea, larvaceans, and nauplii. Rock sole and adult masked greenling had generalized diets—that is, no single food item was greatly pre-

Table 13-6.

Average lengths (\bar{x}), standard deviation (SD), and sample sizes (n) by depth zone for survey-caught fish in samples taken in 1981 and 1982 in southeastern Alaska.

SPECIES	YEAR	AVERAGE LENGTH (cm)								
		10-25 fm (18.3-45.7 m)			26-40 fm (47.6-73.2 m)			41-70 fm (74.9-128 m)		
		\bar{x}	SD	n	\bar{x}	SD	n	\bar{x}	SD	n
Black rockfish	1981	42.7	5.55	864	45.3	5.46	141	48.4	4.48	201
	1982	41.6	5.50	731	46.2	5.32	18	46.5	4.67	95
Yellowtail rockfish	1981	34.9	5.31	255	37.8	5.77	204	43.7	3.79	384
	1982	35.4	4.78	347	41.5	4.82	85	44.7	4.68	149
Dusky rockfish	1981	35.8	4.14	69	39.8	3.50	99	42.0	3.33	123
	1982	32.2	3.26	61	40.2	3.55	64	43.5	2.84	71
Yelloweye rockfish	1981	53.1	12.44	30	57.7	12.06	29	58.8	7.96	81
	1982	57.2	10.66	16	60.9	5.26	18	53.6	9.37	26
Quillback rockfish	1981	37.7	3.98	60	36.6	3.95	34	37.6	2.82	31
	1982	35.5	4.42	30	39.8	2.84	20	39.4	4.22	9
Widow rockfish	1981	45.0	6.70	31	43.8	8.29	14	48.8	5.60	80
	1982	36.1	2.75	17	40.9	4.61	20			
Redstripe rockfish	1981	29.8	2.97	10	29.5	4.14	32	30.8	3.27	80
	1982	27.1	2.59	34	29.2	4.95	31	29.9	3.53	39
Silvergray rockfish	1981	35.9	5.33	32	39.2	6.89	14	44.4	1.00	44
	1982	37.5	6.93	29	43.4	11.25	15	41.9	7.62	59
Canary rockfish	1981	41.2	3.92	6	48.5	3.92	12	46.9	4.50	59
	1982	44.3	3.51	3	44.3	3.51	3	48.1	4.76	26
Lingcod	1981	84.2	21.75	43	85.9	21.47	24	83.2	17.69	17
	1982	73.1	14.74	29	82.9	14.91	16	74.6	5.46	5

dominant. Dolly Varden diets were also diverse, although fish was the most important item in their diet.

The contents of 14,000 fish stomachs that were collected from the Kodiak bays in 1978-1979 were analyzed according to season, gear/habitat, bay, and predator length. Traditional food webs that indicated the percentage of each food in a particular species' diet were created for those fish spe-

cies that composed 5% or more of the catch by weight (Rogers, Wangerin, and Rogers 1983). 'Dot/box' diagrams were also constructed to indicate the relative impact that predators had on their food sources.

Seasonal food webs and diagrams for the rock/kelp habitat (trammel net) are shown in Figures 13-7 and 13-8. Fish were least abundant in the winter in all habitats and the amount of food in their stomachs was likewise the smallest during the winter. The more abundant species in the intertidal and shallow subtidal zones (rock, masked, and white-spotted greenling; and rock, yellowfin, and flathead sole) had generalized diets. Most of the crabs they consumed (*e.g.*, *Telmessus cheiragonus*, *Pugettia gracilis*, and *Cancer oregonensis*) were not commercially important species. Most of the fishes they consumed included Pacific sand lance, capelin, small cottids, gunnels (Pholididae), and pricklebacks. However, both rock and yellowfin sole also took juvenile Pacific cod, walleye pollock, and Pacific herring. Polychaetes were especially important in the diets of both the rock and the yellowfin sole; the rock sole took mainly motile forms (errantiaes), whereas the yellowfin sole consumed more non-motile forms (sedentariaes). Clam siphons were important to the diet of both the rock sole and the rock greenling during the spring. Gammarid amphipods were an important food for juveniles of nearly all of the benthic and intertidal fishes.

The large cod, walleye pollock, great sculpins, yellow Irish lord, and the flathead sole consumed large numbers of both fish and shrimp. The great sculpin ate about 50% (by weight) of all the fish and crab that were consumed by the fishes that were sampled, while the Pacific cod consumed nearly 50% of the shrimp. These larger predators tended to stay in the deeper waters of the bays (otter trawl catches),

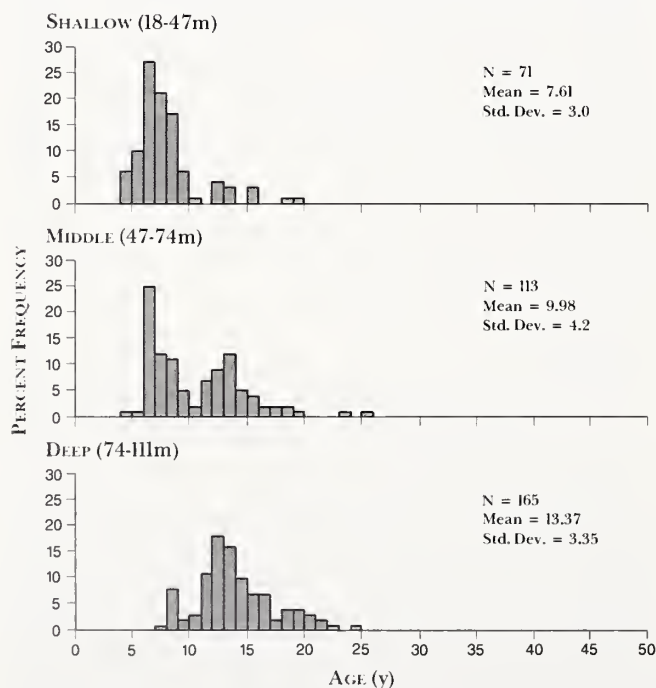


Figure 13-5. Age frequency distributions of yellowtail rockfish (sexes combined) from three depth zones in Southeast Alaska.

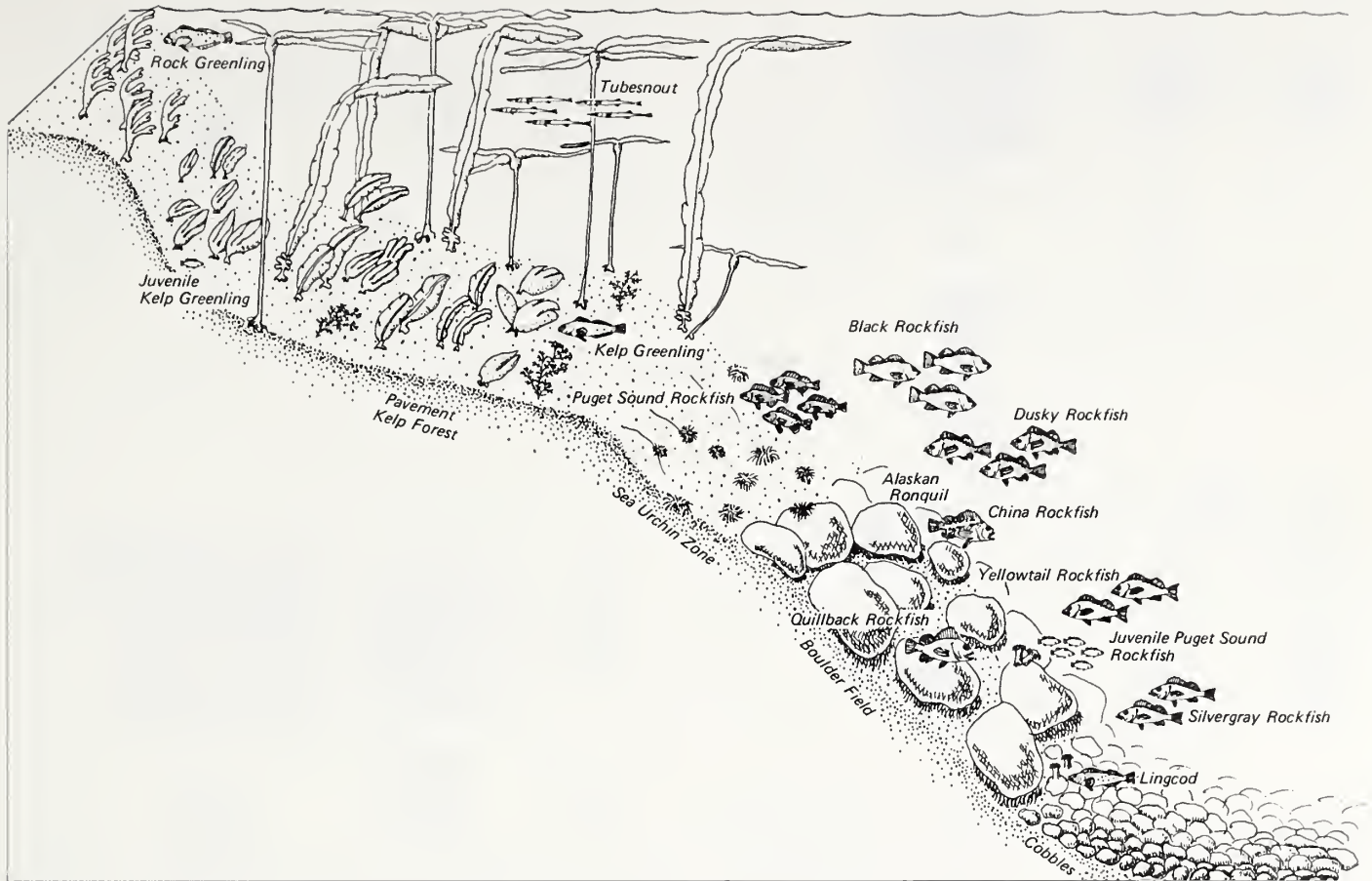


Figure 13-6. Habitat relationships of nearshore fish during summer.

and their diets contained commercially important species of both shrimp (*Pandalus borealis*) and crab (Tanner, *Chionoecetes* spp.). However, king crabs—which constituted a greater proportion of the crab biomass (based on trawl and otter trawl catches)—were relatively uncommon in the diets of the fish. They were perhaps too large to be eaten. The fishes that were preyed upon by those fish caught in the deep waters of the bays were similar to those consumed by the shallow nearshore fish (e.g., Pacific sand lance, cottids, capelin, and juvenile walleye pollock and flatfishes). Instances of cannibalism (adults eating juveniles) were common but never constituted a major portion of their diets.

Blackburn *et al.* (1983) examined ~900 stomachs taken from 17 fish species that were collected in lower Cook Inlet. An additional 258 stomachs were examined by Dames and Moore (1983). The most common foods of non-schooling fishes were amphipods, brachyuran crabs, caridean shrimp, brittle stars, gastropods, and hermit crabs. Prey most commonly taken by fish from rocky intertidal habitats were both epifaunal and were associated with macrophytes. Fish found over soft substrates consumed planktonic and benthic foods. Schooling species, such as juvenile salmon, herring, and Pacific sand lance usually ate planktonic organisms, whereas non-schooling species either ate benthos or fish.

Rosenthal (1983) examined 486 stomachs from 26 fish species caught in Prince William Sound and observed that bottom dwellers preyed heavily on benthic invertebrates

such as gammarid amphipods, polychaetes, snails, shrimp, and crab. Pelagic fish ate more of the zooplankton and forage fish associated with the water column than other types of food. There was considerable overlap in the diets, especially among the bottom feeders.

The summer diets of ten common species of rockfish that were collected in the inshore waters of southeastern Alaska's outer coast during 1980 to 1982 were determined based on a collection of 1,030 specimens. Stomachs from about 62% of the specimens contained some food. Each of the species ate a variety of food items and usually capitalized on the most accessible prey. The bottom-dwelling species were highly dependent on detrital-based food sources, whereas more pelagic rockfish consumed substantial quantities of zooplankton and small schooling fishes. A number of food items such as crabs, shrimps, brittle stars, and fish were shared in common by the demersal rockfish, and dietary overlaps were strong. Pacific sand lance was the dominant food of the more pelagic black, yellowtail, and widow rockfishes (*Sebastes entomelas*). Two other pelagic schoolers, the Puget Sound and dusky rockfishes, ate significant amounts of Crustacea and gelatinous zooplankton.

Discussion

The main concern for nearshore fishes in the Gulf of Alaska has been twofold: 1) their potential susceptibility to

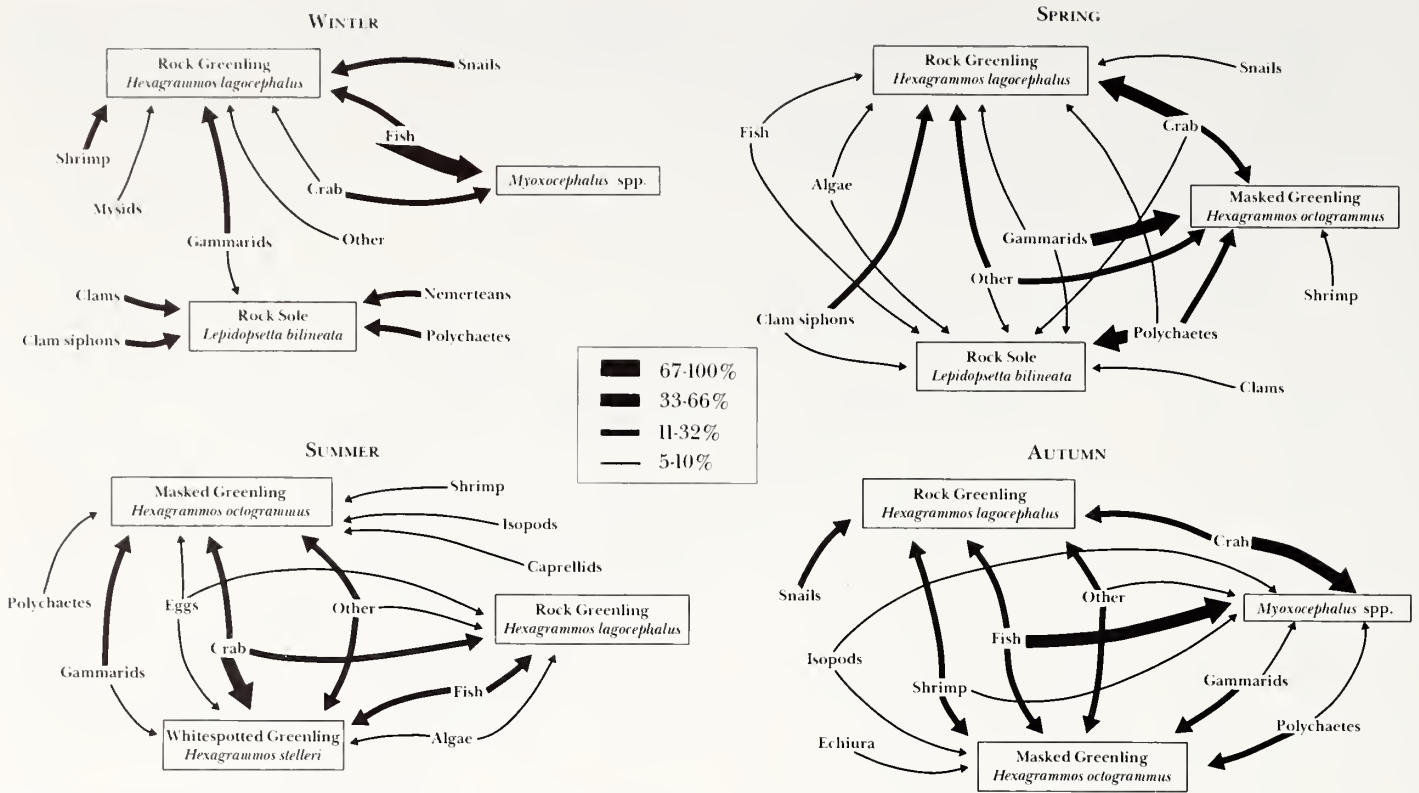


Figure 13-7. Food webs, by season, for fish caught by trammel net.

environmental impacts (mainly petroleum-related), and 2) their economic importance. Therefore, the extensive, multi-gear studies have concentrated primarily on lower Cook Inlet and the Kodiak Archipelago, and our knowledge of the nearshore fishes throughout most of the Gulf remains relatively limited. The exception is for those commercially important species such as salmon, herring, and rockfish. Some large coastal areas such as the south side of the Alaska Peninsula and the coast between Southeast Alaska and Prince William Sound have not been investigated by multi-gear sampling.

The nearshore fish assemblages of the Gulf of Alaska are composed of numerous species, many with widespread distributions along the coast of North America. The fish fauna has been characterized as a mix of temperate and subarctic species (Quast and Hall 1972; Hart 1973). The greenlings, cottids, rockfishes, and flatfishes were the prominent large predatory fishes near shore, whereas Pacific sand lance, capelin, and juveniles of many species—including the Pacific salmon—were the prominent forage fishes. The relative abundance of these species varied considerably among locations and the abundance of the forage fishes probably varies considerably from year to year. Interannual variation in abundance, however, is poorly documented and represents the area of greatest need for future research in order to evaluate environmental impacts as well as to understand the dynamics of the nearshore communities.

The Alaska Current and the Alaska Coastal Current constitute the major transport mechanisms in the Gulf of Alaska (Reed and Schumacher, Ch. 3, this volume). Both currents flow in a northerly direction off southeastern Alaska and

then turn southwestward along the Alaska coast. Beyond Kodiak Island, the Alaska Current intensifies and becomes the Alaskan Stream as it flows along the Alaska Peninsula and the Aleutian Islands. The eggs, larvae, and juvenile stages of many inshore fishes may be transported by these currents (OCSEAP Staff, Ch. 14, this volume). Peden and Wilson (1976) found no distinct boundary for fish off northern British Columbia, and if such a barrier exists in the Gulf of Alaska, it is unknown. It would seem that the fish fauna of both the Pacific Northwest and the southern Alaska region are highly cosmopolitan.

Visual investigation revealed that the fish fauna of the exposed rocky inshore zone of the Gulf of Alaska was dominated by greenlings, sculpins, ronquils, and rockfish. Pronounced differences in species composition and abundance were seen when the more protected areas such as bays, fjords, and lagoons were compared with areas exposed to wave action and strong currents. Large segments of the coastal area from Dixon Entrance to Kodiak Island are composed of rock substrates (O'Clair and Zimmerman, Ch. 11, this volume). The substrates of the more protected bays and estuaries of the Gulf—which are composed of sandy-silt, mud, and shell debris—contained fish assemblages that were numerically dominated by flatfishes, sculpins, and cod. During the summer months, more transitory schooling fishes such as Pacific salmon, herring, capelin, and sand lance enter these systems.

Commercial fishing for stocks of shallow-water bottom-fish has been relatively light in the Gulf of Alaska, especially when compared with the more traditional fisheries for halibut, crab, and salmon. However, a new domestic fishery

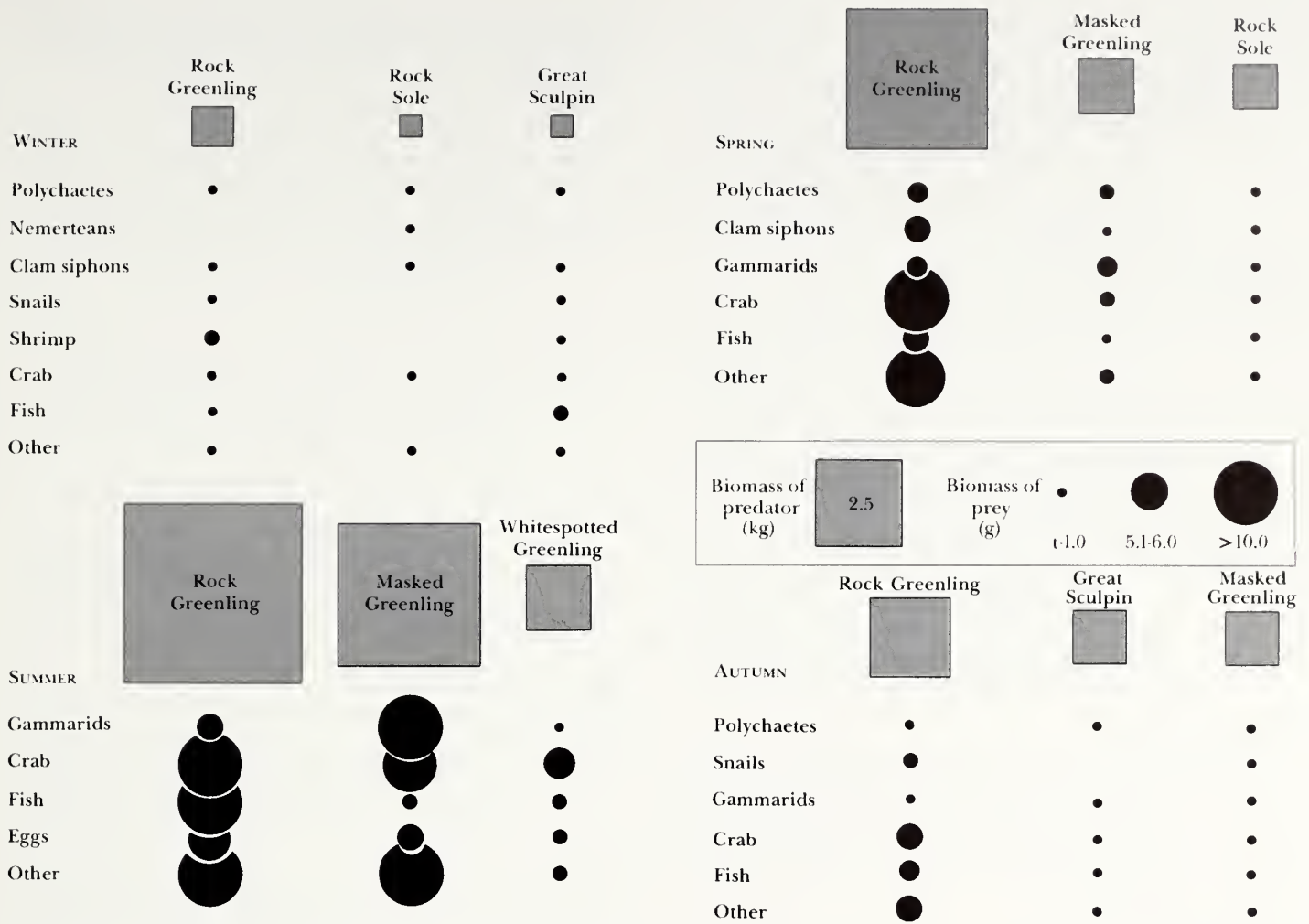


Figure 13-8. Quantitative food diagrams, by season, for fish caught by trammel net.

for rockfish and lingcod has developed off the coast of southeastern Alaska. In 1984, 3,520 mt (1.6 million pounds) of rockfish were caught in the directed nearshore fishery alone. Fish were caught using longline or hook-and-line gear, and self-imposed three-day trip limits were instituted to insure a high-quality product. The potential for expansion of the nearshore fishery has increased the need for more detailed scientific information in order to determine sustainable yields.

While the bays and coastal waters of the Gulf of Alaska offer some potential for recreational and commercial fisheries on nearshore fishes, their economic significance lies more in their importance as spawning habitats and rearing areas for juveniles of other commercially important fish species. It is this aspect that makes the nearshore zone unique relative to the open waters of the Gulf of Alaska.

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Our knowledge of the nearshore fishes in the Gulf of Alaska has benefited from the work of many biologists, students and fishermen; however, we would like to single out, and to acknowledge separately, Mr. Colin Harris (FRI) at

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OCSEAP Staff*

ABSTRACT

Approximately 287 species of fish belonging to 55 families occur in the Gulf of Alaska. This chapter summarizes information relating to the abundance, distribution, and life history aspects of the most important commercial species. Among those species considered here are Pacific cod, Pacific halibut, rockfish (with emphasis on Pacific ocean perch), sablefish, walleye pollock, Atka mackerel, lingcod, and herring. Commercial species of shrimp, crab, and squid are also discussed. Because commercial exploitation of these species has had major influence on fish stocks in the Gulf of Alaska, the development of fisheries for each of the stocks is described. Wherever possible, descriptions of life history events are integrated with recently available oceanographic data. In many cases this has led to new hypotheses concerning the dispersal and recruitment patterns that had been noted in past research.

Introduction

Beginning with the Outer Continental Shelf Environmental Assessment Program (OCSEAP) studies, marine investigations in the Gulf of Alaska came of age. For the first time, resources such as aircraft, large oceanographic and fishery research vessels, moored buoys and satellite-tracked drifting buoys, drift cards and bottom drifters, and a number of other resources and instruments were used to conduct by far the most extensive research on the northern Gulf of Alaska. OCSEAP was also the first broad-scale, long-duration, environmental study ever conducted in the area that did not use the commercial fisheries as a rationale.

Historically, research resulting from such cruises as that of the U.S. Fish Commission's steamer *Albatross* at the turn of the century, studies by the International Fisheries Commission (IFC) from 1927 to 1934, and studies by the International North Pacific Fisheries Commission (INPFC) from the period between 1955 and 1965 (see Hood, Ch. 1, this volume) were all dictated by interest in groundfish, Pacific halibut, or Pacific salmon. Little was accomplished in the decades between such investigations. In the early 1970s, the National Marine Fisheries Service (NMFS) established a comprehensive Marine Resources Monitoring, Assessment and Prediction (MARMAP) program in the northeast Pacific that contained strong environmental and fisheries oceanography components, but a lack of financial support

prevented a long-term commitment to that program. Because the priorities of OCSEAP were dictated largely by specific oil-lease considerations, and its emphasis was on finding out which organisms were present within the lease areas at any given time, no broad-range fisheries oceanography studies were funded or carried out by that program. In spite of this, the interdisciplinary aspects of OCSEAP research led to an immense computerized database containing fish and environmental data. Using these data, it is possible at this time to present new information, new ideas, and even a few speculations concerning profitable lines of both current and future analyses. We can also identify potentially rewarding avenues for future research.

The complex interaction that exists between the ocean and its biota frequently obscures the effects that changes in the physical environment can have on both the distribution and the productivity of marine organisms. Although the correlation can sometimes be seen, more often the influence of environmental factors is ameliorated in terms of time, area, and intensity. This is true because the effects are manifested by way of complex biological processes which are collec-

*This chapter was extracted by the editors from a larger document prepared under contract by Favorite Associates, Seattle, WA for the Outer Continental Shelf Environmental Assessment Program. As such, its emphases and content differ from those presented by the original document's authors.

tively described as ecosystem effects. Most events in fisheries oceanography, therefore, are not easily explained by simple cause-and-effect associations because the multifaceted relationships mean that the effect either lags behind the cause or shows itself in an irregular manner. Nonetheless, both seasonal and interannual cyclic changes in oceanographic conditions can alter fish abundance by directly influencing factors such as behavior, growth, survival, and reproduction, or the survival of eggs, larvae, and juveniles. Changing oceanographic conditions also indirectly influence abundance by affecting food or other habitat requirements.

Phenomena such as El Niño demonstrate the economically catastrophic consequences of dramatic reductions in the abundance or availability of commercially valuable resources. Declines in abundance result from undesirable changes in near-coastal conditions. These changes are thought to be related to variations in complex trans-Pacific Ocean currents which in turn are thought to be associated with changes in transoceanic surface-winds.

Similar phenomena—albeit with less dramatic consequences—probably occur with regularity in the Gulf of Alaska and in other important North Pacific fishing areas. However, little emphasis has been placed on developing and testing hypotheses concerning the effects that the changing oceanographic environment has on resource distribution, availability, and productivity.

It is easy to pose questions that involve environmental considerations which go beyond the simplistic effects that air or water temperatures have on fish. For the Gulf, such questions include:

- Why is there such a diversity of flatfish, but no dominant species (compared to the Bering Sea)?
- Why are there juvenile halibut and sablefish in the Bering Sea but little or no evidence of eggs or larvae? Does the Gulf of Alaska sustain the Bering Sea stocks and, if so, where do the eggs originate and how are they transported?
- What roles do sea-floor topography and near-bottom currents play in the distribution of groundfish, shrimp, and king and Tanner crab? What roles do the surface currents play in exchanges of eggs and larvae among stocks in Prince William Sound, in Cook Inlet, and in the Kodiak and Shumagin areas?
- To what extent do the juvenile salmon that come from areas south of Yakutat transit the coastal areas in the northern Gulf of Alaska? How do environmental conditions affect seaward-migrating juveniles and shoreward-migrating adults?
- How do currents affect invertebrate populations?

Although OCSEAP-sponsored investigations were extensive, they were essentially discipline oriented and any fishery assessments were conducted independently from other oceanographic studies. As a result, no fish/environment relationships were evaluated. However, it is obvious from the summaries of these investigations—many of which are chapters in this book—that new information has been obtained that bears both directly and indirectly on such fish/environment relationships.

The Gulf of Alaska (hereafter referred to as the Gulf) (see Hood, Ch. 1, this volume) is the eastern sector of the subarctic Pacific region and is part of the near-surface trans-Pacific subarctic gyre. This gyre extends from the northern Bering Sea to the oceanic subarctic/subtropical boundary near 40°N. Environmental conditions and processes in any given area in the Gulf are affected by pronounced seasonal cycles of insolation, wind stress, and coastal runoff. In addition, exchanges of surface and deep water along the southern boundary and limited exchanges in Bering Strait also affect the environment (Dodimead, Favorite, and Hirano 1963; Favorite, Dodimead, and Nasu 1976).

The Alaskan Gyre is the dominant oceanographic feature in the Gulf of Alaska. However, this is not a simple rotary system such as those established by long-term cyclonic or anti-cyclonic winds, because major cyclonic systems constantly pass through the area. Nor is it similar to gyres that are driven by constant zonal winds from opposite directions at different latitudes. These winds often drive flows that are constrained at east-west boundaries by land masses as in the case of major ocean gyres.

Flow in the Gulf results when oceanic flows with northward components extending to depths below 1,000 m converge in the northeastern Gulf. Then, after interacting with flow on the continental shelf (above 200 m) and after being influenced by local wind stresses and extensive runoffs, these flows are discharged southwestward along the western boundary. While earlier investigations contain much pertinent information on the oceanic area of the Gulf, it is in their direct observations of flow (although they were limited to the area over and adjacent to the shelf in the northern Gulf), that OCSEAP-sponsored studies have notably advanced our knowledge of Gulf oceanographic conditions.

In the Gulf, there are ~287 fish species that belong to 55 families (Table 14-1). Sculpins (Cottidae) and snailfish (Cyclopteridae) represent 19 and 13%, respectively, of the total species numbers. Ten dominant families constitute about 68% of the total species reported by Quast and Hall (1972) (Table 14-2). Bottom sampling has captured 138 species representing 26 families (Ronholt, Shippen, and Brown 1978)—39% of which were included in the ten largest families. Rockfish (Scorpaenidae) were the largest group, accounting for 10% (Table 14-2). Other family groups included the sculpins (8%) and flounders (Pleuronectidae) (6%).

Several species found in the Gulf are of commercial importance. Of these, the Pacific cod (*Gadus macrocephalus*), Pacific halibut (*Hippoglossus stenolepis*), Pacific ocean perch (*Sebastes alutus*), sablefish (*Anoplopoma fimbria*), and walleye pollock (*Theragra chalcogramma*) are the five most important. In 1984, ~3.65 × 10⁵ mt of demersal fish were landed. Bait and sac roe herring (*Clupea harengus pallasi*) also constituted very valuable landings. At least 3.07 × 10⁴ mt of sac roe herring and 3.4 × 10³ mt of bait herring were landed in 1982, having a value of \$13.7 million and \$958,000, respectively.

The Gulf is the feeding ground for millions of fish. Among the salmonids, tagging has provided evidence that it is the principal feeding area for: 1) chinook salmon (*Oncorhynchus tshawytscha*) from the Columbia River, 2) all

Table 14-1.

Fish families and the approximate number of genera and species reported from the Gulf of Alaska (from Ronholt, Shippen, and Brown 1978).

FAMILY	QUAST AND HALL ^a		MISCELLANEOUS SURVEYS ^b	
	NUMBER OF GENERA	NUMBER OF SPECIES	NUMBER OF GENERA	NUMBER OF SPECIES
Petromyzontidae	2	3	—	—
Hexanchidae	1	1	—	—
Lamnidae	2	2	1	1
Carcharhinidae	1	1	—	—
Squalidae	2	2	1	1
Rajidae	1	7	1	4
Acipenseridae	1	2	—	—
Clupeidae	2	2	1	1
Salmonidae	6	12	1	3
Osmeridae	5	6	5	6
Bathylagidae	1	4	—	—
Opisthoproctidae	1	1	—	—
Gonostomatidae	2	4	—	—
Melanostomiidae	1	1	—	—
Chauliodontidae	1	1	1	1
Alepocephalidae	1	1	—	—
Anotopteridae	1	1	—	—
Scopelarchidae	1	1	—	—
Myctophidae	7	10	1	1
Oneirodidae	1	3	—	—
Moridae	1	1	—	—
Gadidae	5	5	5	5
Ophidiidae	2	2	—	—
Zoarcidae	6	11	4	7
Macrouridae	1	3	1	1
Scomberesocidae	1	1	1	1
Melamphaidae	3	3	—	—
Zeidae	1	1	—	—
Lampridae	1	1	—	—
Trachipteridae	1	1	—	—
Gasterosteidae	2	2	—	—
Scorpaenidae	2	22	2	30
Hexagrammidae	3	6	3	5
Anoploplatidae	2	2	1	1
Cottidae	30	54	15	24
Psychrolutidae	1	1	—	—
Agonidae	8	12	8	9
Cyclopteridae	12	38	5	7
Bramidae	1	1	—	—
Pentaceroptidae	1	1	—	—
Sphyrnidae	1	1	—	—
Trichodontidae	2	2	1	1
Bathymasteridae	2	4	2	2
Anarhichadidae	1	1	1	1
Stichaeidae	10	15	4	6
Ptilichthyidae	1	1	—	—
Pholididae	2	4	—	—
Scytalinidae	1	1	—	—
Zaprionidae	1	1	1	1
Ammodytidae	1	1	1	1
Scombridae	2	2	—	—
Centrolophidae	1	1	—	—
Bothidae	1	1	—	—
Pleuronectidae	15	17	15	16
Cryptacanthodidae ^c	2	2	2	2
Totals	167	287	84	138

^a After Quast and Hall (1972).

^b Gulf of Alaska exploratory, BCF, IPHC, and NMFS trawl survey data.

^c Quast and Hall (1972) include these genera and species in the family Stichaeidae while Hart (1973) recognizes a separate family.

Table 14-2.

Proportion of the total species composition of Gulf of Alaska fish fauna that is contributed by the ten dominant fish families.

FAMILY ^a	PERCENTAGE OF TOTAL FISH SPECIES	FAMILY ^b	PERCENTAGE OF TOTAL FISH SPECIES
Cyclopteridae	13	Cottidae	8
Scorpaenidae	8	Pleuronectidae	6
Pleuronectidae	6	Agonidae	3
Stichaeidae	5	Zoarcidae	2
Salmonidae	4	Cyclopteridae	2
Agonidae	4	Stichaeidae	2
Zoarcidae	4	Osmeridae	2
Myctophidae	3	Gadidae	2
Rajidae	2	Hexagrammidae	2
Total			
	68		39

^a From Quast and Hall (1972).

^b From Gulf of Alaska exploratory cruises and resource assessment surveys.

species of salmon from British Columbia streams, and 3) all species of salmon from thousands of streams found not only in the western Gulf region, but in southeastern, northeastern, and central Alaska as well. There is also evidence that sockeye salmon (*O. nerka*) from western Alaska, chinook salmon from the Arctic-Yukon-Kuskokwim area, pink (*O. gorbuscha*) and chum (*O. keta*) salmon from Kamchatka, and chum salmon from Hokkaido seasonally inhabit the western Gulf (French, Bilton, Osako, and Hartt 1976; Neave, Yonemori, and Bakkala 1976; Takagi, Aro, Hartt, and Dell 1981; Godfrey, Henry, and Machidori 1975; and Major, Ito, Ito, and Godfrey 1978). Greater detail on Gulf salmonids is given by Rogers (Ch. 15, this volume).

Although numerous invertebrate species inhabit the Gulf, there is a paucity of knowledge regarding most of this fauna (Feder and Hoberg 1983; Feder, Paul, Hoberg, Jewett, Matheke, McCumby, McDonald, Rice, and Shoemaker 1981; and Feder and Jewett, Ch. 12, this volume). However, information is available concerning commercially important species (crabs, shrimps, and clams) and concerning the conspicuous macrobenthic species (seastars and snails). Commercially important invertebrates represent ~13 species in five families (Table 14-3), including four crab species, eight species of pandalid shrimp, and one scallop species (*Pecten caurinus*). Shellfish landings from the Gulf in 1982 accounted for ~4.93 × 10⁴ mt, with a value of \$118.5 million.

About 30 bird species can be found on a yearly basis in the Gulf (Gusey 1978; DeGange and Sanger, Ch. 16, this volume). Approximately 340 colonies of seabirds have been identified and catalogued. Of these, 226 occur in the western Gulf from the Kenai Peninsula to Unimak Pass. The seabird population in the western Gulf is estimated at five million individuals (Lensink and Bartonek 1976). Seabirds are a very important component of the Gulf ecosystem because they depend on land only for reproduction and subsist entirely upon food obtained from the sea. Therefore, they are predators as well as competitors for the commercially important fish.

Table 14-3.

List of the commercially important invertebrate families and species collected in the Gulf of Alaska during exploratory cruises and resource-assessment surveys (from Ronholt, Shippen, and Brown 1978).

SCIENTIFIC NAME	COMMON NAME
Canceridae	
<i>Cancer magister</i>	Dungeness crab
Inachidae	
<i>Chionoecetes bairdi</i>	Tanner crab
Lithodidae	
<i>Lithodes aequispina</i>	Golden king crab
<i>Paralithodes camtschatica</i>	Red king crab
Pandalidae	
<i>Pandalus borealis</i>	Pink shrimp
<i>Pandalus danae</i>	Dock shrimp
<i>Pandalus gonivurus</i>	Humpy shrimp
<i>Pandalus hypsinotus</i>	Coonstripe shrimp
<i>Pandalus jordani</i>	Ocean pink shrimp
<i>Pandalus platyceros</i>	Spot shrimp
<i>Pandalus montagui tridens</i>	
<i>Pandalopsis dispar</i>	Sidestripe shrimp
Pectinidae	
<i>Pecten caurinus</i>	Weathervane scallop

Twenty-six species of marine mammals have been identified in the Gulf (Calkins, Ch. 17, this volume). Of these, sea otters (*Enhydra lutris*), Steller sea lions (*Eumetopias jubata*), harbor seals (*Phoca vitulina*), northern fur seals (*Callorhinus ursinus*) and belukha whales (*Delphinapterus leucas*) appear at predictable times and places. Certain other whales, harbor porpoises (*Phocoena Phocoena*), and Dall porpoises (*Phocoenoides dalli*) are present but are less predictable. Walrus (*Odobenus rosmarus*), right whales (*Balaena glacialis*), pilot whales (*Globicephala macrorhynchus*), white-sided dolphins (*Lagenorhynchus obliquidens*), and three species of beaked whales (Ziphiidae) are rare (Scheffer 1972). The total number of marine mammals entering or living in the Gulf has been estimated to be 90- to 100,000 (Gusey 1978). These mammals are estimated to consume 7.77×10^6 mt of biomass per year (Calkins, Ch. 17, this volume).

Vertebrate Fisheries

Demersal and Semi-Demersal Fishes

Demersal fish spend most of their lives on or near the bottom and are caught by using bottom trawls or longlines. Their food in the adult stage consists primarily of benthos, as well as other demersal or semi-demersal fish. All flatfish (Family Pleuronectidae) belong to this group. Most of the larger gadoids such as the Pacific cod (*Gadus macrocephalus*) and the sablefish (*Anoplopoma fimbria*) are also semi-demersal fish. However, their larvae can be pelagic in the first year, although they settle to the bottom after metamorphosis (Fig. 14-1). In addition to feeding on or near the bottom, some demersal fish may also make daily feeding migrations throughout the water column.

The pelagic larvae of demersal fish are subjected to large and sometimes rapid environmental changes resulting from temperature fluctuations and surface currents. For exam-

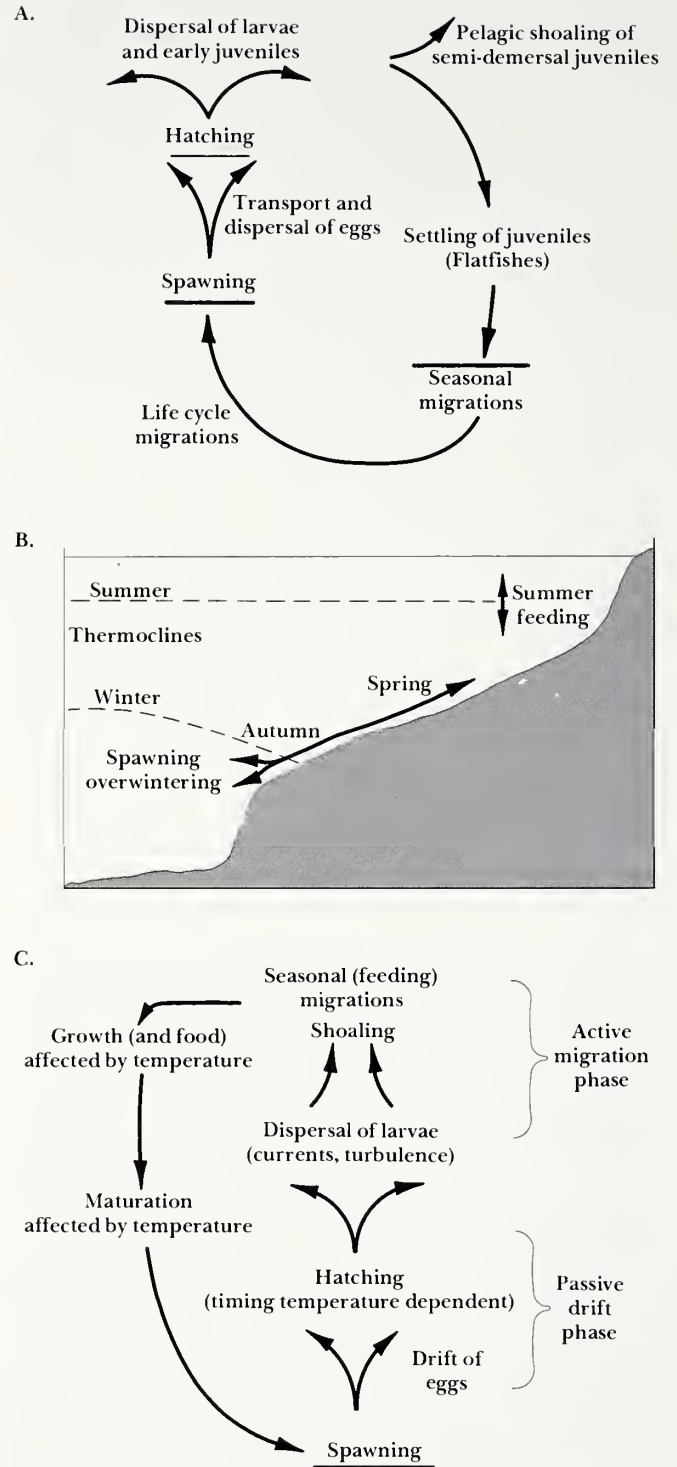


Figure 14-1. Schematic diagrams of dynamic processes in the life cycle of demersal fishes that might be affected by the environment (A and B), and the effects of the environment (mainly current and temperature) on active and passive phases of their life histories (C).

ple, the larvae and juveniles of some semi-demersal fish such as the Pacific hake can spend several years in the pelagic realm where they feed on zooplankton, fish and shellfish larvae, and juvenile fish. While there, they are at the

mercy of surface currents and may undergo long-distance passive migrations while being subjected to a variety of short-term, seasonal, and annual anomalies of the near-surface environment. In the adult stage, these fish return to the continental shelf and slope to feed and spawn where they are caught by fishermen using otter trawls and longlines.

Demersal fish are important to the Gulf ecosystem and include several groups or species (Table 14-4) that are of value to the United States' North Pacific fisheries. The Bering Sea cod fishery and the United States/Canadian halibut longline fishery have been active since the latter half of the 19th century. The large oceanic fisheries in the eastern Bering Sea and Gulf of Alaska, however, commenced on a modest scale in the mid-1950s. These fisheries were characterized by distant-water fleets of factory ships with accompanying trawlers, as well as by independent trawlers and longliners from Japan, the Soviet Union, and the Republic of Korea.

These multinational fisheries expanded very rapidly after 1961 with their main target being the Pacific ocean perch (Major 1986) (Fig. 14-2 and Table 14-3). Total catch peaked at 3.71×10^5 mt, of which 3.49×10^5 mt was Pacific

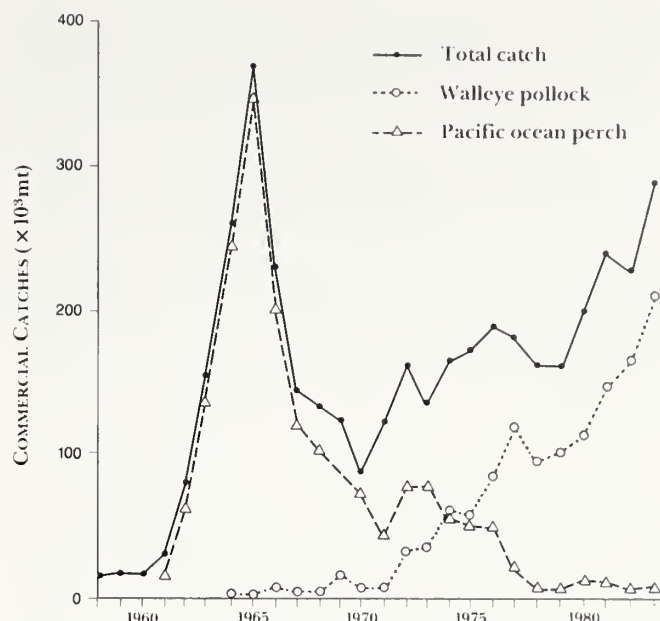


Figure 14-2. Commercial catch data for Pacific ocean perch (*Sebastes alutus*) and walleye pollock (*Theragra chalcogramma*) from the Gulf of Alaska between 1958 and 1983.

Table 14-4.

Total foreign, domestic, and joint-venture catches (mt) of demersal fish from the Gulf of Alaska for the period 1958 to 1984.^a

YEAR	POLLOCK	SABLEFISH	PACIFIC COD	ATKA MACKEREL	FLATFISH	PACIFIC OCEAN PERCH ^b	PACIFIC HALIBUT ^c	TOTAL
1958							14,570	14,570
1959		962					16,564	17,526
1960		1,348					15,512	16,860
1961		606				16,000	16,532	33,138
1962		684				62,000	17,610	80,294
1963		2,298				136,000	16,752	155,050
1964	1,126	2,214				243,400	17,185	263,925
1965	2,749	3,155				348,600	17,050	371,554
1966	8,932	4,565				200,800	17,038	231,335
1967	6,276	5,164				120,000	15,018	146,458
1968	6,194	13,998				100,200	14,007	133,399
1969	17,553	19,889				70,724	125,766	125,766
1970	9,343	21,766				40,386	91,395	91,395
1971	9,458	25,921	656			7,513,161	126,696	126,696
1972	34,081	36,505	3,573			7,611,734	163,493	163,493
1973	36,836	30,296	6,059			548,403	137,994	137,994
1974	61,880	26,550	5,251	17,531		51,000	4,593	166,805
1975	59,512	25,698	5,958	27,776		50,400	6,015	175,359
1976	86,527	27,514	6,524	20,032		45,500	6,334	192,431
1977	118,064	17,136	2,258	19,455	16,723	23,451	5,610	202,697
1978	97,470	8,866	12,163	19,588	15,171	8,179	5,584	167,021
1979	105,784	10,350	14,872	10,949	13,930	9,923	5,317	171,125
1980	115,037	8,543	35,322	13,166	15,846	12,471	5,553	205,938
1981	147,744	9,916	36,087	18,727	14,864	12,184	6,659	246,181
1982	168,746	8,556	29,379	6,760	9,278	7,993	8,314	239,026
1983	215,649	9,001	36,401	12,260	12,661	7,406	9,917	303,295
1984	306,693	10,230	23,219	1,153	6,879	4,452	12,008	364,634

^a Source: for the period 1958 to 1976 from Ito and Balsiger (1983); for the period 1977 to 1984 from Major (1986).

^b Source: Ito (1982). Excludes unknown catch by U.S.S.R.

^c Source: International Pacific Halibut Commission Technical Report No. 14 for annual statistics for the period 1929 to 1975. Landings for the period 1975 to 1984 obtained from Annual Reports of IPHC. Catches indicated are from IPHC Regulatory Areas 3A and 3B (Cape Spencer to Cape Lutke).

ocean perch. Landings declined to a minimum of 9.1×10^4 mt in 1970. The increasing trend in total landings after 1970 resulted from increased exploitation of walleye pollock, Pacific cod (beginning in 1971), and Atka mackerel (beginning in 1978).

Although demersal fish in the Gulf are not as abundant as they are in the Bering Sea, where maximum annual catches have exceeded 2.2×10^6 mt ($\sim 2.0 \times 10^6$ mt of which were walleye pollock), demersal fish of the Gulf are closer to domestic markets and have considerable potential commercial value to a growing United States fishery. Further details regarding the history of the fisheries, the distribution of species, and the condition of the Gulf stocks can be found in Ito and Balsiger (1983).

Pacific Cod (*Gadus macrocephalus*). Fifty years ago, the Pacific cod (*Gadus macrocephalus*) was considered a subspecies of the Atlantic cod (*Gadus morhua*), although it is now considered a separate species. The essential difference is that the eggs and larvae of the Pacific cod are demersal, whereas the eggs and larvae of the Atlantic cod are pelagic. The Pacific cod, which is known also as true cod, gray cod or just 'cod', was the target species of one of the oldest non-aboriginal fisheries of the west coast of North America. Although market demand has fluctuated considerably over the years, the demand appears to be increasing, and cod is a species of principal interest to the newly developing North Pacific trawl fisheries of the United States.

Pacific Cod Distribution. Since 1981, commercial fishing and joint Japan/United States longline surveys (Bakkala, Westheim, Okada, Zhang, and Brown 1981; Sasaki, Rodman, Onoda, and Rosapepe 1982) have provided considerable information regarding the distribution and relative abundance of Pacific cod. Although some cod were taken as deep as 500 to 600 m, they are most abundant at depths of less than 300 m, particularly at 100 to 200 m (Fig. 14-3). More details relating to the distribution and abundance of cod

can be found in Ito and Balsiger (1983), and in Bakkala and Low (1985).

The bottom layer at the depths where cod are most often found (100–300 m) is not motionless, but circulates in approximately the same pattern as the surface layer, although friction may slow the speed of the bottom currents. It should be noted that 1) the currents (including the near-bottom currents) are stronger along the continental slope (where the cod spawn), and 2) they follow the contours of the slope. Therefore, we postulate that cod larvae are carried westward by bottom currents along the northern Gulf slope and are then dispersed over both the continental shelf and deeper waters when the larvae become more pelagic. According to this hypothesis, larvae from the Kodiak spawning area will provide recruitment to the cod stock(s) in the Aleutian Islands, and to some extent, to those stocks in the southern Bering Sea.

We hypothesize similar drift patterns for halibut larvae (see section on Pacific halibut) and for Pacific ocean perch, although the larvae of both these species are pelagic. The Kodiak stock must receive recruitment from spawning stocks along the coast further to the east and south. Some recirculation of the larvae caught in the gyre may be possible.

Circulation time for the Gulf gyre might be of the order of 6 to 9 months (Reed 1980; Reed and Schumacher, Ch. 3, this volume). This much time may allow juvenile cod to attain a length of 11 cm and longer—the size at which they have been found in shallow-water exploratory surveys (Fredin 1985). Juveniles 6 to 10 cm long have been taken in shallow bays (<20-m depths) both in the Gulf of Alaska and in Puget Sound. The results from trawl surveys that were conducted in the eastern Bering Sea suggest that juvenile cod gradually disperse offshore as they attain progressively larger size (Gunderson 1983).

Pacific Cod Catch Statistics. The history of the United States cod fishery has most recently been summarized by Rigby

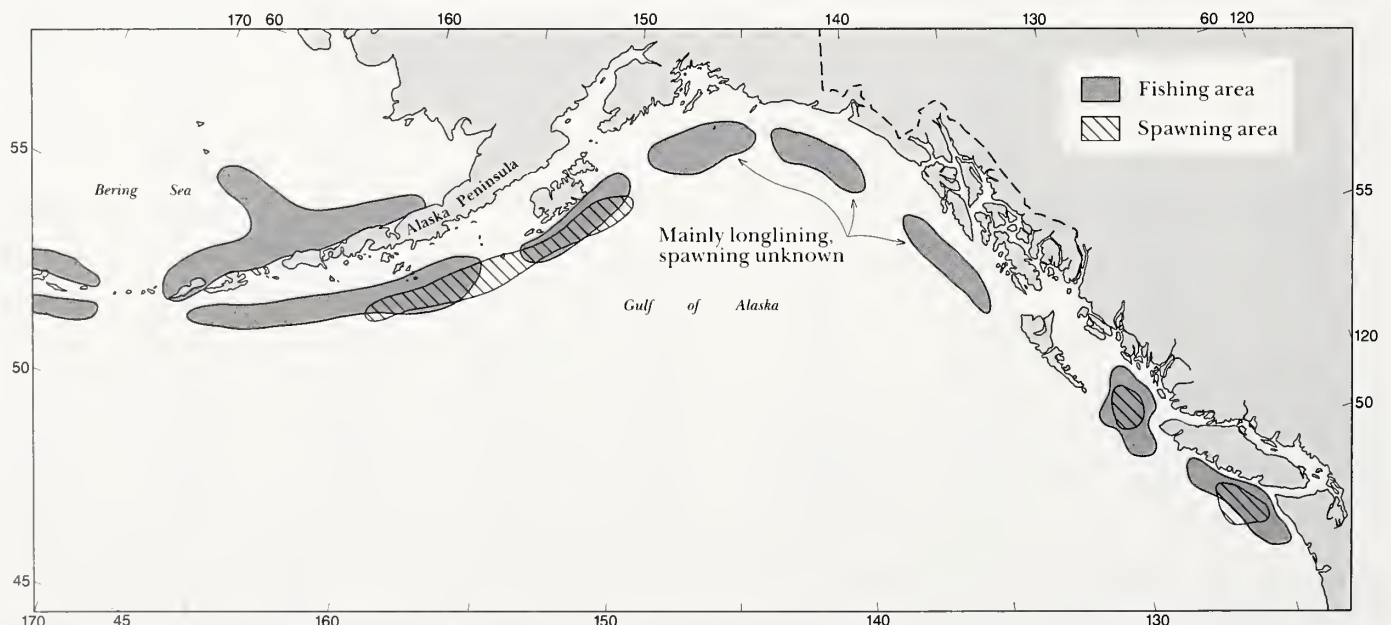


Figure 14-3. Spawning and fishing areas for Pacific cod (*Gadus macrocephalus*).

(1984). It began as a distant-water, sailing-vessel operation where United States fishermen exploited cod in the Okhotsk Sea during the years 1863 through 1909. Cod fishing in the Bering Sea began in 1864, and the pre-World War II cod fishery peaked in 1920 at 5.8×10^3 metric tons. However, poor market conditions reduced the catch to $\sim 1.0 \times 10^3$ mt by 1942, and then to less than 500 mt through 1950. No catches were made from 1951 through 1954.

The post-World War II Pacific cod fishery resumed in 1964 off the Aleutian Islands and in the Bering Sea. In 1971, it was extended into the Gulf by the distant-water, engine-powered vessels of Japan. In the latter area, total foreign catches increased from $\sim 6.50 \times 10^2$ mt in 1971 to $\sim 3.6 \times 10^4$ mt in 1981 (Table 14-5). The relative abundance of cod is indicated by the commercial landings: the Gulf catch of 3.6×10^4 mt in 1981 (Ito and Balsiger 1983) was 3.4 times as

Table 14-5.

The annual Gulf of Alaska Pacific cod catch (mt). Catch is shown by International North Pacific Fisheries Commission (INPFC) area for the period 1971 to 1981 as reported for Japan, U.S.S.R., Republic of Korea (R.O.K.), Poland, Mexico, the United States^a, and U.S.-foreign joint venture^b (from Ito and Balsiger 1983.)

	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
Japan											
Shumagin	119	167	329	689	1,451	1,542	377	4,073	3,067	6,624	9,032
Chirikof	57	83	957	614	746	492	296	3,537	5,598	17,403	14,807
Kodiak	262	453	972	1,185	694	760	457	971	1,414	4,551	2,334
Yakutat	23	70	332	440	362	479	285	199	294	1,961	1,517
Southeastern	0	43	15	44	27	35	13	66	55	43	78
Total	461	816	2,605	2,972	3,280	3,308	1,428	8,846	10,428	30,582	27,768
U.S.S.R.											
Shumagin			739	40	309	267	196	86	6	361	
Chirikof			829	^d	0	514	50	995	165	906	
Kodiak ^c	176	2,696	1,732	2,096	2,226	1,520	279	60	663	675	
Yakutat			95	^d	16	694	0	0	1		
Total	176	2,696	3,395	2,136	2,551	2,995	525	1,141	835	1,942	
R.O.K.											
Shumagin								1,361	788	1,627	2,241
Chirikof								8			4,069
Kodiak											25
Yakutat									56 ^e	39	731
Total								1,369	844	1,666	7,066
Poland											
Shumagin									9	9	41
Chirikof									118	46	94
Kodiak								14			
Total								14	127	55	135
Mexico											
Shumagin									100		
Chirikof									376		
Kodiak									463		
Total									939		
U.S.											
Shumagin		36		2	1	13	53	64		70	238
Chirikof				1	42	52	16	167	267	49	38
Kodiak	12	10	28	71	40	96	140	443	606	415	679
Yakutat				2	10	8	6	2	27	4	2
Southeastern	7	15	31	67	34	52	55	107	85	190	30
Total	19	61	59	143	127	221	270	783	985	728	987
U.S.-Foreign Joint Ventures											
Shumagin								7	11	13	T
Chirikof									17	223	58
Kodiak									683 ^f	230	
Total								7	711	466	58
Grand total	656	3,573	6,059	5,251	5,958	6,524	2,223	12,160	14,869	35,439	36,014
Percent of total ground-fish catch	0.5	1.8	3.4	2.6	3.3	2.2	1.2	7.4	9.1	17.0	15.1

^a Data supplied by Alaska Department of Fish and Game.

^b Data source NMFS Foreign Observer Program (French, Wall, Berger, and Gibbs 1981).

^c Reported as western Gulf in 1971 and 1972; includes Shumagin, Chirikof, and Kodiak INPFC areas.

^d Catch, if any, reported in Other Species category.

^e Includes 7 mt from the Southeastern area.

^f Includes 0.6 mt from the Yakutat area.

T = Trace amounts

large as the catch in the Aleutian Islands (1.05×10^4 mt) (Bakkala and Low 1985), but only 69% of the 5.2×10^4 mt catch from the eastern Bering Sea.

Pacific Cod Reproductive Biology and Life History. Descriptions of both the life history and the biology of Pacific cod have been summarized by Gunderson (1983). Fredin (1985) has presented a comprehensive synopsis of the species.

Pacific cod spawn off Vancouver Island in February and March as well as in Hecate Strait in March. They spawn at depths of from 100 to 150 m and at temperatures of 6 to 8°C (Ketchen 1961; Westrheim 1977). Canadian research shows that both the size and the age at maturity increase in a northward cline. Off southern Vancouver Island, 50% of the population matures at 50 to 53 cm (2–3 y) as compared to 53 to 56 cm (3–4 y) in Hecate Strait. Both the growth rate and the maturation of adult cod can be assumed to be a function of temperature.

Canadian tagging studies indicate that the Pacific cod found off Washington and British Columbia migrate short distances and that the differences in both the growth rate and the size/age at maturation vary with latitude and temperature. These findings indicate that the Pacific cod is considerably less migratory than its Atlantic relative. Spawning cod have been taken from January through May off Siberia (Musienko 1970) and from January through March in the northern Bering Sea (Svetovidov 1948), whereas cod in spawning condition have been taken by the Japanese fishery southwest of the Pribilof Islands from late January through March and by United States fishermen from December through April in bays along the north side of Unimak Island as far as False Pass (Fredin 1985). Hirschberger and Smith (1983) reported finding cod in spawning condition along the outer edge of the continental shelf from Yakutat Bay to Chirikof Island (during February through July) in bottom-water temperatures of 4.5 to 5.9°C.

Although cod in spawning condition are rather ubiquitous in the region, very little is known regarding 1) their reproductive biology, 2) their fecundity or the ecology of their eggs, or 3) the ecology of the larvae and young juveniles (Gunderson 1983). The capture of significant numbers of cod larvae in the relatively enclosed waters of Puget Sound has been reported by Gunderson (1983). However, even though there have been numerous ichthyoplankton surveys conducted in the Gulf, no eggs or larvae have been found. In addition, only five larvae have been captured in the eastern Bering Sea (Waldron 1981), and these were found south of Nunivak Island near the 40-m contour.

Pacific cod eggs are slightly heavier than seawater and are adhesive until they hatch. The timing of the various Gulf ichthyoplankton surveys has included the period when cod eggs and larvae should have been present. The fact that they have not been found is attributable to the ineffectiveness of sampling for them in the upper water column using plankton and nekton nets. This suggests that the eggs and even the larvae develop very near the bottom at depths below those that were sampled.

The selective advantage offered by adhesive eggs with negative buoyancy is not clear, but it may become more apparent as we learn more about the reproductive biology

of cod and the ecology of their embryological development. Since we know from aquarium research in both Korea and Japan that cod eggs lose their adhesiveness shortly before they hatch (Fredin 1985), the fact that larvae are not captured in the water-column plankton tows is indirect evidence that both the eggs and the larvae remain in the bottom water layers.

Staying near the bottom through the larval stage may have two selective advantages. First, the optimum temperature for cod egg development is 3 to 6°C (the limits are 1 to 8°C) (Fredin 1985) and lower winter temperatures occur in the shelf and slope areas where the cod spawn. The higher winter temperatures of this near-bottom environment might provide better growth conditions. Second, as cod larvae emerge at a very small size in early spring, they must have a ready supply of food. Food such as copepod eggs and early-stage nauplii can be found in the deeper layers during early spring, coincidental with emergence of the larvae.

*Pacific Halibut (*Hippoglossus stenolepis*).*

Pacific Halibut Distribution. The northern Gulf is not only an important nursery area for Pacific halibut eggs, larvae, and juveniles, it also provides habitat for local adults as well as for those transient adults that migrate into the area from as far west as Cape Navarin and from as far south as Santa Barbara (Skud 1977)—a range of several thousand kilometers (Fig. 14–4).

The shelf-break environment throughout the range frequented by adults features conditions which are relatively constant all year around at any given depth. For example, at the 400-m contour, temperatures of 5 ± 1 °C are found with salinities of 34.1 ± 0.1 ‰ and dissolved oxygen levels of 0.71 ± 0.35 mM/l. Even over the slope across the northern Bering Sea such values are not altered enough to preclude the survival of larvae during a trans-Bering Sea migration.

Halibut rise in spring from winter depths of 300 to 1,000 m, moving over the shelf edge to forage and even to enter the warm, dilute, coastal bays. Best (1981) has shown that in the southeastern Bering Sea, the on-shelf migration is retarded by bottom temperatures of near 0°C that are caused by a winter turnover of the water column under the ice. However, in the Gulf, any extensive ice formation is limited to the dilute, inshore areas such as Cook Inlet or to areas along the northern and western coasts where ice does not extend far seaward and is therefore not a major impediment to migration.

Pacific Halibut Catch Statistics. The commercial fishery for Pacific halibut started in 1888 off Cape Flattery, expanded into the northeastern Gulf by 1913, and stretched into the western Gulf by 1921. Since 1924, the fishery has been managed by both the International Pacific Halibut Commission (IPHC) and its predecessor, the International Fisheries Commission (IFC). The total commercial catch in 1982 was 1.32×10^4 mt, compared to an average catch during the period from 1919 to 1928 of 2.27×10^4 metric tons. The 1982 catch had a dockside value of \$32 million. The northern and the western Gulf management areas (designated 3A and 3B) constitute 49% of the halibut habitat in United States and Canadian waters. Kodiak and Seward were the primary and secondary unloading ports, respectively.

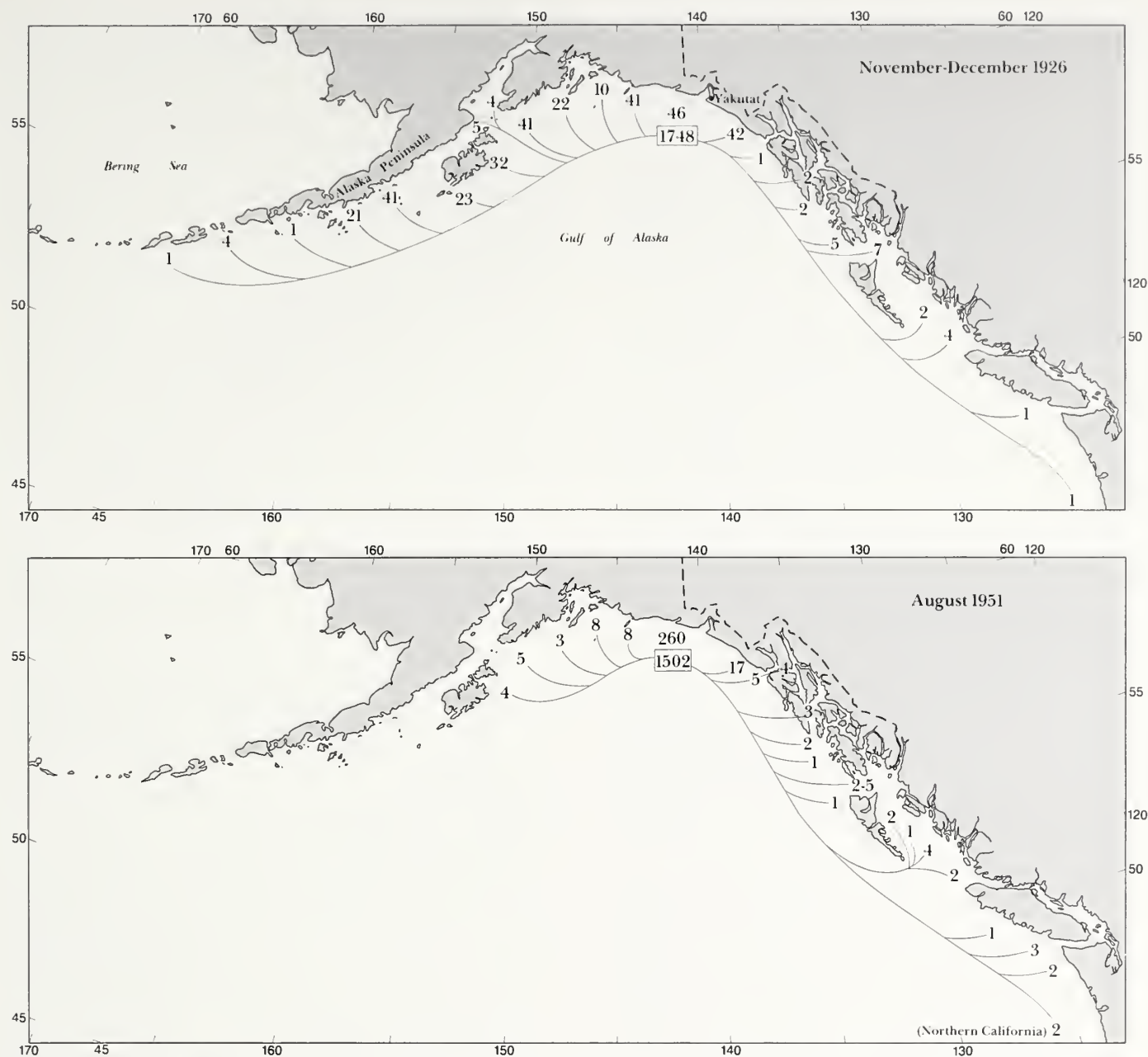


Figure 14-4. Distribution of tag recoveries from Pacific halibut (*Hippoglossus stenolepis*) tagged off Yakutat. Number of fish tagged is shown in the boxes. (Modified from Skud 1977.)

Halibut are long-lived, with those under eight years of age considered juveniles. Adults may live as long as half a century and weigh several hundred pounds. The IPHC adult surveys conducted in 1982 from the Canadian coast northward around the Gulf to the Shumagin Islands indicated a stock that averaged nearly 11 years of age and 13.2 kg in weight (females averaged about twice the weight of males). Most adults taken in the survey were caught at bottom temperatures that ran between 4.6 and 6.6 Celsius.

Pacific Halibut Reproductive Biology and Life History. During the fall, halibut retreat back over the shelf edge as the onset of winter cooling and winter storm systems create increased turbidity over the sea floor and stir up unconsolidated sediments over the shallow banks. This offshore retreat is also a

prelude to spawning that occurs in winter at depths typically between 300 to 600 meters. The females release between 0.5 - and 2.0×10^6 eggs, which are denser than the surrounding water and hatch within several weeks. Environmental conditions play a major role in the survival of both the eggs and the larvae.

Much of our present knowledge of the early life history of halibut in the Gulf stems from IFC studies (Thompson, McEwen, and Van Cleve 1936). However, laboratory studies indicate that halibut eggs will not survive to hatching at temperatures of 4C (Forrester and Alderdice 1973). This can be interpreted to mean that even *in situ* eggs and larvae are at risk at such temperatures—in which case, the western Gulf may be a hostile environment. Even though spawning

occurs in this general area (Best 1981) and eggs released in the Gulf may be advected here in great numbers, survival may be minimal. New information on the currents in this area indicates that the dispersal of both eggs and larvae in the Gulf may be more complicated than we previously assumed.

Oceanographic Considerations. The first extensive oceanographic studies of the northern Gulf were conducted by the IFC during the winters of 1927, 1928, and 1929, in order to determine the drift of both halibut eggs and larvae (McEwen, Thompson, and Van Cleve 1930). An intense westward Gulf flow had been reported for over half a century in this area; the IFC studies (McEwen *et al.*, 1930, Thompson *et al.* 1936) showed that the maximum flow was indeed generally westward around the Gulf (off Ocean Cape, Cape Clear, and Cape Chiniak). The maximum speeds occur in a narrow band 50 km wide just seaward of the shelf edge that is usually bounded by weak easterly currents. The one exception—and an important one in terms of egg and larval drift—is the area off Cape Clear where in 1929, larval drift was eastward and not westward, although the maximum flow still occurred at the shelf edge. In view of recent studies that reflect a general complex westward flow in this area, a closer inspection suggests that these station data are in error, although the irregular bathymetry in this area could be a factor.

Perhaps the most ambiguous result in view of recent data is the fact that without exception, the IFC flow calculations show that low current speeds (~ 5 cm/s) are restricted to the upper 300 m and the calculations invariably show either no or very weak westerly flow (< 2 cm/s) and even easterly flow adjacent to the slope between depths of 300 and 1,000 meters. These flow calculations imply little egg or larval drift unless the eggs or larvae were to rise above the 200-m contours.

Particularly significant in this respect are the more recent direct current measurements that were taken at the shelf edge south of Cape Clear between April 1976 and March 1977 (Niebauer 1981). These measurements (averaged velocity time-series data), indicated that there is a 19 cm/s (max. 58 cm/s) along-slope flow out of the northern Gulf in the spring at a depth of 273 meters. Summer and fall data indicate flows at depths of 278 m of 13.8 cm/s (max. 48.4 cm/s), and a partial winter record taken at 307 m indicates a flow of 33.5 cm/s (max. 65.3 cm/s). Near-surface speeds averaged ~ 50 cm/s (on a bearing true of 198–207°) during the three measurement periods, with a maximum average speed of 133.5 cm/s occurring in spring. In addition, whereas IFC studies off Cape Chiniak indicated no flow within 50 to 100 m of the bottom in an area extending from the coast out over the shelf and down the slope to 800 m, a current meter moored at a depth of 100 m near the shelf edge (183 m) during the fall of 1975 recorded a mean speed over an 18-d period of 30.2 cm/s.

Our new data come from direct current measurements rather than from geostrophic computations, which are invalid 1) in the presence of physical constraints such as bottom topography and 2) because they require a level of 'no flow'. (In the case of IFC data, no-flow is assumed to be at or near the bottom.) In light of the new data, it appears that

flow over the slope in the northern Gulf is considerably higher than the IFC data indicated and, except for along-shelf perturbations, it is continually westward below 200 to 300 meters. One can safely assume a flow of 10 cm/s at 300 to 600 m—the depth range that both halibut eggs and larvae occupy from December to March.

Eggs that are released in December in the northeastern Gulf drift westward along the slope, attaining larval stages and reaching a position seaward of Cape Chiniak by March. By this time, they would also have risen into the upper 100 m of the water column where they would encounter speeds of 50 to 100 cm/s in the Alaskan Stream (Favorite and Ingraham 1976). In the summer of 1978, satellite-tracked drogued buoys moved southwestward in this area at average speeds of 29, 15, and 27 cm/s (Reed 1980). If we accept a mean flow of 25 cm/s, by May when larvae are normally expected to have arrived in shallow water and metamorphosed to demersal fish, these larvae would either have been transported past Unimak Pass and out along the Aleutian Islands, or would have been recirculated into the Gulf. In the former case, three results can be anticipated (Fig. 14–5):

- 1) The larvae could settle on the bottom near any of the Aleutian Islands.
- 2) The larvae could move through deep passes at 170°W and eastward to the Bering Sea shelf by June (Favorite and Fisk 1971).
- 3) The larvae could move through Amchitka Pass (180°W) and then eastward to the southwestern Bering Sea shelf, perhaps arriving near the Pribilof Islands by August (Favorite, Laevastu, and Straty 1977).

In making such transits, the larvae will encounter temperatures of 3 Celsius.

In the latter case, the southward displacement of larvae, which can occur at various locations, will result in recirculation into the Gulf. Recirculation in summer from south of Kodiak Island and from south of Unimak Pass to the northern Gulf—as demonstrated by satellite-tracked drogued buoys—requires four and six months, respectively, and an additional month to reach Kodiak Island (Reed 1980).

Recirculation from south of the central Aleutian Islands to the coast of North America would require about 12 months—although such trajectories are largely hypothetical because Skud (1977) infers that an extended pelagic life for halibut larvae is unlikely. Thus it appears that any successful contranant displacement of larvae must stem from eggs released over the mid-Gulf slope in winter and whose larvae have risen in the water column sufficiently to be advected across the ridge domain (~ 200 m) in a recirculation flow in February. Those larvae that endure the pelagic regime until June could survive, and during that time, they may be advected to the northeast Gulf shelf.

Flow over the shelf is important to the larvae that have risen into the surface layer and require transportation into the coastal regime if they are to survive. Geostrophic calculations of flow over the shelf (from IFC data taken off Ocean Cape, Cape Clear, and Cape Chiniak in the winters of 1928 and 1929) reflected 1) low flows (2 to 10 cm/s), 2) a general flow trend toward the west, and 3) marked irregularities.

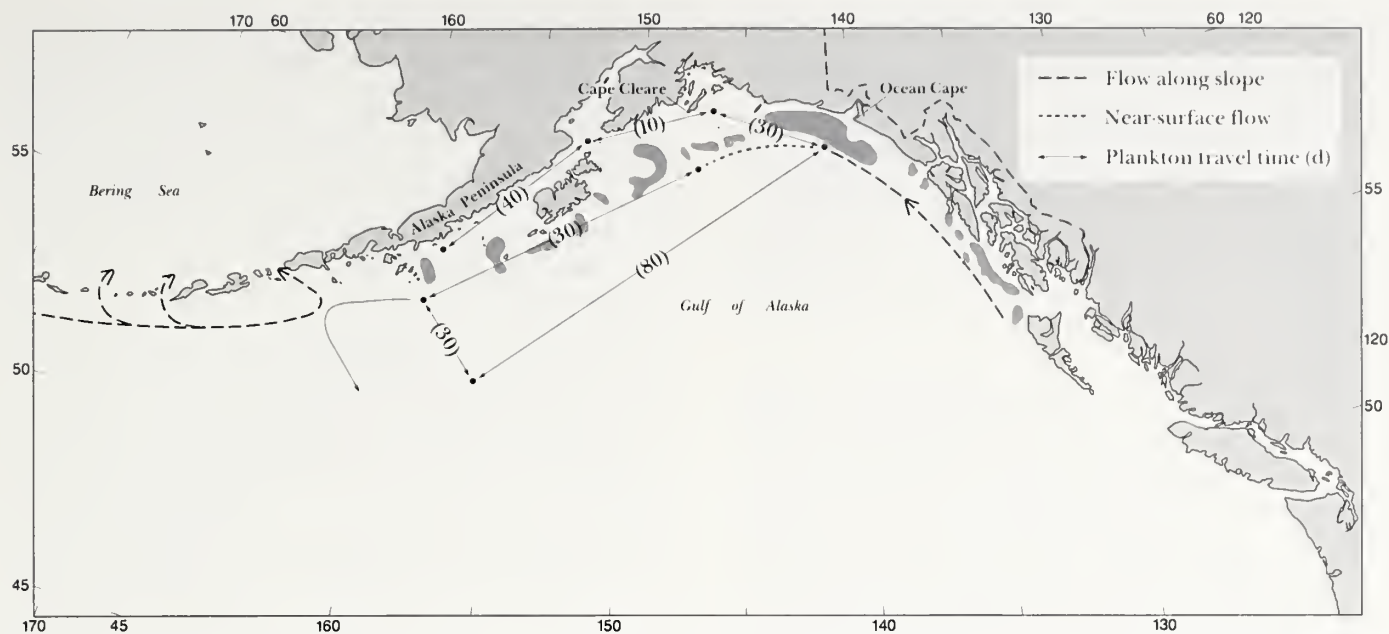


Figure 14-5. Locations of spawning areas and fishing grounds for Pacific halibut (*Hippoglossus stenolepis*) (modified from St-Pierre 1984), and the estimated time (in days) required for plankton in the surface layer to travel between indicated points (based on data from OCSEAP satellite-tracked drogued buoys). Near-surface flow is based on geostrophic considerations.

Opposing flows alternated seaward from the coast off Ocean Cape and Cape Clear. The flows started westward inshore, then moved eastward, changed to westward, and subsequently headed eastward again near the shelf edge that lies just inshore from the intense westward flows that are seaward of the shelf. The wide spacing between the lines of measuring stations made it impossible to determine any continuity between these flows or to find any possible eddy structures. However, the extensive IFC drift-bottle program from the period between 1930 and 1934 (Thompson *et al.* 1936) clearly demonstrated that cross-shelf flow was a major feature in the northeast Pacific because onshore recoveries were made all along the coast from Cape Flattery to Unimak Pass after offshore releases.

Vessel transits between northern ports consistently reflected an organized westward flow inside the shelf edge at the head of the Gulf. IFC drift-bottle data also provide additional insight into the continuity of flow in this area. A drift bottle (#2219) that was released in March 1932 off the coast of the Queen Charlotte Islands had moved northward as far as Prince William Sound by June—traveling a distance of 1,220 km in 91 days for an average speed of 18 cm/s. Another drift bottle (#3806) released in January 1934 near the coast south of Ocean Cape (Yakutat) moved across the Gulf through Shelikof Strait to the west side of Kodiak Island—traveling a distance of 1,111 km in 78 days for an average speed of 19 cm/s. It is possible that the actual transit times could be much less and the speeds proportionately higher since it is possible the bottles are trapped in inshore oscillatory tidal flows. Larvae are not necessarily at the sea surface, however, and reduced speeds and even shifts in direction are possible at increased depths.

Considerable advances have been made by using satellite-tracked drogued drift buoys for this research (Royer, Hansen, and Pashinski 1979). Three buoys were released

~100 km south of Yakutat in the summer of 1976. All three moved westward at speeds as high as 40 cm/s before moving into an eddy west of Kayak Island and then into Prince William Sound. Once they were in the Sound, one buoy circled the Sound clockwise in 20 days, suggesting that many of the drift bottles that were released offshore east of the Sound and recovered west of it may have completed the same circuit.

The transit time required by the drift bottles to go from off Yakutat Bay to the exit of Prince William Sound was just under two months, whereas the satellite-tracked buoys (Reed 1980) moved from a nearly identical position off Yakutat Bay westward to a point south of Prince William Sound and then via the southwestward Kenai Current (Schumacher and Reed 1980) to Shelikof Strait in less than 30 days (December 17, 1978 to January 13, 1979). This means that it is possible for halibut larvae that are spawned at depths of ~500 m and at a distance of 800 km south of Yakutat off the Queen Charlotte Islands to move north at 10 cm/s to arrive in the northeastern Gulf in the upper 100 m of the water column by March. The larvae can then be transported over the shelf edge into the coastal regime rather than being transported westward along the slope as planktonic organisms at depths below 200 m would be. Once in the coastal regime, they are dispersed throughout the northern and western Gulf before their metamorphosis occurs and they descend to the sea floor.

Some drifting buoys have moved into Prince William Sound during the summer. In winter, one buoy moved westward south of Prince William Sound to a point west of Kodiak Island. Muench and Schumacher (1980) have shown that there is a wide dispersal both east and west of Kodiak Island based on drift cards they released northeast and southwest of the Island. Dispersal currents had velocities of between 10 and 30 cm/s in Shelikof Strait. Based on these

data, the dispersal of those halibut larvae that are ready to descend to the bottom throughout the shelf area as far south as Unimak Pass and the southeastern Bering Sea would require less than an additional month.

Ingraham (1979) has shown that during late summer, the runoff from the Copper River could be traced for over 300 km to the southwest of Kayak Island. Runoff moved as far as the shelf break off Kodiak Island where it may have started to recirculate back to the northeastern Gulf. This pattern would agree with early IFC interpretation of drift-bottle data in the 1930s. However, such a flow is not clearly documented at this time.

Complex circulation in this area can be assumed because the flow over the slope turns southward as part of the Alaskan Stream. In any event, it can also be assumed that any near-surface drogues or planktonic organisms, or even surface fish, may be carried southwestward across the shelf in such a system. But since dilute coastal flow and runoff from the Copper River is a summer or fall condition, it is unlikely that halibut larvae are present in surface flow at this time.

In spite of the complexity and annual variability of currents in the Gulf, recent direct current measurements have indicated 1) that there is a basic order to the flow in the northern Gulf, and 2) that there are subsurface flows over the shelf and slope that have much higher speeds than earlier data indicated. This gives rise to the general hypothesis that young-of-the-year halibut throughout both the northern and the western Gulf may originate from eggs that are released in the Queen Charlotte area, or just north of that area. Spawning in the northeastern Gulf near Yakutat would result in young-of-the-year being deposited along the Aleutian Islands as well as in the southeastern Bering Sea, but losses could be high. Spawning in the western Gulf could result in a contranant transport of larvae east of Kodiak to the northeast Gulf, but larvae are probably advected along the slope to the extreme western Aleutian Islands where the cold temperatures (3C or less) could limit their survival.

Rockfish (Scorpaenidae)

The genus *Sebastes* of the family Scorpaenidae, is remarkably diverse, and it includes ~100 species worldwide (Chen 1971). Although a few species occur in the South Pacific Ocean, most inhabit the temperate North Pacific and North Atlantic Oceans. Sixty-five species have been recognized in the temperate North Pacific Ocean, whereas in contrast, only three or four species have been recognized in the North Atlantic Ocean (Tåning 1949; Templeman 1959). Species diversity in the eastern North Pacific Ocean appears to be greatest between 34 and 38°N, with as many as 50 species found between these latitudes.

Between 38 and 40°N, there is an abrupt decrease in diversity, with 12 fewer species found there, and north of 40°N, an average of one less species is found for every degree of latitude (Chen 1971). Alverson, Pruter, and Ronholt (1964) reported a decrease in species diversity from south to north and an increase in diversity with depth, with the maximum number of species encountered in trawl surveys at depths of between 183 and 256 meters. Thirty species

have been captured in trawl surveys in the Gulf of Alaska (Ronholt *et al.* 1978). Quast and Hall (1972) reported eight species in the Bering Sea, although trawl surveys of the eastern Bering Sea in 1980 captured only five of these species (Umeda and Bakkala 1983). Fifteen species have been identified in the rockfish catches of the foreign fisheries in the Aleutian Islands/eastern Bering Sea slope, while an additional 14 species were tentatively identified, but their identity was not verified (Ito 1984).

Considering the similarities in the apparent requirements of the genus, it is curious that species diversity should be so much greater in the North Pacific Ocean. Chen (1971) considered geographic speciation as a partial explanation for the abundance of species of *Sebastes* in the North Pacific, also taking sympatric speciation into account. The fact that new species evolve through the shifting of their bathymetric preference or their association with different bottom types has been suggested by Barsukov (1964). Many authors have shown that each species of *Sebastes* has a characteristic depth range (Templeman 1959; Alverson *et al.* 1964; Chen 1971; Gunderson 1977; and Anderson 1984).

Although rockfish can be found in a range of water temperatures at given depths (Gunderson 1977), they have been found at specific depths even when desirable temperatures prevailed in shallower waters (Templeman 1959). There is, however, overlap in the distribution of sympatric species which Chen (1971) attributes in part to younger fish in shallower waters mingling with adults of shallower-water species. The discreteness of the distribution of species by depth is further confused by the fact that the same species in different geographic locations may occupy different depth zones. However, it should be noted that rockfish also undergo diurnal movement, albeit at relatively great depths.

There is no apparent reason why these same mechanisms of geographic and sympatric speciation should not also apply to *Sebastes* of the North Atlantic. There are only four species of *Sebastes* in the North Atlantic and, although this genus is distributed from the northwestern areas to the Barents Sea, obviously, both geographic and sympatric speciation occur to a lesser degree than in the North Pacific Ocean. The oceanographic structure of the North Atlantic may contribute to the difference because there is a greater seasonal turnover of the water column as evidenced by the near absence of a winter thermocline or its existence at great depth. There is also less salinity stratification and swifter currents (Dietrich 1965). Further investigation into the comparative environments of *Sebastes* is required.

Greater rockfish species diversity in the North Pacific Ocean than in the North Atlantic may also indicate that the species originated in the Pacific Ocean and has a considerably longer history there than in the Atlantic. If species diversity is considered a criterion for the antiquity of a genus, it might further be inferred that *Sebastes* first evolved in the eastern North Pacific Ocean in the area between 34 and 38° North.

Barsukov's (1964) hypothesis concerning sympatric speciation appears very reasonable inasmuch as the feeding habits of rockfish range from benthic to pelagic. Adult rockfish characteristically inhabit the continental shelf edge and slope. There—within relatively short distances—large

changes occur in the light, the pressure, the temperature, and the salinity. In addition, as indicated by Anderson (1984), the currents are stronger along the continental slope, and may transport more pelagic food past a stationary, feeding, rockfish shoal. All rockfish appear to have an affinity for certain substrates, although as pelagic feeders, it is not readily apparent why the type of bottom would be a necessary condition for survival. The mechanisms for sympatric speciation in pelagic-feeding rockfish are not obvious, but they must be associated with either clines or discontinuities in pressure, light, temperature, and salinity.

The species diversity within *Sebastes*, their bathymetric distribution, and the dominance of certain sympatric species (*S. alutus*, in particular) are of considerable biological interest. Further insights into these subjects will require a better understanding of their environment, including the nature of their niches and the niche diversity in their mid-water environment. The spatial and the bathymetric distribution of zooplankton and nekton and the diversity of herbivores must be determined, then linked to the specific specialization in rockfish foraging.

Rockfish are an important component of the total demersal fish complex in all areas south of the Alaska Peninsula. They dominated the pre-fishery demersal fish community, particularly at depths between 183 and 274 meters. Their relative importance generally declines 1) north of Cape Spencer, 2) on the inner shelf (< 183 m), and 3) at depths greater than 549 m (Alverson *et al.* 1964). Pacific ocean perch (*Sebastes alutus*) are the most abundant of these rockfish (Alverson *et al.* 1964; Pereyra, Reeves, and Bakkala 1976; and Ronholt *et al.* 1978). This species constituted 90% of the rockfish catch in Canadian surveys in the Gulf from 1963 to 1966 (Westrheim 1970). The Pacific ocean perch has historically been an important target of both domestic and foreign trawl fisheries (Ito 1982, 1983). We emphasize Pacific ocean perch in this section because of their dominance among continental slope rockfish, their commercial importance, and because of the knowledge we have of their distribution, abundance, and biology.

Pacific Ocean Perch (*Sebastes alutus*).

Pacific Ocean Perch Distribution. The Pacific ocean perch is broadly distributed over the outer continental shelf and the slope of the Asian and North American continents (Figure 14-6). Adults are usually found in gravel, rocky, or boulder-strewn substrates in and along the gullies, submarine canyons, and depressions of the upper continental slope (Alverson and Westrheim 1961). Both their larvae and their juveniles are pelagic and they join the adults in the demersal habitat after 2 or 3 years (Alverson and Westrheim 1961; Lyubimova 1964). Little is known of their distribution or movements before they join the adult population.

Pacific Ocean Perch Catch Statistics. The history of the exploitation of Pacific ocean perch is summarized in Figure 14-7. The fishery commenced in about 1960 with the annual catch peaking in 1965 at $\sim 4.74 \times 10^5$ metric tons. Thereafter, catches declined sharply to recent levels of $\sim 1.55 \times 10^4$ metric tons. In 1977, catch limits were imposed under authority of the Magnuson Fishery Conservation and Man-

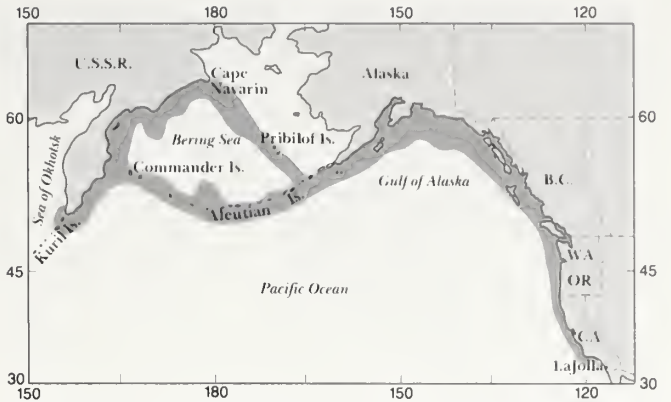


Figure 14-6. Distribution of Pacific ocean perch (*Sebastes alutus*) in the North Pacific. (Modified from Ito 1982.)

agement Act of 1976. The decline in the catch after 1976 is a consequence of this management action and may not reflect ocean perch abundance. There is no doubt, however, that in less than 25 years of exploitation, the once abundant Pacific ocean perch stocks of the eastern North Pacific Ocean have declined considerably. For a number of reasons, the prospects of any rapid return to former levels of abundance appear to be quite remote.

The continued low productivity of Pacific ocean perch stocks in the Gulf (and elsewhere) is probably not attributable to a single factor. Pacific ocean perch once dominated the biomass of the Gulf, indicating their high efficiency in competing for food. There is no obvious reason why this efficiency should be reduced simply because they are now less abundant. However, although there is little supporting evidence, predation by the increasing pollock population may contribute to the suppression of rockfish stocks. In addition to pollock predation, there is also evidence that chinook salmon may prey on both larval and juvenile perch.

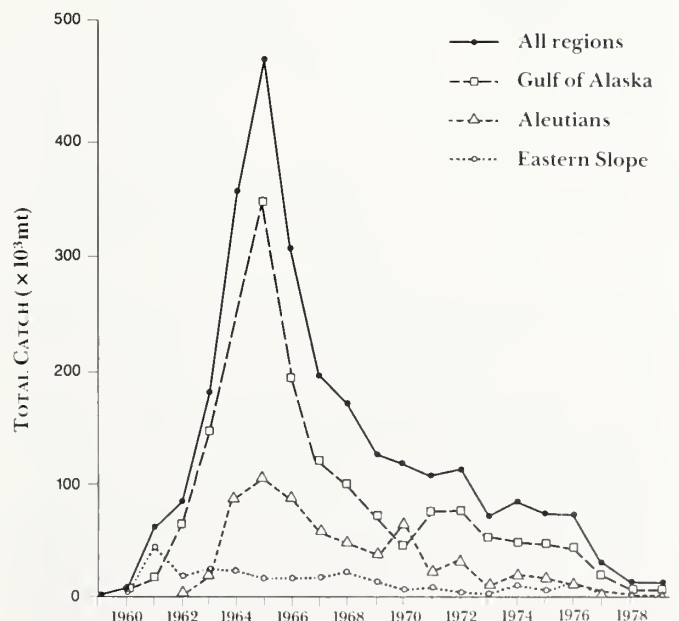


Figure 14-7. Catch trends for Pacific ocean perch (*Sebastes alutus*) by region, for the period 1959 to 1979. (Modified from Ito 1982.)

The greatest impediment to rebuilding the Pacific ocean perch stocks may be intrinsic to the life history of the species. Rebuilding the population of any slow-growing, long-lived species after it has been over-exploited is a slow process.

Pacific Ocean Perch Reproductive Biology and Life History. Rockfish in general grow slowly (Chikuni 1975), may live to between 80 and 140 years (Chilton and Beamish 1982), and have comparatively low fecundity (Westrheim 1958; Paraketsov 1963; Lisovenko 1965; Snytko 1971; Alverson and Westrheim 1961; Chikuni 1975; and Gunderson 1977). Pacific ocean perch live from between 25 and 30 years (Alverson and Westrheim 1961; Chikuni 1975), although some may live for more than 70 years (Beamish 1979).

In the eastern North Pacific, larvae and juveniles of various rockfish species form both a large and an important part of the diet of other fish, including chinook salmon, *Oncorhynchus tshawytscha*, albacore, *Thunnus alalunga*, petrale sole, *Eopsetta jordani* (Phillips 1957), and Pacific whiting, *Merluccius productus* (Livingston 1983). There is, however, very little information regarding predation on the rockfish in the Gulf or in the Aleutian Islands/Bering Sea areas. The bones of adult rockfish were found in the stomach of a sperm whale (*Physeter catodon*) that was caught in the northern Kurile area (Frederikhsen 1977).

Although there is no direct evidence, it is possible that there is increased predation on rockfish larvae as a result of the recent apparent increase in the abundance of Pacific cod (*Gadus macrocephalus*) and walleye pollock (*Theragra chalcogramma*). Other ecosystem changes may also be contributing factors in the slow recovery of the Pacific ocean perch population.

Present knowledge indicates that all rockfish larvae are pelagic. Although there is information that indicates when and where rockfish larvae can be found, information about individual species is not easily obtained because species identification of the larvae is very difficult. Although some rockfish species are far more abundant (as ascertained from the abundance of adults), competitive exclusion has not occurred. Sympatric rockfish species, therefore, have developed coexistence strategies rather than competitive strategies during their larval stages in the pelagic environment.

We can only guess how interspecies competition is avoided. Perhaps different species prefer different food. They may avoid direct competition for the same size food because of interspecies differences in parturition timing or in larval growth rates. Laevastu and Larkins (1981) estimated that the productivity of both phytoplankton and zooplankton was greatly in excess of the consumption, so it seems unlikely that there is much competition for food. This is only speculation, however, until individual species of rockfish larvae and juveniles can be reliably identified and their feeding habits clarified.

Quantitative information concerning the feeding habits of sympatric species of adult rockfish is scant, and information on the diets of larvae and juveniles is almost nonexistent. Any diversity of environmental niches that might account for the profusion of rockfish species in the North Pacific Ocean (as contrasted with the North Atlantic Ocean)

is not readily apparent. This raises interesting questions as to the comparative ecology, zoogeography, phylogeny, and population genetics of *Sebastes*.

One question focuses on the fact that Pacific ocean perch are dominant among the rockfish. On the basis of the available evidence, the dietary preference of Pacific ocean perch, which feed primarily on euphausiids and copepods (Livingston and Goiney 1983), appears to be less varied than that of other species of rockfish. Feeding almost exclusively on euphausiids and copepods would be a disadvantage to Pacific ocean perch if the abundance of those zooplankton dropped. However, as noted before, zooplankton consumption in the North Pacific Ocean is far less than the annual production (Laevastu and Larkins 1981). Therefore, the food supply is not a constraint on their productivity, but perhaps an explanation of their dominance among the rockfish.

The stock composition of the Pacific ocean perch is of fundamental importance in the management of the resource. Lyubimova (1964) suggested that *S. alutus* was a single stock in the Gulf, the adults of which inhabit the 4 to 6.5C waters (Plakhotnik 1964) of the Alaska Current all year. According to her hypothesis, the stock migrates upstream in autumn and winter, traveling through the Alaska Current to the northeastern Gulf, where warmer temperatures provide more favorable conditions for egg maturation and larval release. These events occur from April to May, followed by a westward, spring/summer feeding migration back to the Unimak Pass area, which then completes the annual cycle (Fig. 14-8, top).

Fadeev (1968) rejected the hypothesis of long-distance migrations of Pacific ocean perch along the continental slope on the evidence of the ubiquitous distribution of Pacific ocean perch along the continental slope of the Gulf, Aleutian Islands, and eastern Bering Sea and the seasonal changes in bathymetric distribution of catches. He concluded that the Pacific ocean perch in these areas consisted of many local populations which overlapped to some extent (Fig. 14-8, bottom), and proposed that only seasonal changes occur in the depth range occupied by local populations. That would mean that these changes depend upon the physiological state of each population.

The prevailing view is that the Pacific ocean perch population in the Gulf is composed of a number of aggregations—each of which has characteristic biological attributes (e.g., age structure, growth rate, and age at maturity). However, these aggregations may not necessarily constitute isolated gene pools, and new genetic material may be introduced through pelagic larvae and juveniles (L.W. Seeb and D.R. Gunderson, University of Washington, unpubl. data). However, in combination with its geographic isolation, the rockfish's ovoviviparousness probably limits both the opportunities for gene flow among aggregations and the hybridization among sympatric rockfish species.

If we accept the prevailing hypothesis that the Gulf population is made up of many local aggregations, then we need to know how each group retains its cohesion. Are the local populations isolated by oceanographic barriers? In addition to the influx of juveniles, is there gene flow between aggregations due to overlap in their distribution? Could this

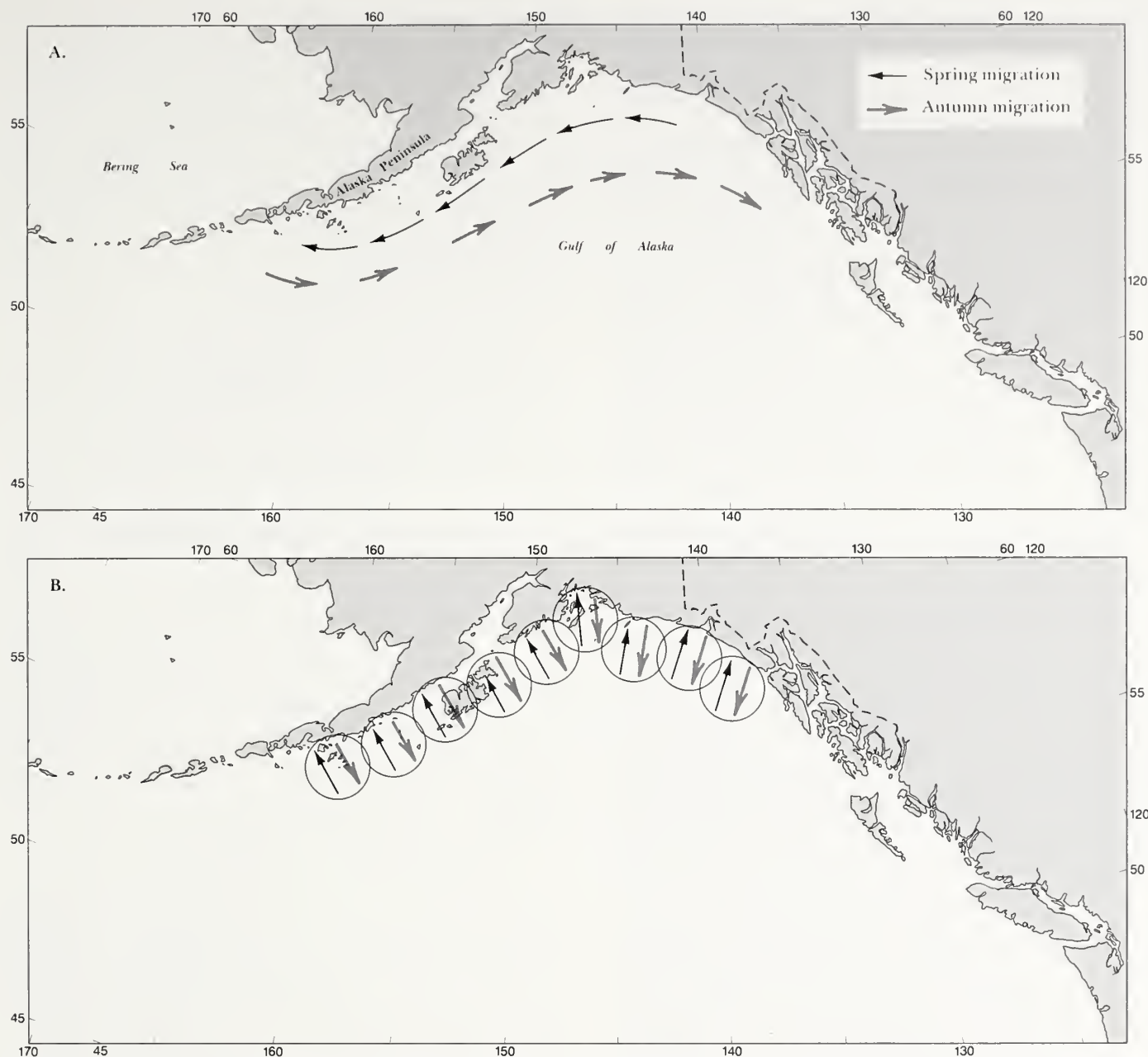


Figure 14-8. A. Seasonal distribution and migration of Pacific ocean perch (*Sebastes alutus*). (Modified from Lyubimova 1964.) B. Multiple aggregation and seasonal bathymetric migration hypothesis of Fadeev (1968).

overlap contribute to geographic phenotypic clines and to the frequency of the alleles observed by L.W. Seeb and D.R. Gunderson (University of Washington, unpubl. data)?

It is also important to know how local rockfish aggregations maintain their geographic position and how they avoid being transported westward along the axis of the Alaska Current. Contact with favorable substrate may help them with their orientation, but favorable substrate is more or less continuous throughout the Gulf. The continuity in Pacific ocean perch aggregations seems to bear out this contention.

If local rockfish aggregations can be shown to be relatively stable in terms of their composition and their location, then perhaps the complex eddy system along the

irregular coastline provides isolating barriers or oceanographic discontinuities which aid rockfish orientation. This could be verified if a method were developed to capture and tag viable rockfish. In this regard, there is an indication that Atlantic redfish (*Sebastes marinus*) off the New England coast migrate from their 200-m daytime depth up to 80-m depths during the night (Templeman 1959). Assuming that the swim bladders of other marine teleosts can adjust in a manner comparable to perch when adapting to pressure changes, diurnal migrations involving more than a 50% pressure change are unlikely.

At least one fisherman in British Columbia routinely captures rockfish at great depths on handlines, transfers them to tanks, and then delivers them alive to market (M. Yesaki,

United Nations FAO, Sri Lanka, pers. comm.). Although the quantity of the catch may not be large, Yesaki's experience is clear evidence that rockfish can adapt to surface pressures if properly handled, and that the method should be investigated for its application to tagging experiments.

Rockfish have adapted to a deep and stable environment—an adaptation that has narrowed the limits of their tolerance to environmental changes. They are confined to certain mid-water depths, although they migrate vertically when they feed—a movement that is synchronous with the diurnal migration of euphausiids and copepods. Their larvae, however, are pelagic for several months and juveniles do not rejoin the demersal population until after two to three years (Alverson and Westrheim 1961; Lyubimova 1964).

In surface waters, larvae are subject not only to currents which might sweep them out of the area but also to high temperatures that are imposed by seasonal increases in insolation. Evidently, both the location and the timing of larval release has been such that those larvae which are either retained or circulated in a favorable environment have been able to maintain a comparatively abundant resource.

Chikuni (1975) suggested that the Aleutian Islands stock receives larvae from the Gulf of Alaska, and the Bering Sea stock receives larvae from both the Aleutian and the Gulf of Alaska spawners. These conjectures, although reasonable, are unverified. There are no quantitative estimates of how many larvae are retained within the territory of the parent aggregation and how many are transported out of the area. If the genetic component of a population outweighs the environmental component, then the retention of aggregational traits such as maximum age, size at age, and age at maturity is evidence that most of the larvae ultimately settle in the habitat of the parent population. Conversely, any substantial transportation of larvae to downstream populations would ultimately alter the genotypic structure of those downstream stocks.

Sebastes have adapted to a narrow range of cool temperatures. Reported optimum temperatures for redfish in both the Atlantic (Tåning 1949; Templeman 1959; and Anderson 1984) and in the Barents Sea (Veshchezerov 1944) were from 3 to 8C. For Pacific ocean perch, optimum temperatures ranged from 1 to 9C. However, like the redfish of the Atlantic, optimum temperatures for Pacific ocean perch appear to be in the 3 to 8C range, with the higher temperatures pertaining to the Vancouver/Oregon stocks (Lyubimova 1965; Snytko 1971; and Pautov 1972).

Larvae are released in late spring and summer and have a pelagic existence when sea surface temperatures undergo rapid heating due to both increased insolation and air temperature. For redfish, *S. marinus*, of Flemish Cap (east of Newfoundland's Grand Banks), Anderson (1984) found that high temperatures reduced growth rates, and that slow growth rates during the warm years were accompanied by an increase in larval mortalities. Anderson (1984) also noted that bottom temperatures of less than 2C adversely affect redfish when they become benthic. Whether this is true for Gulf rockfish is unknown. However, the Pacific ocean perch releases its larvae in the Alaska Current during April and May. These larvae would be transported westward where

water temperatures decrease even as seasonal warming of the atmosphere occurs.

Although egg fertilization and embryological development occur externally for many marine fish, rockfish are ovoviviparous and release yolk sac larvae. There is very little known regarding the time and place of mating for most species. The stock structure at mating is also not understood. Neither is it known whether the species is polygamous or polyandrous. Knowledge concerning the latter may be pertinent to the management of species such as Pacific ocean perch where sexes may be segregated except during mating and where exploitation might be highly selective for one sex over the other.

Because Pacific ocean perch are ovoviviparous, both their eggs and their embryos are protected from the external environment and from predation. Larval mortality, however, is apparently quite substantial because fecundity is high. Fecundity estimates range from 1.0×10^4 to 3.0×10^5 eggs per gravid female (Ito 1982). These estimates are, however, much less than for species such as yellowfin sole, *Limanda aspera* (1.3 – to 3.3×10^6 eggs), Pacific cod, *Gadus macrocephalus* (2 – to 6×10^6 eggs), sablefish, *Anoplopoma fimbria* (8.2×10^4 to 1.3×10^6 eggs), or Pacific halibut, *Hippoglossus stenolepis* (1.01×10^5 to 2.8×10^6 eggs), which all extrude eggs into the sea for fertilization.

Not all rockfish eggs develop into larvae; some are used as an energy store. Anderson (1984) estimated larval survival for Flemish Cap redfish at less than 1% between April and July. Such high larval mortality is typical for marine fishes. Comparable larval mortalities have been calculated for cod, plaice, and herring (Cushing 1974), and for North Sea plaice (Bannister, Harding, and Lockwood 1974). On the basis of this limited evidence, starting life as a yolk sac larva appears to have no obvious survival advantages.

The fecundity of Gulf Pacific ocean perch is lower than fecundity for either the eastern Pacific or the Aleutian Islands/Bering Sea stocks (Fig. 14–9, top). This suggests that the natural mortality rate is lower for the Gulf stocks. Paradoxically, the growth rate for the Gulf stocks is also lower (Fig. 14–9, bottom) suggesting a higher natural mortality rate—if we assume that the growth rate is directly related to survival. In spite of the evidence that points to a lower fecundity and a slower growth rate, the Gulf stocks were overwhelmingly dominant during the early fishery (1963–1968) and remain dominant, although at much lower levels. The dominance of the Gulf stocks, in spite of their lower fecundity and growth rates, raises three basic questions:

- 1) Does the total area encompassed by the continental slope and edge in the Gulf exceed the area of other regions enough to explain this overwhelming dominance?
- 2) Is there less predation?
- 3) Do catch statistics reflect both the availability and the trawlability of the Gulf rather than reflecting the abundance of Pacific ocean perch in the area?

The comparatively slower growth rate for Gulf *Sebastes alutus* appears to be manifest after the onset of maturity. The growth rate prior to maturity, when natural mortalities can

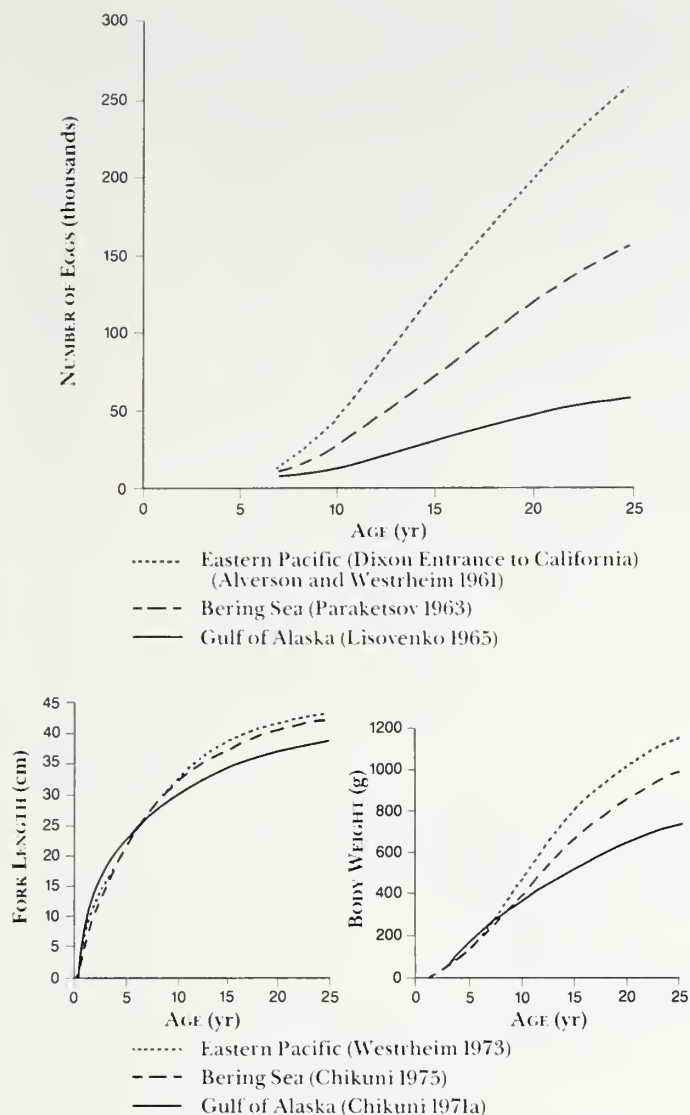


Figure 14-9. Comparisons of age versus fecundity (top) and age versus length and age versus weight relationships (bottom) for Pacific ocean perch (*Sebastes alutus*) from three regions of the North Pacific. (Adapted from Chikuni 1975.)

be expected to be the highest, is both rapid and similar for all stocks. It may be, therefore, that the comparatively lower, postpubescent growth rate for Gulf stocks does not significantly impact their relative productivity.

Sablefish (*Anoplopoma fimbria*).

Sablefish Distribution. Adult sablefish are found along both the shelf edge and the continental slope from Mexico around the Pacific rim to Japan (except for the Sea of Okhotsk). They inhabit depths between 150 and 1,200 m, (predominantly between 400 and 500 m), and have been caught by trawl, longline, and pot. About 75% of the sablefish biomass is found between Vancouver Island and the Aleutian Islands. Tagging studies have indicated that they make long migrations that cross the Gulf in both easterly and westerly directions (Fig. 14-10). Environmental conditions such as temperature, salinity, and oxygen level

over the slope are quite uniform at corresponding depths throughout their distribution range and do not pose any barriers to the adult migrations.

Sablefish Catch Statistics. The sablefish or blackcod fishery began over a century ago off the Washington-British Columbia coast, primarily incidental to halibut catches. It expanded to include California and Alaska during the first 25 years. Exploitation was limited to Canada and the United States, and annual catches remained at about 1.5×10^3 mt until the 1960s. After that, foreign fishing resulted in a marked rise in the catch. Recent summaries of sablefish research have been presented by Low, Tanonaka, and Shippen (1976), Balsiger (1983), and Sasaki, Rodman, Onoda, and Rosapepe (1984).

After Japan entered the Gulf sablefish fishery in 1963, the catch increased from 2.3×10^3 mt to a maximum of 3.65×10^4 mt in 1972, when over 95% of the catch was taken by Japanese vessels (see Table 14-4). As other nations such as Russia and Korea joined the fishery, regulations were applied and catches for the period from 1978 to 1982 averaged about 9×10^3 metric tons. By 1982, a quota of 8.23×10^3 mt was in force. In the early 1970s, the average United States catch of about 1.5×10^3 mt was used as follows:

- industrial 3%
- food 97% (smoked 77%, fillet 16%, salted 6%, and pickled 1%).

The domestic catch had a value of \$3.8 million (Low *et al.* 1976). This suggests the peak catch in the Gulf area in 1972 had a potential value of nearly \$1.0 billion.

Sablefish Reproductive Biology and Life History. Little is known about sablefish spawning migrations or about the time associated with their egg and larval development. We do know that spawning occurs during the winter at depths of between 250 and 750 m, and occurs rather ubiquitously throughout the distribution area (except in northern Bering Sea). The demersal larvae must adjust to vastly different pelagic and inshore environmental conditions in the surface layers where they occupy depths down to 150 meters. The juveniles range in age from one to four years. Although little is known about their movements during this period, they

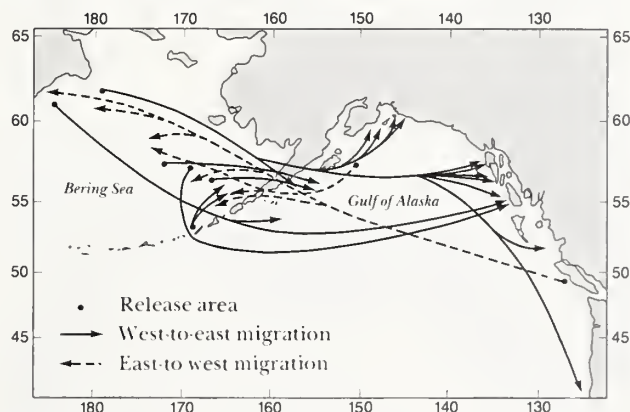


Figure 14-10. Release and recovery locations of tagged sablefish (*Anoplopoma fimbria*) for long migrations across the Bering Sea and the northeastern Pacific Ocean. (Modified from Low, Tanonaka, and Shippen 1976.)

are present around the periphery of the Gulf. The fishery concentrates on fish between three and eight years of age, even though adults may live longer than 20 years.

Both the spawning activities and the widespread adult migrations bear a certain likeness to those of halibut. However, the sablefish larvae do not require a substrate for survival for the first year, but instead, are pelagic. Therefore, one would expect that those larvae that develop from eggs that have been released seaward of the shelf in the Gulf would be transported by the Alaskan Stream. According to Kodolov (1968), sablefish larvae are found over the slope from California to the southeastern Bering Sea shelf, as well as westward from there in a trans-Pacific latitudinal band (from 3 to 5° wide) between the Alaska Peninsula and the southeastern end of the Kamchatka Peninsula, including portions of the Aleutian Islands. Much of the latter areas encompass a pelagic regime that is under the influence of the Alaskan Stream.

The apparent absence of larvae in the Bering Sea north of ~55°N (particularly on the eastern side) suggests two things: (1) there is a low threshold temperature (~2C) for sablefish eggs and larvae, and (2) the presence of sablefish along the Asian shores is dependent on, or at least enhanced by, spawning activity in the Gulf of Alaska. Although a large proportion of the eggs released in the Alaskan Stream in winter will recirculate in the Gulf as larvae (as indicated by the halibut larvae), some will also be transported westward along the Aleutian Island chain into the vicinity of the Commander Islands by spring and summer. These larvae will metamorphose into juveniles prior to winter cooling and will have access to the currents associated with the western subarctic gyre (Favorite *et al.* 1976). Any subsequent movement must be understood before an effective management plan can be devised or before the effect that the Gulf environment has on sablefish can be properly assessed.

Walleye Pollock (*Theragra chalcogramma*).

Walleye Pollock Distribution. The walleye or Pacific pollock is a cod-like species which is broadly distributed throughout the subarctic North Pacific Ocean and adjacent seas (Fig. 14-11). It can be found in depths ranging from near the ocean surface to the ocean bottom in waters over the conti-

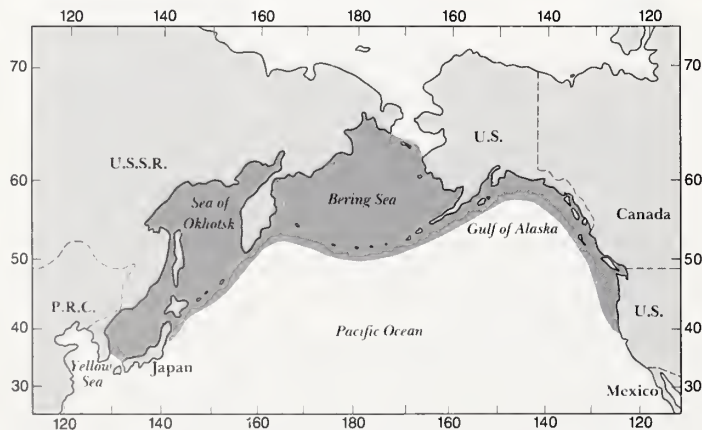


Figure 14-11. Distribution of walleye pollock (*Theragra chalcogramma*) in the North Pacific. (Adapted from Bakkala, Maeda, and McFarlane 1984.)

mental shelf and slope. It also inhabits both surface and intermediate waters over the very deep Aleutian Basin in the Bering Sea (Okada and Yamaguchi 1983) and the Aleutian Trench (Larkins 1964) and it appears to prefer lower temperatures. In waters off the Korean Peninsula, pollock is generally found at temperatures between 2 and 5C, but is never found in the Yellow Sea where other subarctic species such as the Pacific cod and the Pacific herring occur year round (Gong and Zhang 1983).

Walleye Pollock Catch Statistics. Throughout most of its range, the pollock is the dominant fish species. It has, in recent years, surpassed the Peruvian anchoveta and the Atlantic cod in terms of total world catch. The world catch of walleye pollock was 6×10^6 mt in 1973, but has since declined to less than 5×10^6 mt (Bakkala, Maeda, and McFarlane 1984) (Table 14-6). In spite of this decline, it has remained at the top (4.5×10^6 mt), exceeding catches of the Japanese pilchard, the second most productive fishery, by almost 0.5×10^6 mt in 1982 (Fishing News International, August 1984).

The commercial use of pollock dates back to the 17th century in Korea (Gong and Zhang 1983); substantial fisheries for other pollock stocks did not develop until considerably later. Asian landings constituted ~60% of the total for the years 1970 to 1972 (Table 14-6), and made up more than 70% (max. = 78% in 1978) after 1972. East of 175°W, landings from the Bering Sea have dominated the fisheries (99% in 1970 to 81% in 1982) (Bakkala *et al.* 1984).

Pollock exploitation in the Gulf began in 1962 when it was taken incidentally by foreign fisheries which were then catching Pacific ocean perch. Prior to 1972, pollock were taken in intermittent directed fisheries by the Japanese or were taken as by-catch in both the Japanese and the Soviet rockfish fisheries (Alton and Deriso 1983). In 1972, the pollock catch increased abruptly to 3.4×10^4 mt and has been about 1.0×10^5 mt since 1976 (Table 14-7). Most of the catch in recent years has been taken west of 147°W in the central and western Gulf, with the largest landings coming from the Kodiak area (Fig. 14-12).

Until very recently, almost all of the pollock taken in the eastern North Pacific Ocean and Bering Sea was taken by foreign vessels. This situation has changed dramatically and

Table 14-6. Catch ($\times 10^3$ mt) of walleye pollock (*Theragra chalcogramma*) from both the western and eastern Pacific for the period 1970 to 1980 (from Bakkala, Maeda, and McFarlane, 1984).

YEAR	WESTERN PACIFIC	EASTERN PACIFIC	TOTAL
1970	1,984.3	1,266.2	3,250.5
1971	2,685.1	1,756.5	4,441.6
1972	2,862.5	1,910.3	4,772.8
1973	4,227.3	1,806.3	6,033.6
1974	4,204.8	1,673.1	5,877.9
1975	4,356.1	1,430.2	5,786.3
1976	4,458.9	1,270.0	5,728.9
1977	4,116.9	1,107.5	5,224.4
1978	3,752.6	1,085.8	4,838.4
1979	3,693.4	1,032.4	4,725.8
1980	3,193.3	1,135.7	4,329.0

Table 14-7. Total trawl catch (mt) and pollock landed (mt) in both the eastern Bering Sea (EBS) and Gulf of Alaska (GA) since 1964.

YEAR	EASTERN BERING SEA ^a			GULF OF ALASKA ^b			GA/EBS	
	TOTAL	POLLOCK	% POLLOCK	TOTAL	POLLOCK	% POLLOCK	TOTAL	POLLOCK
1964	393,891	174,792	0.44	263,925	1,126	0.00	0.67	0.01
1965	344,369	230,551	0.66	371,554	2,749	0.01	1.08	0.01
1966	452,081	261,678	0.57	231,335	8,932	0.04	0.51	0.03
1967	836,308	551,562	0.66	146,458	6,276	0.04	0.17	0.01
1968	977,083	702,181	0.71	134,399	6,164	0.05	0.14	0.01
1969	1,192,020	862,789	0.72	125,766	17,553	0.14	0.11	0.02
1970	1,593,649	1,265,565	0.79	91,395	9,343	0.10	0.06	0.01
1971	2,157,326	1,743,763	0.81	126,696	9,458	0.08	0.06	0.00
1972	2,249,092	1,874,534	0.83	163,493	34,081	0.21	0.07	0.02
1973	2,064,444	1,758,919	0.85	137,994	36,836	0.27	0.07	0.02
1974	1,900,092	1,588,390	0.84	166,805	61,880	0.37	0.09	0.04
1975	1,645,232	1,356,736	0.82	175,359	59,512	0.34	0.11	0.04
1976	1,428,575	1,177,822	0.82	192,431	86,527	0.45	0.13	0.07
1977	1,173,457	978,370	0.83	202,011	118,064	0.58	0.17	0.12
1978	1,312,030	979,431	0.75	169,749	97,470	0.57	0.13	0.10
1979	1,167,464	913,881	0.78	172,022	105,784	0.61	0.15	0.12
1980	1,221,914	958,279	0.78	211,242	115,037	0.54	0.17	0.12
1981	1,260,297	973,505	0.77	253,829	147,744	0.58	0.18	0.15
1982	1,212,045	955,964	0.79	236,095	168,746	0.71	0.19	0.18
1983	1,276,061	982,363	0.77	299,446	215,649	0.72	0.23	0.22
1984	1,457,601	1,098,783	0.75	356,311	306,693 ^c	0.86	0.24	0.28

^a Bakkala and Low (1984).

^b Ito and Balsiger (1983).

^c Major (1986).

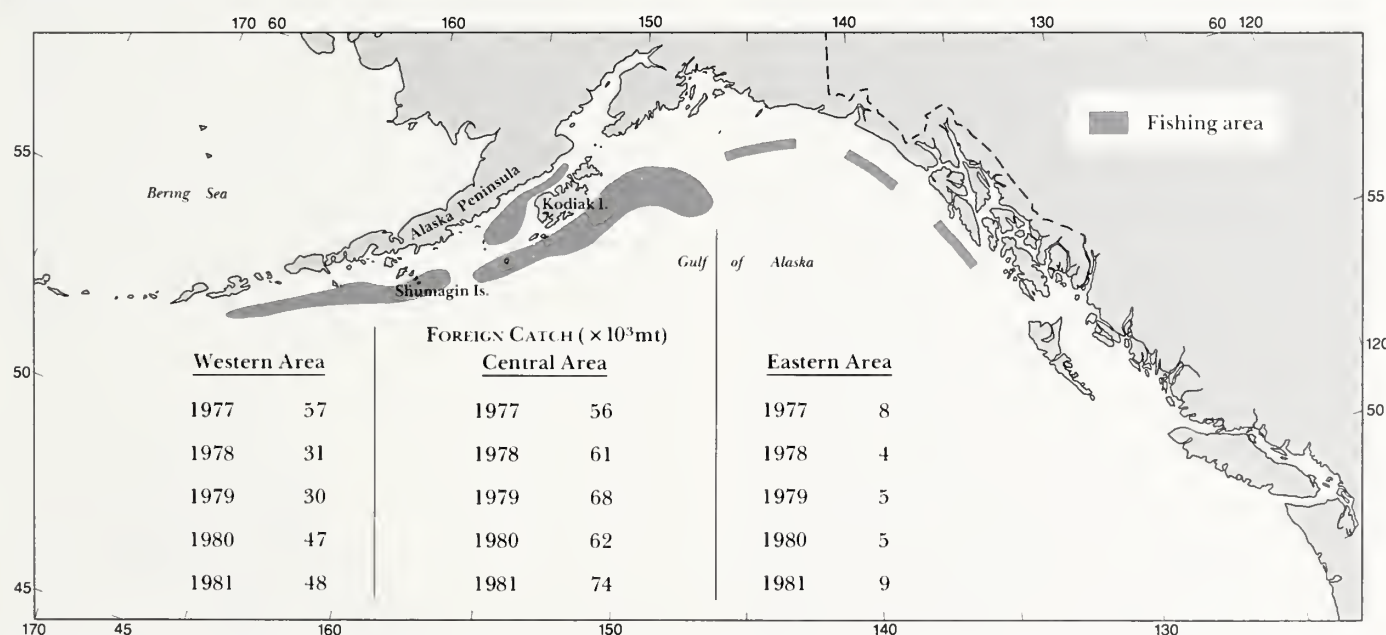


Figure 14-12. Principal regulatory fishing areas and total foreign catch for walleye pollock (*Theragra chalcogramma*) during the period 1977 to 1981. (Adapted from Alton and Deriso 1983.)

it is expected that eventually the United States trawl fishery will catch most, if not all, of the harvestable surplus of walleye pollock in the eastern North Pacific Ocean and Bering Sea (Hughes and Draves 1984). In addition to their immediate importance to the developing United States fishery, pollock are so abundant and broadly distributed that they constitute a very significant component in the dynamics of the subarctic region's ecosystem in their roles as prey, competitors, and predators. Their recent proliferation in the

Gulf and the corresponding interest in their exploitation have raised a number of questions relating to the biology and management of this resource. Many of these questions can only be answered through a better understanding of the interaction between pollock and the oceanography of the area.

Both the catch statistics and survey information for pollock indicate that their abundance in the Gulf has increased since the mid- and late 1960s (Ronholt *et al.* 1978). Surveys

conducted in the mid-1970s indicated abundance increases of several orders of magnitude (Alton 1981). This increase is reflected in landings that increased from less than 1.0×10^4 mt for 1970–1971 to more than 1.3×10^5 mt for 1981. Considering both the overlap in the depth distribution and the prey spectra for pollock and Pacific ocean perch, Alton (1981) associated the increase in pollock to the overexploitation of the perch. There is, however, no direct evidence that pollock displaced the diminished Pacific ocean perch stocks or that the proliferating pollock population has contributed to the suppression of the Pacific ocean perch resource.

Alton's (1981) hypothesis infers that the sudden increase in the pollock population resulted because they used both the space and the prey which became available when a substantial biomass (2- to 3×10^5 mt) of Pacific ocean perch was removed. Removing that many perch has undoubtedly severely depleted and depressed the perch population and should make food available to pollock which would have been consumed by the perch. This cannot, however, explain the proliferation of pollock in the Gulf unless it can be established that competition with perch for food had limited the pollock productivity before large numbers of Pacific ocean perch were removed.

Pacific ocean perch and pollock may compete for prey because euphausiids and copepods are important in the diets of both species. However, Pacific ocean perch are far more specialized feeders and depend upon these zooplankton through adulthood. Copepods and euphausiids (particularly the latter) are also consumed by pollock. However, as pollock grow, their diet shifts to fish (mostly other pollock), as well as to shrimp and crab (Takahashi and Yamaguchi 1972). Furthermore, copepods and euphausiids (and their eggs and larvae) are consumed not only by Pacific ocean perch and pollock, but also by many other marine fishes and organisms. There is no direct evidence that the abundance of zooplankton has limited the productivity of any fish stocks in the North Pacific Ocean. Estimates indicate that the annual zooplankton production far exceeds its consumption by predators (Laevastu and Larkins 1981).

It is not known whether pollock in the Gulf constitute one or several stocks. On the basis of differences in the relative abundance of two principal year-classes, Hughes and Hirschhorn (1979) hypothesized that stocks were separate for areas east and west of Kodiak. Somewhat in support of the two-stock hypothesis, Grant and Utter (1980) found pollock of the western Gulf to have a closer biochemical affinity to Bering Sea pollock than to those from areas south and east of Kodiak Island. However, other evidence indicates that pollock in the Gulf are essentially a single stock (Strickland and Sibley 1985).

Data from acoustic surveys conducted during 1981 in the Shelikof Strait area indicated that the spawning aggregations totaled 2- to 4×10^6 individuals (Alton and Deriso 1983)—a number that is equivalent to the estimated standing stock of pollock from Kodiak to the Shumagin area. The fisheries, the trawl surveys, and the ichthyoplankton surveys that all took place at roughly the same time indicated, however, that spawning pollock also occurred outside the Kodiak area.

Shortcomings in both survey and analytical methodology make present stock abundance and condition estimates provisional. The evidence indicates, however, that pollock in the Gulf of Alaska have continued to increase through the 1984 season. The trends indicate an increase in the exploitable biomass as well as surplus production. The average biomass of the exploitable stocks ranges from 5.9×10^5 to 1.5×10^6 mt and the surplus production ranges from 1.8- to 5.1×10^5 metric tons. Equilibrium yield (for the period from 1976 to 1980) has fallen within the range of surplus production (Alton and Deriso 1983).

As is the case with most marine fish species, the natural mortality rate for Gulf pollock has not been reliably ascertained. However, mortality estimates range from 0.20 to 0.43. The stock has been conservatively exploited, with annual fishing mortality ranging from 0.16 in 1976–1977 to 0.07 in 1981, for an average mortality of 0.13 for the 6-year period (Alton and Deriso 1983).

Data from one United States/Japan joint-venture pollock fishery in the Shelikof area in 1984 indicate that the fishery was primarily supported by 3-, 5-, and 6-year-old fish from the 1981, 1979, and 1978 year-classes. The 1980 year-class of 4-year-olds was very poorly represented in the landings, although the 1981 year-class appeared to be reasonably abundant (Hughes and Draves 1984).

Walleye Pollock Reproductive Biology and Life History. Pollock are found in spawning condition throughout the Gulf and their eggs and larvae may be encountered at almost any time of the year. Zooplankton studies by Kendall, Dunn, and Wolotira (1980) indicated that pollock eggs were concentrated toward the southern end of Kodiak Island and near Shelikof Strait during the fall, spring, and summer. Large aggregations of spawning pollock occur in specific places during the spring months (Fig. 14–13), with the Shelikof Strait aggregation by far the largest. It is not known whether each spawning population is genetically isolated or where pollock of the Shelikof spawning population spend the rest of the year (Alton and Deriso 1983).

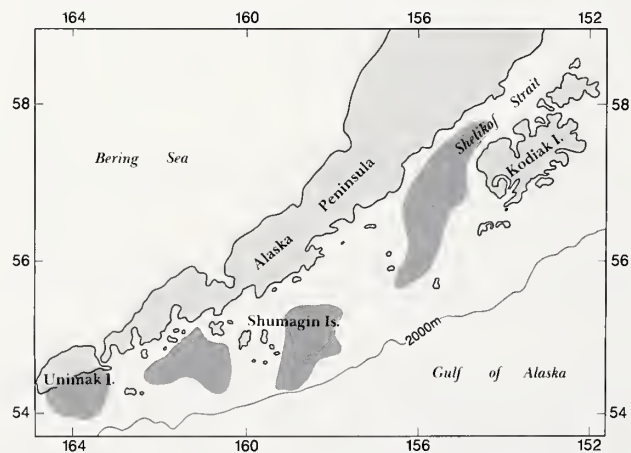


Figure 14–13. General regions where walleye pollock (*Theragra chalcogramma*) spawn as deduced from ichthyoplankton surveys conducted during 1980. (Modified from Alton and Deriso 1983.)

Strickland and Sibley (1985) hypothesized that the Shelikof Strait spawning population migrates eastward (upstream) during the autumn and winter to spawn, and then migrates downstream again in spring and summer. Spawning occurs from February through August; 60% of the spawning occurred in March and April and 82% occurred at depths between 150 and 300 m (Hirschberger and Smith 1983). During spring, the mid-water schools are segregated by sex and are 80 m off the bottom along the deepest troughs (~300 m) of Shelikof Strait (Nunnallee, Williamson, and Nelson 1982).

Pollock spawn upstream in the Alaska Current, and their eggs and larvae drift downstream. This phenomenon also occurs with Pacific ocean perch in the western Gulf of Alaska and has been observed for marine fishes in the North Atlantic Ocean (Walford 1938; Carruthers, Lawford, and Veley 1951). It is not known what environmental stimuli trigger the behavioral events (spawning migration and aggregation by sex) or the physiological events (such as sexual maturation) that lead to spawning. These events must be highly synchronized in shoaling species such as pollock. Neither is it known whether spawning selection and timing are keyed to the needs of the adults or whether they anticipate the conditions necessary for maximum egg and larval survival.

Pollock eggs are fertilized externally. Experimental evidence indicates that the time required for eggs to hatch depends upon the incubation temperature (10 d at 8C: see Table 14-8). Newly hatched larvae are ~3.5 to 4.0 mm in length (Gorbunova 1954) and the yolk sac is completely absorbed by the time they reach 7.0 to 7.5 millimeters. Larvae are at the surface at all times. Postlarvae and juveniles move to the surface at night and then sink to mid-water levels during the daylight hours (Gong and Oh 1977). Gong and Zhang (1983) report that in Korean waters where the currents are not so swift, pollock remain in coastal waters until they reach 7 cm in size (4-5 mo).

Strickland and Sibley (1985) have presented evidence suggesting that pollock eggs and larvae in Shelikof Strait are also found in association with reduced currents and strong upwelling conditions. Shallow, coastal areas may provide a favorable environment for the growth and survival of postlarval pollock.

Both the fertilization success and the survival rate for fertilized eggs and for larvae in Gulf pollock are unknown. However, the natural mortality during the early life of marine fish species is typically very high. If comparable to larval mortality estimates for other marine species such as

Atlantic cod, plaice, and herring, walleye pollock larval survival is probably less than 1% (Cushing 1974).

Pollock attain a size of ~15 cm by age 1 and grow very rapidly (5-10 cm/y) during the first four or five years of life (Niggol 1982). Both males and females mature at about three years of age or at ~30 cm in length. Pollock longevity in the Gulf of Alaska is not known but may be about 13 years (Niggol 1982). The oldest pollock captured in the trawl surveys conducted by the NMFS in the eastern Bering Sea was a 17-year-old female (Pereyra *et al.* 1976).

Pollock may first be recruited into the fishery in substantial numbers at two years of age, but they are not fully recruited into the Gulf trawl fishery until age 4 (or until they reach about 35 cm in length). Although 10 or more year-classes may be represented in commercial landings, the fishery in the Gulf is primarily supported by only four year-classes (ages 3-6). A failure in one year-class, therefore, may have a significantly negative impact upon the fishery and the failure of two of the four principal year-classes may be economically catastrophic. On the other hand, the economic potential that results from an unusually strong year-class can be realized within a few years, and may sustain high productivity in the fishery for four successive years.

Adult pollock in the Gulf are found at depths ranging from 30 to 2,000 m, although the fishery generally captures pollock at 100 to 200 m in winter and 50 to 150 m in the summer (Niggol 1982). They appear to feed very actively except during spawning, when they do not feed at all. Information on pollock feeding habits in the Gulf is pretty much limited to information from certain bays and inlets. The principal food items in Cook Inlet were Tanner crab megalops, gammarid amphipods, and shrimp (Blackburn, Anderson, Hamilton, and Starr 1983). In certain Kodiak Island bays, seasonal changes in diet were observed. Chaetognaths and calanoid copepods were the predominant food in May, and euphausiids and shrimp were eaten in July (Rogers, Robin, Rogers, Garrison, and Wangerin 1979). There is no direct evidence that food supplies limit the productivity of Gulf pollock populations. However, Strickland and Sibley (1985) argue that the food available to pollock in the Gulf of Alaska may be limited because both their size and their growth rates are smaller in strong year-classes.

Examinations of the stomach contents of eastern Bering Sea pollock indicate that their diet changes markedly as they grow. Until they reach ~500 mm in length, their stomachs typically contain euphausiids, copepods, and amphipods, although the importance of these zooplankters decreases with increasing length. At 250 mm, fish, shrimp, and crab begin to appear in the diet. Pollock larger than 350 mm are cannibalistic, and other pollock constitute an increasingly larger percentage of their diet (40-70% in pollock >500 mm) as they increase in size.

Pollock (>35 cm) prey very heavily on other pollock and, in addition, both the juvenile and the adult pollock in the Gulf are eaten by at least 11 species of marine mammals, 13 species of pelagic birds, and 10 other species of fish. Marine mammals alone have been estimated to consume 3.4×10^5 mt of pollock in the Gulf each year (Livingston 1977).

Table 14-8.
Incubation period for pollock eggs in relation to water temperature.

AUTHOR	TEMPERATURE	DAYS TO HATCH
Yusa (1954)	6-7C	12
Gorbunova (1954)	\bar{x} = 3.4 (0.11-11.5C)	20.5
	\bar{x} = 8.2 (2.0-12.2C)	10
Uchida (1964)	8C	10
	1-2C	20

Although there is little documentation of predation on pollock eggs and larvae, several species of fish (including pollock), and invertebrates such as squid, may consume pollock eggs and larvae. The eggs are fragile and probably very rapidly digested beyond recognition. It is therefore difficult to detect them in the stomach contents of either fish or squid predators.

Accumulating evidence indicates that predation is the largest component of natural mortality and may be a very substantial limiting factor in the productivity of fish stocks. To improve our understanding of natural mortality we must have much better information on both the prey and consumption rate for predators on the pollock during all their life-history stages. We also need information on the pollock's food habits, not only when they are near the bottom and available to bottom trawls, but also when they are feeding off the bottom and nearer to the surface.

Greenlings (Hexagrammidae). Nine species of greenlings from the genera *Hexagrammos*, *Pleurogrammus*, and *Ophiodon* are found in the Gulf of Alaska; only three have any commercial importance.

Most greenlings of the family Hexagrammidae inhabit shallow water and are non-shoaling species. Of these, only the kelp greenling (*Hexagrammos decagrammus*) is an appreciated sports fish species. It can grow up to 42 cm long and weigh ~1.4 kilograms. The adults are semi-demersal in kelp beds, whereas juveniles are found in the high seas in the Gulf of Alaska and along the Aleutian Islands. The fish biomass in shallow water along the Gulf coast averages ~850 kg/ha during summer, consisting largely of kelp greenling (30–80%) (Rosenthal 1980). During the winter most kelp greenlings move into deeper water.

Atka Mackerel. The Atka mackerel, *Pleurogrammus monopterygius*, is quantitatively the dominant greenling; it is also the most important commercially.

Atka mackerel occurs near and to the west of Kodiak Island. The importance of Atka mackerel in the Gulf's fish ecosystem can be ascertained only when considerably more empirical research (e.g., stomach content analysis) is done on the feeding habits of the pelagic feeders, including mammals, which prey on it. Furthermore, the locations of Atka mackerel pre-fishery juveniles must be determined before any conjecture can be made concerning the effect which environmental anomalies might have on the mackerel's population. Its greatest abundance is in the Aleutian area. While it is a pelagic fish, found over the continental shelf as well as over deep water, it is a demersal spawner that attaches its eggs to the bottom substrate.

Atka Mackerel Catch Statistics. Neither the Gulf catches of ~2.0 × 10⁴ mt in the late 1970s nor the catch per unit effort (CPUE) reflects the abundance of the species for several reasons, including: 1) variable demand, 2) targeting, and 3) the nations involved in the fishery. Despite the meager amount of reliable data, the exploitable biomass of Atka mackerel in the Gulf has been estimated to be ~8.0 × 10⁴ mt (Ronholt 1983).

Atka Mackerel Reproductive Biology and Life History. Another example of upcurrent spawners, Atka mackerel aggregate in the Kodiak area from July to October (Albatross and Port-

lock Banks) in order to spawn. The species is caught mainly during spawning aggregations in the Kodiak, Chirikof, and Shumagin areas in 50- to 350-m depths. The mean age of the spawning population is estimated at three to four years, with mean lengths of ~30 cm, and weights of up to ~400 grams.

Since eggs of Atka mackerel are attached to the bottom, spawning areas have been estimated either from knowledge of spawning concentrations or from the results of limited larval surveys. Age determinations are controversial, because the ages that were determined by Soviet scientists who were using scales, and ages determined by United States scientists using otoliths do not agree and show considerable variability (Ronholt 1983).

Lingcod. The lingcod (*Ophiodon elongatus*) is caught commercially. It occurs from Baja California to Kodiak Island, and some specimens have also been found along the Alaska Peninsula (Hart 1973). It frequents offshore reefs and may occur at depths exceeding 500 meters.

Lingcod Catch Statistics. As lingcod does not shoal much, it is only incidentally caught in trawls. Some lingcod are taken by sports fishing (jigging), but the main fishery is longline. Off the Canadian coast, between 2.5- and 3.5 × 10³ mt have been taken annually. The average length of commercially caught lingcod is between 80 and 90 cm, with weights ranging from 10 to 20 kilograms. Fish this size are 6 to 8 years old. In Alaska, most lingcod are taken off the Southeast coast incidental to halibut, sablefish, and cod long-lining operations (Rigby 1984).

Lingcod Reproductive Biology and Life History. Little is known about fluctuations in the abundance of lingcod stocks in the Gulf or about lingcod ecology in relation to environmental anomalies. Female lingcod deposit sticky eggs on rocky substrate in February and March, and males guard the deposited egg masses (Rosenthal, Haldorson, Field, O'Connell, LaRiviere, Underwood, and Murphy 1982).

Because lingcod is not only demersal, but is also non-shoaling and deposits eggs on rocks, it may be assumed that environmental influences might have little effect on lingcod stocks. This would mean that fluctuations in recruitment would be caused by predation on juveniles. The adult lingcod is highly piscivorous and also cannibalistic. The adults also feed on benthic macro-invertebrates, including gammarid amphipods.

Pelagic Fishes

The many pelagic species of fishes in the Gulf of Alaska include:

- five species of salmon (*Oncorhynchus* spp.)
- steelhead trout (*Salmo gairdneri*)
- sea-run cutthroat trout (*Salmo clarki*)
- Dolly Varden (*Salvelinus malma*).

A detailed discussion of the salmonid species is given elsewhere (Rogers, Rogers, and Rosenthal, Ch. 13, this volume; Rogers, Ch. 15, this volume). Other than Pacific salmon, the single most commercially important pelagic species in the Gulf is Pacific herring.

Pacific Herring (*Clupea harengus pallasii*).

Pacific Herring Distribution. The Pacific herring is a subspecies of the Atlantic herring and is believed to have entered the Pacific Ocean in the post-glacial era. It exists today from southern California to Korea. Macy, Wall, Lampsakis, and Mason (1978) present an excellent summary of the herring research conducted in the northeast Pacific, and the results of a recent herring symposium can be found in Melteff and Wespestad (1980).

Pacific Herring Catch Statistics. Herring are perhaps the most abundant fish in the ocean. In the past, the annual world catch has been in excess of 2×10^9 metric tons. They are particularly important to the marine ecosystem because they effectively convert plankton into fish biomass that is readily consumed by larger demersal, pelagic, and anadromous fish.

The commercial fishery in areas of the Gulf of Alaska began:

- during 1882 in southeastern Alaska
- during 1906 south of the Alaska Peninsula
- during 1913 in Prince William Sound
- during 1914 in Cook Inlet.

Prior to 1911, Alaska catches never exceeded 1.0×10^4 mt, but within a decade they had doubled, and by 1925 catches had reached 8.0×10^4 metric tons. The maximum catch— 1.2×10^5 mt—was attained in 1937.

Over the years, herring have been processed in a number of ways:

- reduced to oil, fertilizer, and fish meal—a practice that started in 1882, peaked in 1937 at nearly 1.14×10^6 mt, and essentially terminated by 1966
- salted and pickled—a use that started at the turn of the century, peaked in 1922, and ceased in 1954
- used as bait—a use that was firmly established by 1913, peaked in 1927, and continues today although at a modest level
- used for roe and egg harvesting—a use that started in the 1960s, and continues to be a profitable venture today.

Gulf of Alaska herring concentrations fall into three groups: 1) southeastern—Chatham Strait, Stephens Passage, and west coast of Baranof Island, 2) central—Yakutat Bay, Prince William Sound, Kachemak Bay, northern and eastern Kodiak Island, and 3) western—Chignik and the Shumagin Islands. Herring fishing permits (Alaska Department of Fish and Game 1983) for various gear indicate that the 1982 fishing effort was divided as follows: Prince William Sound—500, Cook Inlet—408, Kodiak—322, Southeastern—234, Alaskan Peninsula—224, and Chignik—128 (versus a total of 3,374 for the Bering Sea). Because Bristol Bay catches are combined with those of both Prince William Sound and Cook Inlet in the statistical summaries, it is difficult to isolate the Gulf catch. However, the total value of the Alaska herring fishery in 1982 was \$51.5 million, over 77% of which was for sac roe.

In 1960, just before the Soviet Union started herring fishing in the eastern Bering Sea, 80% of the Pacific herring catch of 2.27×10^5 mt was Canadian. By 1964, the catch

nearly quadrupled to 8.42×10^5 mt, of which 40% went to the Soviet Union and 30% went to the Canadians. In 1968, the catch was reduced to 5.1×10^5 mt, but the Soviet Union share was 90% and the Canadian share was only 5% (Buck 1973). The cause for the demise of the Canadian herring fishery is not clear, but it is apparent that useful large-scale studies of the herring–environment relationships cannot be made until both the oceanic distributions and the movements of herring stocks are known.

Pacific Herring Reproductive Biology and Life History. Herring spawning is a spectacular event that occurs during a period that lasts for several days to a week. Herring milt turns the water opaque, giving it a white cast that is visible even from the air. Many thousands of birds as well as large numbers of demersal, pelagic, and anadromous fish and various marine mammal groups prey in a feeding frenzy on both the eggs and the spawners. Because herring attract so many predators, species survival is related to fecundity (only one egg in 10,000 will produce a spawner). However, adaptability to varying environmental conditions also plays a major role in their survival.

Although spring and summer spawning occurs along the northeast coast of the United States, spawning in the Gulf occurs only in the spring. Sometimes beginning in March and sometimes as late as early June, eggs are deposited both intertidally and subtidally on vegetation along rocky shores or sandy beaches. Deposit densities can vary from 1.0×10^6 to 1.0×10^8 eggs/m² (as many as 3.0×10^5 eggs can cling to a single strand of eel grass). Although water temperatures of 5 to 9°C and salinities of 8 to 28‰ are considered favorable for egg survival (Alderdice and Velsen 1971), values of –1 to 15°C and 0 to 70‰ are apparently acceptable. Surviving eggs usually hatch within three weeks (but may require as many as seven weeks), and the larvae are planktonic for about three months. After this period, they actively swim in schools and migrate offshore during the fall, where they remain until they mature at age 3. There is still controversy as to whether or not juveniles join adult schools in winter and as to whether or not they participate in spawning migrations.

Food organisms consisting of microscopic eggs, diatoms, and the nauplii of small copepods at densities of 2.2×10^4 /m³ (20 to 50 mg/m³) are required for larval herring survival during early stages (Nikitinskaya 1958). By age 1, their diet consists largely of copepods, and at age 2 euphausiids have become the dominant food. Conversely, over 40 groups of invertebrates, fishes, birds, and mammals prey on herring. Maturation occurs at age 3, and age 4 herring dominate the fishery (38%); very few survive to age 10.

Although there are well-known, basic patterns to the herring's life-cycle, these patterns are by no means rigid and must be more completely understood before predictions about the herring and its response to environmental perturbations can be made. Traditional spawning locations have been identified, but there are many instances where both the spawning times and the locations vary. There is evidence of discrete local stocks which show limited onshore-offshore movement, while other stocks appear to arrive from unknown oceanic areas. Further, it is unclear whether or not juveniles accompany adults on spawning migrations, so it is impossible to know whether the migrations are a

learned response rather than an instinctive one. We also do not understand what triggers spawning activity and whether it can be delayed or advanced, protracted or accelerated, by environmental conditions. Since we have so little opportunity to observe such behavior in other species, better information on herring would be valuable to our understanding of pelagic fisheries in general.

Favorite and McLain (1973) have indicated that the October-to-March mean sea-surface temperatures over a broad area off southeastern Alaska were directly related to the large CPUE of herring that occurred there both in 1953 and in 1958. Subsequent year-classes were evident in the fishery for six years (for the period 1955 to 1960 and for the period 1960 to 1965). Such correlations certainly deserve closer scrutiny. One obvious question that arises is why the CPUE in 1953 was roughly ten times the CPUE in 1952 or 1954.

We also know little about either the distribution or the movements of juvenile herring. Rounsefell (1929) reported that second-year herring were numerous in inlets, whereas Tester (1946) noted that little was known about second-year herring and assumed that most remained on oceanic feeding grounds. Recently, Hourston (1980) reported that juveniles appear to remain on offshore feeding grounds until the end of their third growth season, at which time they join the adults' spawning migration.

There is no information on what triggers spawning activity. One suggestion is that spawning is synchronized with the full moon. It is important that the roe-herring fishery be timed so that it starts immediately before spawning, when the roe is in prime condition. More investigation is required as to whether herring can control the final stage of spawning (ovulation) so that optimum success is achieved. We also need to know the length of time that this process can be blocked in anticipation of more favorable conditions for egg and larval survival.

We assume that for spawning, coastal salinity is only secondarily important compared with temperature, because extreme salinity dilution occurs more frequently in the summer than it does in the spring. Where fresh water is bound up in ice, melting may occur, but temperature conditions above the freezing point are also delayed in such a circumstance, so that any temperature signal (if one exists) would still be a controlling factor. Other questions also remain unanswered:

- At what point do the herring decide that the temperature is acceptable?
- Are herring able to make a subsequent decision as to whether delaying egg release will result in a more favorable temperature?
- To what extent are herring able to control year-class success when short-term anomalous environmental conditions occur?

In an attempt to clarify herring distributions on the northeast Atlantic coast, Parrish and Saville (1965) separated herring into three population types: 1) oceanic, 2) shelf, and 3) coastal. Perhaps some consideration should be given to the possibility that similar divisions exist in the Gulf, as well as to the possibility that herring spawn in deep water, which

also occurs in the Atlantic Ocean. Although these three divisions are supplemented by the additional presence of summer/autumn spawners that are not normally present in the Gulf, Atlantic shelf populations migrate from Georges Bank as far south as Chesapeake Bay for the winter, a distance of over 1,500 kilometers. Commensurate migrations in the Gulf of Alaska would permit herring to spawn in southeastern Alaska even if they originated in the Aleutian Islands or Bering Sea area.

Offshore herring surveys took place in the Gulf during the 1920s and again in 1957 (Carlson 1980), but they were considered unsuccessful. Herring have been found in the stomachs of fur seals taken from areas that were 100 to 200 km south of the Alaska Peninsula, and unusually large herring were caught in salmon gillnets 100 to 200 km south of the Bering Sea shelf during the INPFC studies.

There is evidence that herring larvae remain near spawning sites for a period of time that correlates with their spawning success. The identification by OCSEAP investigators of both inshore and coastal eddies in the northern Gulf that would make this feasible should benefit future herring research. Nevertheless, until we know what proportion of the herring actually move offshore to their unknown oceanic wintering sites, and until we know the distribution and movement of these stocks, it will remain impossible to assess any damage to the herring fishery that results from perturbations in the Gulf environment.

Invertebrate Fisheries

The invertebrate fisheries of the Gulf of Alaska include both arthropods (crabs, shrimps) and mollusks (scallops, snails, and squids). An historical review of many of these fisheries is provided elsewhere (Feder and Jewett, Ch. 12, this volume). Here we highlight three taxa from among these:

- pink shrimp
- red king crab
- oegopsid squids.

The fisheries for both the pink shrimp and red king crab are in decline, while those for squids have so far only developed as incidental catches.

Shrimp (Pandalidae)

Larval Distribution. Cruises in the Kodiak Island area during 1977 and 1978 provide the first detailed description of the occurrence, the distribution, and the abundance of shrimp larvae (Kendall *et al.* 1980). During bongo-net sampling, larvae belonging to the following taxa (by frequency of occurrence) were collected:

- hippolytid shrimps
- crangonid shrimps
- *Pandalus borealis*
- *P. stenolepis*
- *P. goniurus*
- *Pandalopsis dispar*
- unidentified pandalid shrimps

- *Pandalus montagui tridens*
- *P. hypsinotus*
- pasiphaeid shrimps.

Although not identified in this list of larval shrimps, adult *Pandalus jordani* and *P. platyceros* occur in commercial catches from the Kodiak area.

Mean densities (numbers/1,000 m³) of the first three taxa (Table 14–9) reflect the surprising predominance of hippolytid shrimp as well as large, but greatly reduced, numbers of crangonid shrimp. Even though over 50 species of these two types of shrimp inhabit the Gulf, none is considered to be of any commercial importance.

Hippolytid and crangonid shrimp larvae were found throughout most of the year, with highest densities occurring in summer. In most portions of the study area, abundance was roughly an order of magnitude greater inshore than offshore.

Although *Pandalus borealis* larvae were the third most abundant species reported, they represent 85% of the commercial catch in the Gulf—although in some locations, *Pandalus goniurus* and *Pandalopsis dispar* may dominate. Subsequent discussion will be limited to pandalid shrimps (specifically *P. borealis*), commonly known as pink shrimp.

Pink Shrimp (*Pandalus borealis*).

Pink Shrimp Distribution. Pink shrimp are rather ubiquitous in northern waters, occurring in the Bering Sea, Gulf of Alaska, Gulf of Maine, off Greenland, off Ireland, in the North Sea, and in the Norwegian Sea. They are found at depths ranging from 20 to 1,450 m, and prefer temperatures ranging from –1.6 to 11°C and salinities that are greater than 32 parts per thousand.

Pink Shrimp Catch Statistics. The shrimp fishery is another example where an unmanaged resource exploitation ended with very strict regulations and pleas for research. Although shrimp were being harvested in southeastern Alaska as early as 1915, the major fishery started after World War II primarily in the Kodiak area. Initial catches exceeded 5.0×10^2 mt, increased three-fold by 1955, and increased ten-fold by 1961. The fishery expanded westward along the peninsula in 1967, reaching the Unalaska Island area in 1972. By 1973, 5.23×10^4 mt were being taken annually from the northern Gulf. By the mid-1970s, over 50% of the catch was made in

the western areas and this increased to 65% by 1979. In 1982, the western areas were closed.

A decline in the Kodiak stocks was readily apparent in 1977 when catches were about 50% lower than during the peak years between 1970 and 1973 (1.44×10^4 mt vs. averages of 3.09×10^4 mt), and there were 16 locations that had separate management regulations. From 1973 to 1977, the average annual catch in the Kodiak area (and west) was 4.81×10^3 mt—which at today's ex-vessel prices (\$.30/lb) represents an annual value of \$31.8 million.

Pink Shrimp Reproductive Biology and Life History. Spawning occurs in late summer or early fall. Females carry the fertilized eggs until they hatch into planktonic larvae—usually by early spring. *Pandalus borealis* larvae are released only during this brief spring period and the number of larvae in inshore areas not only diminishes in late spring, but by late summer, none are present. Further, in offshore areas greatly reduced concentrations of *P. borealis* are found in the spring and summer, and none are found in fall or winter.

Within three months the juveniles start their semi-benthic existence after which (in one or two years) most mature first as males (maturing in the second year), and thereafter spawn as females.

Pink Shrimp Oceanographic Considerations. Although physical/chemical oceanographic data from OCSEAP cruises show that currents east of Kodiak Island are weak and variable compared with the 50 to 100 cm/s southwestward flow at the shelf edge in the Alaskan Stream, both surface and bottom drifters reflect southwest flow along both sides of the island. This suggests a contranant movement of the adults that is similar to the one discussed in relation to halibut. However, even though shrimp have mobility in the water column, it is assumed that most movement occurs along the bottom.

It is unlikely that any bottom movement would be adequate to maintain the long-term stock distributions in the Kodiak area. Rather, it appears that those larvae that are released in (and not flushed out of) the extensive bays are adequate to maintain discrete local stocks. Those larvae that are carried out of the bays contribute to stocks along the Alaska Peninsula.

Shrimp behavior may be related to both air and sea temperatures (Niebauer 1981; Weingartner 1981). For example, Ingraham (1981) was able to show that environmental conditions off Kodiak Island during a good shrimp catch in the spring of 1972 were cold compared to those during a poor shrimp catch in the spring of 1978. However, the former data were part of a MARMAP study which was subsequently discontinued and the latter were part of an OCSEAP study which commenced in 1977. No comparable data were obtained in the intervening period.

Studying the relationship between shrimp and the warm-temperature stratum at the shelf edge (discussed as favorable to halibut larvae) reveals a temperature regime that is reasonably constant. Since *P. borealis* tolerates a wide temperature range, it seems that temperature studies would not be as informative as salinity studies.

If, as Ivanov (1963) reports, adult *P. borealis* avoid salinities below 32.34‰, this would explain not only why there are limited distributions in both hyposaline Prince William

Table 14–9.

Mean densities (numbers/10³ m³) of the three dominant taxa of shrimp larvae in the Kodiak area (from Kendall, Dunn, and Wolotira 1980).

AREA	HIPPOLYTID	CRANGONID	<i>P. BOREALIS</i>
Inshore			
Izhut Bay	4,054	408	120
Chiniak Bay	4,524	312	182
Kiliuda Bay	4,391	1,326	49
Kaiugnak Bay	1,698	135	131
Offshore subareas			
Portlock	355	52	16
Marmot	270	121	23
Albatross	465	178	6
Sitkinak	211	15	–

Sound and Cook Inlet, but also why distributions are abundant on the east side of the Kodiak, Afognak, and Shumagin Islands where there are deep troughs (*i.e.*, Stevenson, Chiniak, Kiliuda, and others) with salinities that are greater than 32.5 parts per thousand.

Although some pandalid shrimp are believed to move offshore in fall and winter (Lukas 1981), it is never clear how far they move and to what depths they descend. Ivanov (1963, 1964) has shown that in December 1962, commercial quantities existed east of the Shumagin Islands at depths of between 100 and 150 meters. This was adjacent to a trough whose depth exceeded 200 meters. Similar quantities were also found in the Bering Sea during the period of December to February 1962–1963, at equivalent depths. Thus it would appear that the shelf provides an adequate year-round environment for shrimp.

Crabs

Several species of crab are commercially caught in Gulf of Alaska waters. These include:

- Dungeness crab (*Cancer magister*)
- Tanner crab (*Chionoecetes bairdi*)
- Red king crab (*Paralithodes camtschatica*)

Both the Dungeness and Tanner crabs are discussed in detail elsewhere (Feder and Jewett, Ch.12, this volume). Here we instead focus on the most abundant of the king crabs, the red king crab.

Red King Crab (*Paralithodes camtschatica*).

King Crab Distribution. The red king crab is the most abundant of the five species of the genus, and is broadly distributed on the continental shelf and upper slope off Asia and North America. It is also found in subarctic waters of the North Pacific Ocean and its adjacent seas. In North America, the red king crab occurs in both the Bering Sea and the Gulf of Alaska.

King Crab Catch Statistics. The major king crab fisheries in the Bering Sea are in Bristol Bay, in Norton Sound, and along the Aleutian Islands. In the Gulf, there are fisheries in Prince William Sound, Cook Inlet, around Kodiak Island, and along the south side of the Alaska Peninsula.

The red king crab catch in the Gulf has been dominated by landings from the western Gulf—from the Kodiak Island and Chignik/South Peninsula fisheries. Catch data from 1950 through 1984 (Table 14–10), indicate a disastrous 1983–1984 season. Red king crab were first taken in Kodiak in 1936, even though the catch was not officially recorded until 1950 (Alaska Department of Fish and Game 1983). The Kodiak fishery had a maximum production in 1965–1966; in the period from 1970 to 1980, catches declined. The Chignik/South Peninsula fisheries declined in a similar manner. Catches in both the Kodiak and Chignik–South Peninsula areas declined very sharply after the 1981–1982 season. Population estimates indicated that the stocks in both areas were seriously depressed and, consequently, no red king crab fishery was permitted in those areas from 1983 to 1985. Declines in the red king crab stocks occurred in virtually all major stocks in Alaskan waters. In the Bering Sea, red king

crab abundance was so low that no fishery was permitted in the 1983–1984 season, but a modest catch of $\sim 1.8 \times 10^3$ mt was permitted in 1984–1985.

The outlook is dim for any substantial abundance increase in the western Gulf. In addition to the fact that there are very few legal-size male crabs, the abundance of pre-recruits and females is at record lows, while the incidence of non-ovigerous females is high. There is no readily apparent reason for the decline in pre-recruit and female crabs (which are not targeted by the fishery) nor for the decline in legal-size males.

There are several theories as to the cause of the decline in the non-exploitable (females and pre-recruits) components of red king crab stocks. These theories include:

Table 14–10.

Historical king crab catch ($\times 10^3$ mt) in both the Kodiak and the Chignik/South Peninsula registration areas from 1950 to 1984 (from Alaska Department of Fish and Game 1983).

YEAR	KODIAK	CHIGNIK/ SOUTH PENINSULA
1950	60.0	2,124.0
1951	200.0	599.0
1952	400.0	298.0
1953	900.0	380.0
1954	4,000.0	317.0
1955	2,000.0	1,641.0
1956	4,800.0	4,221.0
1957	5,000.0	6,687.0
1958	5,200.0	7,246.0
1959	10,200.0	6,167.0
Subtotal	32,760.0	29,680.0
Average	3,276.0	2,968.0
1960–1961	21,064.8	6,700.0
1961–1962	28,962.9	3,900.0
1962–1963	37,626.7	2,273.0
1963–1964	37,716.2	6,539.0
1964–1965	41,596.5	14,354.0
1965–1966	94,431.0	14,713.0
1966–1967	73,817.8	22,577.0
1967–1968	43,448.5	17,252.0
1968–1969	18,211.4	10,944.0
1969–1970	12,200.5	4,137.0
Subtotal	409,076.3	103,389.0
Average	40,907.6	10,338.9
1970–1971	11,719.9	3,425.7
1971–1972	10,884.1	4,123.1
1972–1973	15,479.9	4,069.3
1973–1974	14,397.3	4,260.6
1974–1975	23,582.7	4,572.3
1975–1976	24,061.6	2,605.3
1976–1977	17,966.8	958.8
1977–1978	13,503.6	726.3
1978–1979	12,021.8	3,093.8
1979–1980	14,608.9	4,453.5
Subtotal	158,226.6	32,288.5
Average	15,822.6	3,228.9
1980–1981	20,448.6	5,080.6
1981–1982	24,237.6	3,147.5
1982–1983	8,729.7	1,627.7
1983–1984	111.4 ^a	CLOSED
Subtotal	53,415.9	9,855.8
Average	17,805.3	3,285.2

^a Brown crab.

Source: Alaska Department of Fish and Game (1983).

- high handling mortalities for crabs discarded from the trawl or the crab fisheries
- increased predation by Pacific halibut and Pacific cod
- parasitism or disease.

Griffin, Eaton, and Otto (1983) observed the catch composition in the red king crab fishery of 1982 (September–October) and in the Tanner crab fishery of 1983 (March–April) for the eastern Bering Sea. In the red king crab fishery, 1 female and 7.3 sublegal males were caught for every legal male crab that was landed. In the Tanner crab fishery, 1.6 king crab were discarded for every legal Tanner crab caught. Red king crab discarded by both trawl and long-line fisheries in the eastern Bering Sea in 1981 and 1982 was estimated at 1.2×10^6 crabs (790 mt) and 3.3×10^5 crabs (245 mt), respectively (French, Nelson, Wall, Berger, and Gibbs 1981; Nelson, Wall, and Berger 1983).

No reliable survival-rate estimates are available for discarded red king crab. Otto, MacIntosh, Stahl–Johnson, and Wilson (1983) did not consider the incidental catch and subsequent discards by the directed and non-directed fisheries to be sufficient to account for the decline in the abundance of the eastern Bering Sea red king crab stock.

King Crab Reproductive Biology and Life History. Predation on king crab by both the Pacific cod and the Pacific halibut has been thought to be a contributing cause in the decline of both female and pre-recruit red king crabs. Both the abundance of these two predatory fish and the numbers of them caught incidental to retrieval of crab pots (Alaska Department of Fish and Game 1983) have increased in recent years. They are both known to consume some red king crab. In the Kodiak area, only 10 of 5,500 Pacific cod stomachs that were examined during the non-molting period contained king crab parts (Alaska Department of Fish and Game 1983). No information is available from the Gulf regarding predation by cod on soft-shelled king crab. However, evidence from studies in the Bering Sea indicate that red king crab predation by Pacific cod may be more serious during the molting season.

June and Shimada (Northwest and Alaska Fisheries Center, NMFS/NOAA, unpubl. data, 1986) found either red king crab parts or whole red king crabs in 10% of the cod stomachs collected in the eastern Bering Sea trawl surveys conducted between May 5 and July 20, 1981. All the crab and crab parts in the stomach had new shells, indicating recent molting. From estimates of the cod biomass in areas where crab are distributed, and assuming certain minimum and maximum consumption rates, potential mortality to king crab females in the eastern Bering Sea was calculated as between 3.3×10^6 and 3.49×10^7 crabs during the single month that the female crabs are in their soft-shelled condition.

Both disease and parasitism are also suspected causes of or contributors to the decline in the productivity of red king crab stocks. Lethal viruses and microsporidians have been estimated to infect about 4% of the red king crab throughout Alaska. In one out of every five cases, the Kodiak crabs that were examined were infected by a virus. The significance of diseases as a source of mortality to Alaskan red king crab is not yet known. However, there is speculation that

epidemic diseases could have been a major factor in the recent decline of red king crab throughout Alaska (Alaska Department of Fish and Game 1983).

The coincidental decline in the abundance of virtually all red king crab stocks in Alaska is surprising since the stocks are apparently independent. There is no direct evidence, such as from tagging, to indicate that adult red king crab from the major stocks in the Bering Sea and the Gulf intermingle (Hayes and Montgomery 1963; Powell and Reynolds 1965; and Simpson and Shippen 1968). Evidence from tagging operations conducted off southwest Kodiak and south of the Alaska Peninsula suggests that there is a regularity to red king crab movement and that the crab population in an area such as Kodiak is composed of many local stocks.

Red king crab form offshore aggregations during the summer and the early fall. Beginning in November, crabs off Kodiak migrate shoreward and by February, large numbers are in depths of 30 fm or less (Powell 1964). Crabs in the offshore feeding areas represent mixed stocks. Crabs dropped at single offshore release sites in both the Kodiak and Shumagin Islands areas migrated to more than one bay. In both studies, very few crabs released in one bay migrated to another. In a given spawning season, the crabs in the various bay systems are apparently isolated, indicating the existence of separate stocks.

Powell (1964) suggests that bay systems include offshore banks which may be occupied by discrete stocks. This evidence indicates that the spawners of the respective bays are isolated during a given mating season. It is not clear, however, if crabs return to the same bay systems in successive years, and therefore retain genetically isolated stocks. It is also possible that if crabs spawn in different bays in successive years, some broader genetic interchange results. If such an interchange does occur, it is probably geographically limited. Evidence from tagging indicates that crabs from single offshore locations usually migrate to adjacent banks and bays.

Those factors that determine the stock formation and which control the crabs' shoreward and seaward migration are not well understood. Powell (1964) suggests that the trenches of the continental shelf, which project into the numerous bays, form a path which is followed by the crabs in their shoreward migration. It is not known if the trenches guide the crabs shoreward or if other environmental gradients come into play. Neither is it known what triggers the beginning of these inshore migrations. Hayes (1983) suggests that there are environmental mechanisms that maintain the apparent separation of stocks and considers stock structure to be the result of certain current patterns that keep the crab larvae within these areas on the Kodiak shelf.

Marukawa (1933) first suggested that crab larvae must be most numerous in vortices and gyres, since the perpetuation of the population depends upon the ultimate settling of the first instar in an environment that is suitable for survival. Powell (1964) also suggested that inshore spawning of king crab assures that their planktonic larvae are not carried out to sea by currents. The same hypothesis has also been proposed with regard to fish eggs and larvae (*e.g.*, see sections on Pacific halibut, Pacific ocean perch, and walleye pollock). There are, however, few, if any, direct measurements of the

flow patterns in the heavily indented coastline south of the Alaska Peninsula and its several archipelagos. Hydrodynamical numerical (HN) models, however, have indicated the presence of gyres and countercurrents in waters off Kodiak Island, and local wind stresses (obtained from meteorological data) indicate periods of both onshore and offshore flow at the surface as well as at depth (Fig. 14–14).

It is often assumed that year-class strength is directly related to larval survival. Larvae are at the mercy of the environment and are particularly vulnerable to mortality due to temperature, flow, predation, and the availability of food. A better understanding of larval distribution and mortality will require much more detailed knowledge of the estuarine, coastal, and oceanic environment of the Gulf. As noted by Hayes (1983), however, abundant year-classes of

juvenile crabs have undergone considerable mortality during either their pre-recruitment size or age. Better understanding of the dynamics of red king crab production, therefore, will require knowledge of both the sources and the magnitude of mortality of all of the red king crab's life history components.

As indicated by the Alaska Department of Fish and Game (1983), the significance of epizootics, parasitism, and predation must also be evaluated. In addition, the interrelationships between the short-term effects of both hydrodynamics and temperature on the distribution and behavior of crab and the effect of longer-term variations in ocean conditions on the productivity of Gulf crab stocks should be studied.

Squids

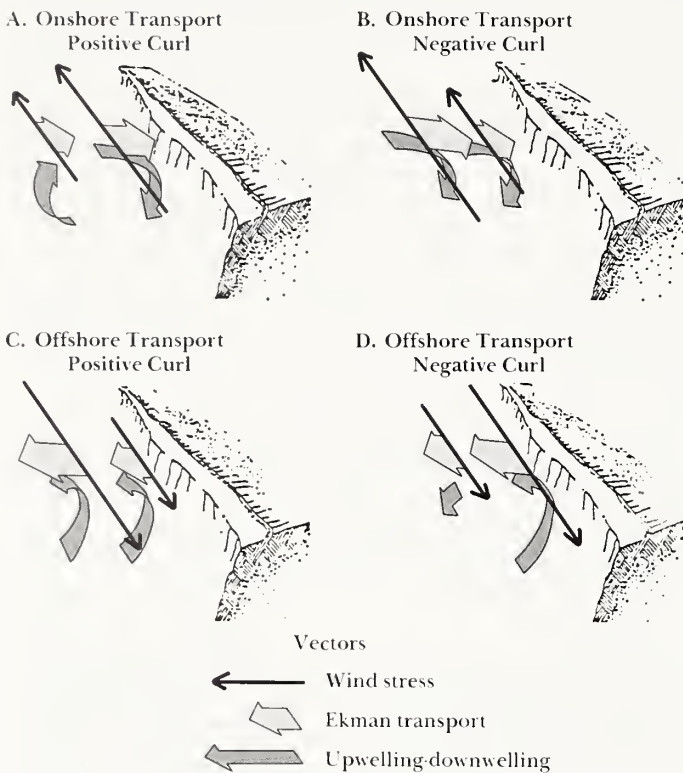
Oegopsid Squids. Squids are pelagic species of cephalopod mollusks having soft bodies and 10 arms. Related to them are octopus and cuttlefish. Representatives of the oegopsid squids include:

- *Onychoteuthis boreali japonicus*
- *Gonatus fabricii*
- *Gonatopsis borealis*
- *Moroteuthis robusta*
- *Beryteuthis magister*
- *Loligo opalescens*.

Squid Distribution. Most squids live in relatively deep water (200 to 2,000 m) in the the Gulf and Aleutian Islands areas. Various cephalopods have been caught in these areas at night-light stations associated with INPFC high-seas salmon research. They are found at a wide range of depths and require high-salinity water (>30‰). Therefore, they do not occur in coastal waters of low salinity. Some species that live near the surface undertake long seasonal migrations as part of large schools—they move toward the north in the spring and then back to the south in autumn. The southernmost species, *Onychoteuthis boreali japonicus*, occurs in the southern part of the Gulf only during summer. It has a life span of only one year and undertakes extensive seasonal migrations in the western Pacific. *Gonatus fabricii* and *Gonatopsis borealis* are both pelagic squids that are common in the subarctic region. *Gonatus fabricii* made up roughly 50% of the stomach contents in sperm whale stomachs in the Commander/Aleutian Islands area during 1961 and 1962 (Kodolov 1970).

Moroteuthis robusta is the largest member of the species considered here and is primarily demersal during its adult stages. It also forms an important part of the diet of sperm whales in the northeastern Pacific and is occasionally caught by trawlers but has little market value. *Beryteuthis magister*, also an important item in the sperm whale diet, is a subarctic littoral species. It changes to a benthic life before maturation and spawns at from 200 to 500 m between June to October along the Aleutian and Bering Sea slopes (Naito, Murakami, and Kobayashi 1977).

Squid Catch Statistics. Direct measurement of squid resources is very difficult, if not impossible. An idea of the



Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
54N, 164W	B	A	A	C	C	C	C	C	C	C	C	C
55N, 160W	B	A	A	C	A	C	C	C	C	C	C	A
57N, 156W	B	A	A	C	C	C	C	C	C	A	A	A
59N, 151W	A	A	A	A	B	D	D	C	A	A	A	A
60N, 140W	A	A	A	A	B	D	D	D	A	A	A	A
59N, 141W	A	A	A	A	B	D	D	B	A	A	A	A
57N, 137W	A	A	A	B	B	B	B	B	B	A	A	A
54N, 134W	A	A	A	A	B	B	A	A	A	A	A	A

Figure 14–14. Classification of transport events according to the combination of both coastal and offshore convergence or divergence and monthly mean transport types in the northern Gulf. (Modified from Ingraham, Bakun, and Favorite 1976.)

great size of the squid standing stock can be obtained by computing the food consumption of sperm whales in the North Pacific. This is done with conservative input values in Table 14–11. For Comparison, Clarke's (1977) conservative estimate of the amount of squid consumed by sperm whales on a worldwide basis is 3.2×10^8 metric tons.

Although there is an intense squid fishery in the western Pacific (Okutani 1977), the fishery in the Gulf is incidental to other target species, with less than 1.0×10^4 mt harvested annually in the Gulf by foreign fleets. Recently, an experimental fishery for squid off the Canadian coast has been carried out in a cooperative effort by Japan and Canada. Although in recent years some research on cephalopods has been conducted in Canadian waters in association with either bait or export fisheries, little has been conducted in the Gulf.

Squid research by United States fishery agencies has been limited and, consequently, the relationship between squids and their environment is unknown. The absence of research on either the abundance or the seasonal behavior of squid in the northeast Pacific precludes any serious quantitative consideration of the effects that squids have on the marine fish ecosystem.

Squid Reproductive Biology and Life History. Squids play an important role in the oceanic ecosystem as prey and predators. They are a major food item for some of the toothed whales (e.g., sperm whales), pinnipeds (e.g., fur seals), porpoises (e.g., Dall's porpoise), and the larger pelagic fish such as salmon. Larger offshore pelagic fish such as tuna, salmon, and pomfret feed to a considerable extent on smaller (juvenile) squid, as do some species of marine birds (e.g., sooty shearwaters). Because pelagic squids form schools that can

move faster than many fish, and because they can sustain high speeds, they are seldom caught in mid-water trawls. Most of the quantitative knowledge on oceanic squid in the Gulf of Alaska originates from food studies conducted on the marine mammals and fish.

Many squid species migrate seasonally in large schools in a north-south direction (Okutani 1977). It has been postulated that these seasonally migrating squid schools are followed by fish, marine mammals, and birds, but no proof of this is available. On the other hand, squid themselves are predators and might affect the marine fish ecosystem to a considerable extent. Juvenile squids (and other juvenile cephalopods) feed on planktonic crustaceans, including euphausiids. As squid grow, the percentage of fish in their diet increases. All squid longer than 20 cm feed exclusively on pelagic fish (myctophids and juveniles of other fish, such as rockfishes) and on other smaller cephalopods. Cannibalism among squids is common (Naito *et al.* 1977).

Adult squid are among the most aggressive inhabitants of the seas, frequently attacking prey that is larger than themselves. Large squids (Architeuthidae) can overpower even large fish such as tuna, and squid attack marks are often found on small tuna and salmon. It has been speculated that the inter-annual variation in squid abundance might cause some fluctuation in the abundance of pelagic fish.

Only a few squid species, such as *Berryteuthis magister* (along the Aleutian Islands) and *Loligo opalescens* (off California), return to shallower water to spawn. Most species undertake diurnal vertical migrations toward the surface in the evening and then back into deep water in the morning. A considerable amount of research on squid and their relationship to the ocean environment has been carried out by Japanese scientists in the western subarctic Pacific (Okutani and Nemoto 1964; Okutani 1977; and Naito *et al.* 1977).

Table 14–11.

An estimation of squid consumption by sperm whales in the North Pacific Ocean to derive squid standing stock estimate.

Harvestable sperm whales in the North Pacific:	175,000 ^a individuals
Mean weight of a sperm whale:	30 mt
Total biomass of harvestable sperm whales:	5.25×10^6 mt
Sperm whale food requirement as	
a) % of body weight daily (BWD):	5 ^b
b) (times body weight annually):	18.25
Total annual food consumption by harvestable sperm whales in the North Pacific:	95.81×10^6 mt
Composition of sperm whale's diet as	
a) squids:	85% ^c
b) fishes:	15%
Annual food consumption by sperm whales in the North Pacific as	
a) squids:	81.4×10^6 mt
b) fishes:	14.4×10^6 mt
Assuming $F_{\max} = 20\%$ ^d , the minimum biomass of squids in the North Pacific is:	400×10^6 mt

^a This is an 'absolute minimum' estimate (International Whaling Commission Special Issue 2 1980). The total number of sperm whales in the North Pacific was estimated for 1977 as: females 411,000 to 525,000; males 376,000 to 474,000.

^b The food consumption of whales is estimated in the literature to be 4 to 6% BWD. The minimum estimate is 2.5% BWD.

^c Some estimates give up to 95% squid (Berzin 1970).

^d This 'fishing coefficient' of squids by sperm whales is probably too high; it corresponds roughly to F for pelagic fish.

Physical Oceanographic Considerations

Perhaps the most interesting and most applicable of the OCSEAP physical oceanography studies are the satellite-tracked drifting buoys. One of the first of the OCSEAP buoy releases clearly established that there is an extensive eddy west of Kayak Island (Fig. 14–15), which trapped the buoy for a number of weeks (Royer *et al.* 1979). Such trapping could have an effect on fish eggs, larvae, and juveniles, as well as on fish homing and the movements of predatory fish. However, no biological sampling was conducted. In addition, the northerly onshore drift of the buoy after it was released resolved a number of theoretical questions about the effects of bottom topography on alongshore flow in the area. Further, subsequent movement of the buoy directly across the mouth of the Copper River and into Prince William Sound was surprising, and suggested that distribution for the tongue of dilute water from the Copper River (extending seaward for 300 km in summer during 1978) may be quite variable.

Equally perplexing are the trajectories of the satellite-tracked buoys that were released south of the Kenai Peninsula in the spring of 1978 (Muench and Schumacher 1980). The buoy released at the southernmost point (No.

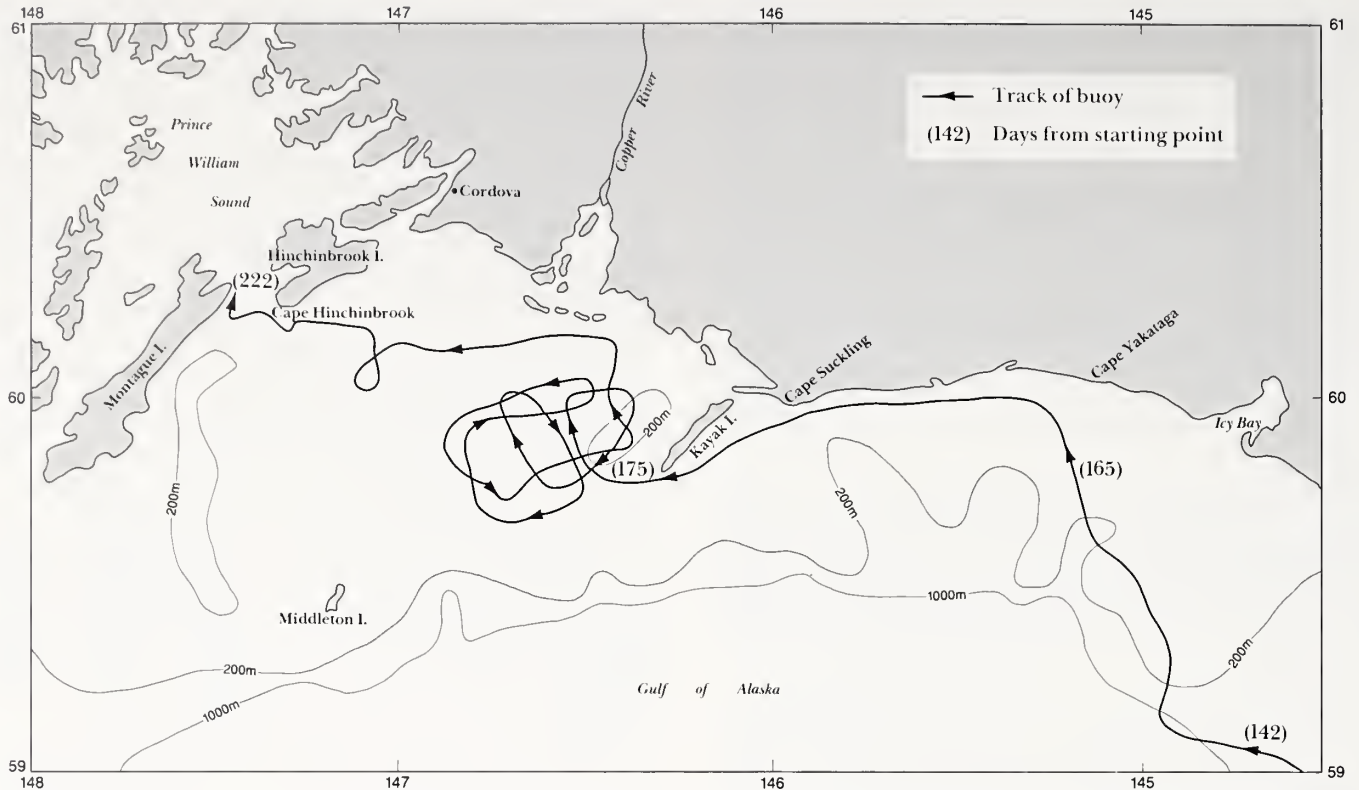


Figure 14-15. Trajectory of a satellite-tracked drifting buoy released in the Gulf of Alaska in summer 1976 showing the extensive along-coast flow near Cape Suckling, the large, non-tidal eddies west of Kayak Island, and movement into Prince William Sound.

1421) moved the farthest northward and went into Cook Inlet (Fig. 14-16), although it only penetrated the Inlet a few tens of kilometers. Other buoys released in the same general area (Reed 1980) have not even penetrated that far into the inlet, indicating an extremely limited surface flow of northern Gulf water into Cook Inlet.

The trajectories of two buoys released in spring 1978 (Nos. 1473 and 1775) nearly crossed each other southeast of the Kenai Peninsula, then moved southeastward on different sides of Kodiak Island. Similar evidence of equally confusing drifts were obtained from drift cards released in the same area during the same time (Fig. 14-17). Evidence from both of these experiments reflects the complexity of flow in the northwest Gulf.

Also interesting is the trajectory of a buoy (No. 1220) that was released at the shelf edge off Kodiak Island in late July 1978. This buoy was tracked through August southwestward along the shelf edge as far as 54.5°N , 159°West . It did not exhibit the eastward movement into the central Gulf that Reed (1980) was able to show by releasing three buoys in this area both at and seaward of the shelf edge. Further, the seabed drifters that were released on the shelf near Kodiak Island by Kendall *et al.* (1980) indicate a complex onshore and offshore cross-shelf bottom flow. The onshore flow extended into the coastal bays in spite of a general southwesterly flow. Such studies mark a tremendous advance in the knowledge of the coastal flow in this area, even though the apparent variability makes it difficult to sort out all complexities. Additional field work and considerable analysis

must be done before such environmental data can be integrated with information on biological phenomena.

An extensive database of Gulf physical and chemical oceanographic data (gathered from nearly 4,000 CTD stations during the period from February 1975 to February 1979) has been compiled as a result of OCSEAP investigations. Although individual disciplines may use these data for specific purposes, an overall synthesis and analysis of conditions and processes should be a high priority. Some of the limitations of such analyses are the aperiodic nature of the

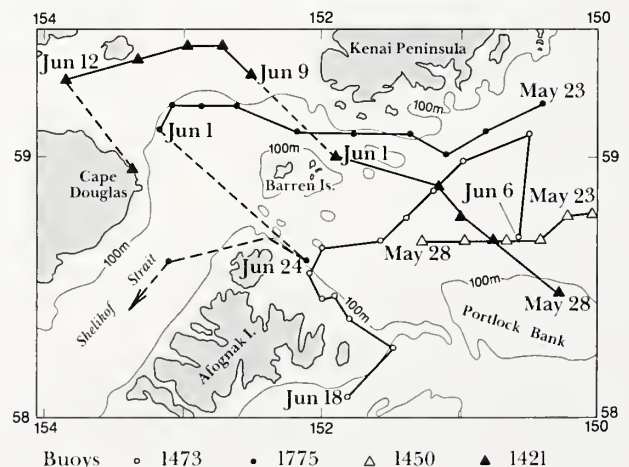


Figure 14-16. Trajectories of drogued satellite-tracked buoys deployed in 1978. Locations are plotted at one-day intervals. (Modified from Muench and Schumacher 1980.)

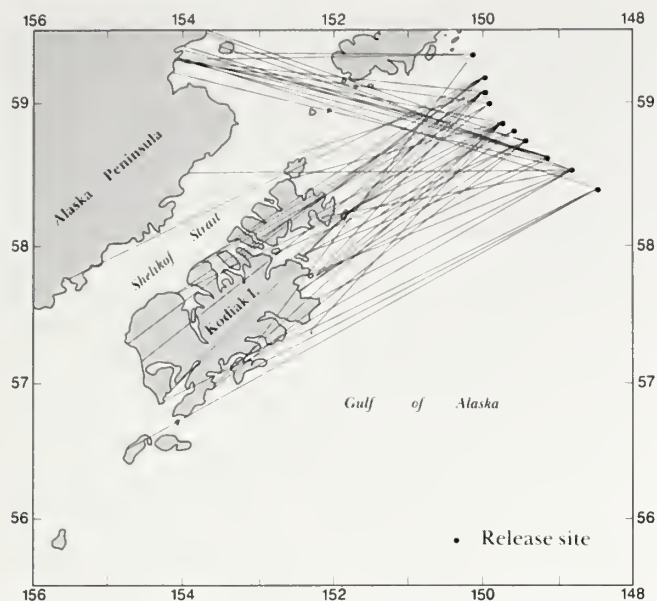


Figure 14-17. Summary of the recovery and release points for OCSEAP drift cards released in May 1978. (Modified from Muench and Schumacher 1980.)

data and the fact that in many instances, tidal currents not only dominate geostrophic flows (based on distribution of mass) but also compromise property distributions where a number of tidal cycles happened during the time it took to gather station data.

Fisheries Interactions and Surveys

The goals of those competing for ocean resources are not necessarily compatible. For example, the goal of preserving marine mammals (which are formidable competitors with fishermen and a serious nuisance to fishing) is accomplished at the expense of the efficiency and the yield of commercial fisheries. In addition, there are concerns over the impact that oil exploration and extraction will have on both the ocean environment and the fish stocks even though there is no evidence of either long-term damage to the oceanic environment or of damage to the marine fisheries.

In order to both adjudicate conflicts and evaluate trade-offs rationally, it is necessary to critically assess the value of the conflicting activities. An important aspect of such an evaluation is an accurate assessment of the abundance and condition of the fisheries. Knowledge concerning the fisheries resources, therefore, is now of interest to parties other than those directly associated with fisheries. There are divergent perspectives and interpretations of resource assessment information even within the fisheries community.

Fish stocks were studied even before the beginning of the present century (Petersen 1894) and are among the best-studied groups of animals. The historical, substantive development of fisheries science has been recently discussed by Cushing (1983). The biological basis for fisheries was first examined by Baranov (1918). Russell (1931) provided a lucid discussion which became the basis for his theory of fishing. Even though later developments have provided extensions, refinements, and elaborations on Russell's work,

his basic considerations still hold. The simple model which he used to describe overfishing will suffice to illustrate some important points regarding the status of our knowledge about Gulf fish stocks.

The dynamics of fish populations are extremely complex. For the sake of simplicity, Russell described the dynamics of a single fish stock (single species) by the equation:

$$S_2 = S_1 + (A + G) - (C + M), \text{ where:}$$

S_2 = stock weight in year 2.

S_1 = stock weight in year 1.

A = the increase in the exploitable biomass that comes from adding fish that are growing to a size where they are retained by fishing gear (recruitment).

G = the increment (in weight) from growth of an individual fish within the exploitable stock.

$(A + G)$ = the total annual population increment.

C = the annual catch, which must include not only the tonnage of fish that were landed but also the weight of the fish that were discarded.

M = the total natural mortality as a result of predation, disease, senescence, and starvation.

$(C + M)$ = the total decrement in the exploitable population.

When $(A + G)$ is equal to $(C + M)$, then S_2 equals S_1 and the population is in equilibrium. When S_2 is greater than S_1 , then $(A + G)$ is greater than $(C + M)$ and, conversely, when S_2 is less than S_1 , then $(A + G)$ is less than $(C + M)$.

The catch (C) and the size at first recruitment are controllable. The quantity C is dependent upon both the quality (the mesh sizes and the efficiency of the fishing gear, the horsepower of the fishing vessels, and other factors) and the quantity (the number and the duration of the trawl tows) of the fishing effort.

Assuming that the catch (C) is controllable, the most important components in the dynamics of a stock are recruitment (A) and natural mortality (M).

The biological effect of the quantity of C on M (or of M on C) is difficult to ascertain. In a cannibalistic species, increasing C would decrease M . Since C and M constitute total mortality in terms of weight, there is an inverse, arithmetic relationship between C and M . If C increases, it will diminish M , since some of the individuals that are caught would have died natural deaths. Conversely, if M is increased, C must diminish, since some individuals will die which otherwise would have been caught.

If food is considered to be a limiting factor, then competition for similar prey exists. Any reduction in biomass that results from an increase in C may also result in an increase in G . With a superabundance of food, variations in C would have no effect on G .

The catch, C , would seem to have no effect on incoming recruitment, (A), unless the species is cannibalistic. In that case, an increase in C would result in an increase in A .

Obviously, fish-stock productivity is greatly influenced by interactions other than those included in Russell's model. Russell's model reflects only the productivity of a single stock of a single species for two successive years. For exam-

ple, the recruitment strength may be associated with the number of spawners in the year of their birth. As a result, the catch that year may affect subsequent recruitment.

Another important consideration is that the habitat and the prey of various species overlap to some extent. Inter-specific competition and predation are factors which may affect both G and M .

The foregoing discussion of Russell's simple model illustrates that some complex interrelationships and some very demanding estimates are required even in an elementary stock assessment. It serves, however, as a basis for understanding the Gulf resources and fisheries.

Population biomass estimates for year 1 (S_1) and year 2 (S_2) pertain to a common spawning stock. In the Gulf, it is not known whether each demersal species is made up of one stock or several stocks. Pacific halibut are presumed to be a single stock (Bell 1981), and there is some evidence to indicate that Gulf pollock are also from a single stock (Strickland and Sibley 1985).

Other evidence, however, suggests that two or more pollock stocks occur in the Gulf (Hughes and Hirschhorn 1979; Grant and Utter 1980; and Alton and Deriso 1983). For Pacific ocean perch, the prevailing view is that discrete stocks occur along the entire rim of the Gulf of Alaska, but stock boundaries have not been clearly delineated. For management purposes, there has been some arbitrary stock delineation using statistical districts which may not correspond to actual stock boundaries.

Although stocks are not clearly identified or delineated, estimates of S_1 and S_2 are nonetheless obtained in surveys using bottom trawls (Ronholt *et al.* 1978; Ito and Balsiger 1983). Trawl survey information is at times supplemented with acoustical survey data.

There are at least two major ways in which errors can be introduced when biomass estimates are made from bottom trawl catches. The first relates to whether or not fish are available to the bottom trawls, and the second relates to the catchability of fish and shellfish even when they are available.

Any trawl survey must assume that the total distribution area for a given stock is known and that the catch in the standardized tows is representative of the species composition, as well as representative of the size, the sex composition, and the abundance of each species. The exploitable portions of the demersal fish are distributed from near the surface—as in the case of pollock—to near the bottom—as in the case of flatfish and shellfish. It is clear that bottom trawls may inefficiently sample semi-demersal and pelagic species such as pollock, which are only partially available near the bottom.

Alton and Deriso (1983) suggest that bottom trawl surveys *per se* may be adequate for detecting several orders of magnitude of change in the abundance of pollock. However, meaningful comparisons cannot be made between estimates which differ by less than one order of magnitude. Supplementing trawl surveys with acoustical surveys will improve the estimates of semi-demersal populations. However, the accuracy of even those biomass estimates remains unverified.

Adult flatfish and shellfish such as king crab are available to bottom trawls. There is, however, some question regarding the efficiency of capturing them. For example, the increase in abundance evident for some species of flatfish during eastern Bering Sea trawl surveys between 1981 and 1982 was so large (~50% overall) that it could not be explained biologically. Bakkala and Wespestad (1985) attributed these increases to rerigging the trawl and improving the bottom-tending characteristics of the trawl used in 1982. If this is true, trawl surveys conducted prior to 1982 have underestimated both the abundance and the biomass of flatfish. It is not clear, however, to what extent the catchability coefficient was improved in 1982, considering that relative abundance (CPUE) increased again by 23% in the 1983 survey.

Estimates of both recruitment and growth in Gulf demersal fish are directly obtainable by systematically sampling at the processing facilities for the sex, the size, and the age of fish that are brought there. Careful appraisal of the fishing methodology of the fleet is also necessary, because size—and, therefore, quantity—at recruitment will vary with the gear type and the mesh size. For Pacific ocean perch and some other species, the age at recruitment cannot be reliably estimated because there are substantial disagreements regarding age determinations.

It has at times been assumed that recruitment is related to the number of spawners. There is, however, little or no information regarding spawner-recruit relationships for demersal fish species in the Gulf.

Growth of the exploitable stock usually is among the more easily estimated components in Russell's simple stock-dynamics model. Growth rate is not, however, constant but varies with such factors as water temperature and, possibly, with the availability of food. It is therefore necessary periodically to update age-length relationships for all exploited species. Reliable age-length relationships cannot be developed for some demersal fish in the Gulf until disagreements over age determination are reconciled.

Catch would seem to be the simplest mortality component to estimate with accuracy. However, there are several error sources in the collection and compilation of catch statistics which have not been evaluated. In the 1984 fishery, observers were aboard foreign fishing vessels during 85% of their operating days and for 85 to 90% of the operating days of the joint-venture fisheries. Although observers make several kinds of observations, their main task is to estimate the catch in these fisheries. In these commercial fisheries, the catch is not actually weighed but is volumetrically estimated either from the dimensions of the fish-storage bins (some of which have irregular configurations) or from the estimated capacity of the cod ends of trawls. The accuracy of these procedures in estimating the weight of the catch has not been evaluated.

Another source of error is the inaccurate reporting of catch statistics. Both under-logging and under-reporting of catch or by-catch data are common among foreign fisheries in Alaskan waters. Catch statistics obtained prior to the placement of substantial numbers of observers were essen-

tially unverified and may have been substantially under-reported. With increased observer coverage during the past two or three years, opportunities for inaccurate reporting have been reduced. However, in spite of the best efforts, the accuracy of catch reports cannot be verified.

Although the fishery targets certain species, sexes, and sizes, the catch often includes other fish. The by-catch should be included as part of the catch; however, it may be discarded either by the fishing vessel or sorted and discarded on the processing vessel. The by-catch very frequently is not estimated (e.g., overflow catch released from trawls prior to deliveries) or may be approximated (with some unknown error) as it is on foreign processing vessels.

The by-catch may be composed of commercially valuable species which must—by regulation—be discarded because they are either prohibited, or of the wrong sex, or are undersized. It is ironic that regulations intended for the welfare of the stock may actually aggravate the problems associated with discards. Discards may also be undesirable species, undersized fish of the target species, or catch which is in excess of the handling and processing capabilities of the factory facility.

There are no fish stocks in the Gulf for which natural mortality (M) has been reliably estimated. The rate of natural mortality is not the same for all ages within the stock. Mortality rates for marine fish tend to be highest in early life (through early juvenile stages), then decrease with growth and increase again in older fish which suffer spawning stress and senescence.

Natural mortality is the result of a number of causes—some of which impose greater impact than others—and the significance of the various mortality sources may vary throughout the life history of a species. However, accumulating evidence indicates that the heaviest mortality after the post-larval stage comes from predation (Cohen, Laurence, and Smith 1984). Predators are frequently other species. An understanding of this important component of M , therefore, must consider interactions between species, which cannot be done using single-species production models.

From the foregoing discussion, it is clear that practically all of the essential components in the simple stock-assessment model are estimated with a degree of uncertainty. The reliability of the estimated stock sizes and evaluation of the condition of resources are, therefore, correspondingly uncertain. Many of the uncertainties are attributable to the difficulties of assessing the dynamics of a number of species which have very complex environmental interactions. The animals cannot be directly observed *in situ* and they live in an environment which is neither readily accessible nor readily understood.

Certain population fluctuations influence the condition of a stock more significantly than others. In most species—and in particular, in relatively short-lived species such as pollock and cod—recruitment is probably the most important population increment. An uncontrolled catch—particularly for long-lived species—can be the major population decrement. Natural mortality is, however, the component which must be estimated with accuracy so that C can be

adjusted both to it and to the population increments in order to achieve the desired biomass in year 2 (S_2).

Estimates of such components as the recruitment (A), the growth of the exploitable stock (G), and the catch of Gulf resources are amenable to improvement through better sampling techniques and analytical treatment. However, even these refinements will do little to improve estimates of these population parameters for some species unless ages can be estimated reliably. Also, since the estimates of A and G relate to the biomass of a single stock, it is necessary to identify and estimate the biomass of all stocks of commercial species in the Gulf. Information on both subjects is difficult to obtain.

In the Gulf, there are several commercially important demersal fish species. Adults of these species typically inhabit different depth strata, although some have broad overlapping distributions or may migrate vertically through the water column. Throughout most of the year, they migrate various distances over the extensive ($\sim 2 \times 10^5$ km²) area of the Gulf shelf and slope. It is very difficult to obtain reliable biomass estimates for an ill-defined or unknown number of stocks for several different species, or to obtain estimates for all of the stocks for even a few species, when all of them are moving as well as growing and dying throughout most of the year over this large, three-dimensional space. In the North Sea—an area of about 5.0×10^5 km²—much more effort is expended (Food and Agriculture Organization 1958), but even estimates of North Sea resources are not without some uncertainty. However, they are undoubtedly far more reliable than population estimates for the Gulf.

Given the present costs of operating research vessels and realistic funding limitations, it is not clear whether continuing the surveys in the present mode will contribute to improved biomass estimates or simply add to a data set which has already reached its limits of accuracy and reliability.

Some aspects of recruitment were discussed earlier in this section. Further understanding both of recruitment and of the causes for its variability require early life-history studies—particularly on juveniles in the pre-recruitment size and age categories. With most fish and shellfish, there seems to be less known about this stage than about any other. Since larvae and young juveniles are especially at the mercy of their environment, understanding their mortality processes means understanding both ocean temperatures and currents. We also need better knowledge regarding their prey and their predators.

Little is known about the early juvenile stages of most marine fish and shellfish. Both sampling gear and sampling procedures have been developed to capture fish and shellfish eggs and larvae. Modified commercial trawling gear is used to sample older juveniles and adults. With few exceptions, neither sampling gear nor sampling strategies have been developed that can capture young juveniles (< 10 cm) or that can quantitatively sample pre-recruit juveniles.

Abnormal development and extreme temperatures may cause high egg mortality rates. In all other life-history stages, however, predation is the most frequent cause of nat-

ural mortality. For a given stock, cannibalism may constitute a large part of predation. However, from egg stage right up through adulthood, all Gulf species are consumed by a variety of predators. An understanding of Gulf predation will require accurate knowledge of both the qualitative and the quantitative food habits of the entire community of species. Abundant community members such as squid—which are known to be voracious predators—must be included in such studies.

Salmon must not be overlooked as a substantial pelagic component of the Gulf even though we have not dealt with them in this chapter. Post-smolt juvenile salmon are heavily preyed upon. However, by the time they reach both the immature and the maturing stages, they may be dominant predators in pelagic waters and may prey upon pelagic larvae and juveniles of other species such as rockfish and Pacific ocean perch.

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ABSTRACT

The Gulf of Alaska is the main oceanic nursery for most North American salmon. The annual abundance figures for the North American runs (catch plus escapement) are estimated from the catch and escapement statistics for the period 1950 through 1984. Both the numbers and the biomass for mature salmon that annually returned from the Gulf of Alaska were estimated by using a combination of North American run statistics and information on the oceanic distribution of the major stocks that resulted from INPFC-related research during the 1960s.

The Gulf of Alaska produced $\sim 2.5 \times 10^5$ mt of mature salmon annually during the period 1950 to 1977. In 1978, the annual runs increased, and during the period of 1981 through 1984, $\sim 4 \times 10^5$ mt were produced annually. The abundance of the runs during the most recent years was probably comparable to the historical peak abundances of the 1930s. The average biomass of adult salmon was ~ 30 times greater than the average biomass of juveniles that entered the offshore waters.

Both the distribution and the growth of salmon at sea are affected by interannual temperature variations. Salmon tended to migrate earlier and grow more when temperatures were warmer and migrate later and grow less when temperatures were colder.

Introduction

Commercial fisheries on anadromous North American salmon (*Oncorhynchus* spp.) developed in the late 1800s, and by the 1920s nearly all of the more abundant North American and Asian stocks were being exploited. The annual salmon catches reached a peak in the late 1930s on both the North American and Asian coasts with an average annual catch of 3.54×10^8 individual fish or $\sim 8.0 \times 10^5$ mt (Fredin 1980; International North Pacific Fisheries Commission [INPFC] 1979). Catches declined significantly in the mid-1940s to early 1950s. Then Japan mounted a highseas fishery which, by the late 1950s, had become the largest salmon fishery in the North Pacific—accounting for nearly 40% of the annual catch in numbers of salmon. However, the total catch remained relatively low until 1978, when highseas fishing had been greatly reduced and there was a significant increase in abundance of most salmon stocks in western and central Alaska (Rogers 1984). The North American catches of salmon during the period 1978 to 1983 were comparable to the catches made during the historical peak production of the late 1930s (Table 15-1).

The annual abundances of salmon runs (the return of mature fish to their spawning grounds for reproduction) are characterized both by considerable year-to-year variation as well as by long-term changes in average abundance. For example, in the coastal areas of the upper Gulf of Alaska alone (north of 55°N), there were 1.6×10^7 salmon caught in 1974 and 9.0×10^7 caught in 1982. The 1982 catch of 1.92×10^5 mt translated into \$217 million for commercial fishermen (Alaska Department of Fish and Game (ADF&G) 1984a).

Some of the annual variability is explained by the abundance of parent spawners. Small numbers of spawners usually produce small numbers of adults; however, average to large numbers of spawners can produce anywhere from small to large numbers of adults. For example, for stocks of Bristol Bay sockeye salmon (*O. nerka*), less than one and up to as many as 20 adults have returned per spawner from the 1956 to 1978 brood years. The causes of this variability in relative production have been the subject of salmon research since the early 1900s; however, this research was largely directed toward the freshwater and nearshore marine phases of salmon life history until the late 1950s.

Table 15-1.
Comparison of the average annual salmon catch both in Asia and in North America during the historical peak-production period (1934-1939) and the recent period (1978-1983).

	SOCKEYE	CHUM	PINK	COHO	CHINOOK	TOTAL
NUMBER ($\times 10^6$ fish)						
1934-1939						
Asia	15	49	154	3	0.2	221
N.Am.	34	14	73	8	3.7	133
Total	49	63	227	11	3.9	354
% N.Am.	69	22	32	73	95	38
1978-1983						
Asia	4	38	84	3	0.3	129
N.Am.	42	12	68	10	4.3	136
Total	46	50	152	13	4.6	266
% N.Am.	91	24	45	77	93	51
WEIGHT ($\times 10^3$ mt)						
1934-1939						
Asia	43	176	216	10	2	447
N.Am.	93	62	134	30	28	347
Total	136	238	350	40	80	794
% N.Am.	68	26	38	75	93	44
1978-1983						
Asia	9	126	116	8	2	261
N.Am.	113	48	118	30	29	338
Total	122	174	234	38	31	599
% N.Am.	93	28	50	79	94	56

Little was known about the oceanic life of the valuable North American stocks of Pacific salmon until a large research program was undertaken by scientists from Japan, Canada, and the United States in response to an extensive Japanese high-seas salmon fishery in the 1950s. Although this research was focused on the central Pacific (in the area of the fishery), a considerable amount of information was gained on salmon in the Gulf of Alaska. This information has been reported in the bulletins of the International North Pacific Fisheries Commission (INPFC 1974). Because salmon abundance has changed considerably since the Gulf of Alaska salmon research was done, the contemporary status of the stocks will be examined in this chapter.

The Gulf of Alaska is the main oceanic nursery for most North American salmon, as well as for some Asian stocks for at least a significant part of their ocean life. Salmon probably constitute over 95% of the large (> 20 cm) fish in the epipelagic offshore waters of the Gulf of Alaska and are the most economically important species in North American fisheries. The distribution of the larger regional stocks (e.g., Bristol Bay, upper Gulf of Alaska, British Columbia) are fairly well known—at least for the summer months (Royce, Smith, and Hartt 1968; French, Bilton, Osaka, and Hartt 1976; Neave, Yonemuri, and Bakkala 1976; Takagi, Aro, Hartt, and Dell 1981; Godfrey, Henry, and Machidori 1975; Major, Ito, Ito, and Godfrey 1978; and Hartt 1980). However, both their distributions and their migrations from fall to

spring must be largely inferred from the early and late summer distributions.

The main objective of this chapter is to estimate both the annual number and the biomass of North American salmon that returned from the Gulf of Alaska since 1950. Information on the oceanic distribution of North American stocks is used first to estimate the annual abundance and then estimate the numbers of North American salmon that returned from the Gulf (east of 165°W and north of 50°N). Also discussed in this chapter are some factors that likely affect the annual numbers and the weights of those salmon that return to coastal fisheries and spawning grounds.

Life History

Salmon spawn in the fall, usually in freshwater and normally in the place where they originated. They die soon after spawning. The eggs, which are buried in the gravel, develop during the winter and the fry emerge in the spring. The remainder of the salmon life cycle varies both among species and among populations within species; however, they spend most of their life at sea and it is there that they attain most of their growth and reproductive potential. All of their ability to successfully complete their life must be inherited, because there is no contact with their parents. It is most likely that each generation of each population inherits the abilities to survive, grow, and reproduce that were most advantageous for the environment of their parents. Thus, changes in the environment will probably cause changes in the stocks. "In almost all cases where both genetic and environmental influences affecting natural stock differences among Pacific salmon and steelhead have been searched for adequately, both have been found; though sometimes one, sometimes the other, is relatively weak, or infrequently expressed" (Ricker 1972).

The following is a brief description of the 'typical' life histories (i.e., the usual age and size both at seaward migration and at maturity) of the five species of Pacific salmon in North America. The largest spawning population of each species is generally distributed according to the habitat that particularly suits the species' reproductive and early life-history needs. These large spawning populations are the ones most often encountered in the Gulf.

Individual Species

Sockeye Salmon. Sockeye salmon (*Oncorhynchus nerka*) are associated with lakes, where they spawn near beaches or in tributary streams and rivers. The juveniles emerge from the gravel in the spring, then rear for one to two years before their seaward migration. They typically weigh between 5 and 10 g when they enter the sea, and after two to three years they return weighing about 2 to 3 kilograms. They are between three and five years old at maturity, but return from the sea between four and six years after their parents have returned. They are more dependent on freshwater rearing than the other species of Pacific salmon and have been the most difficult species to propagate artificially in hatcheries. Large sockeye concentrations are found both in

the large lake systems that drain into Bristol Bay and in the lakes of the Fraser River system. Their bright red flesh has made the sockeye the highest valued and most desirable salmon for canning.

Pink Salmon. Pink salmon (*Oncorhynchus gorbuscha*) are associated with small- to intermediate-sized coastal rivers, with large concentrations occurring in southeastern Alaska, British Columbia, Prince William Sound, Kodiak, and a few large rivers such as the Nushagak and the Fraser. They migrate to sea soon after they emerge in the spring, weighing ~1 gram. They return the next year (summer-fall) at an average weight of between 1.5 and 2.0 kilograms. Since pink salmon have an invariable age structure, there are even- and odd-year runs, which do not interbreed. While there are strong even- and odd-year runs throughout the coastal regions of the Gulf, at present, only strong odd-year runs occur along the southern boundary of the large populations (Fraser River) and only strong even-year runs occur along the northern boundary of the large populations (Nushagak River). Historically, pink salmon have been more abundant in Asia than in North America.

Chum Salmon. Chum salmon (*Oncorhynchus keta*) are also more abundant in Asia than in North America. Large chum salmon populations occur in all large northern rivers as well as in many of the same small- to intermediate-sized rivers used by pink salmon. Since the mid-1970s, the largest concentration of chum salmon has probably been from hatcheries in northern Japan. Natural populations of chum salmon migrate to sea in the same spring or early summer in which they emerge from the gravel and weigh ~1 gram. They return to spawn after two to four years at sea and weigh between 3 and 6 kilograms. Chum, pink, and sockeye salmon constitute about 90% of the number and weight of salmon in the North Pacific; however, the other salmon species in North America—coho (*O. kisutch*) and chinook (*O. tshawytscha*)—are most abundant in southern regions (California to Washington).

Coho Salmon. Coho salmon (*Oncorhynchus kisutch*) typically spawn in tributary streams in river systems. The juveniles spend one to two years in the stream (predominantly one year in the south and two years in the north) and they are the largest of the Pacific salmon when they migrate to sea, averaging between 10 and 20 grams. Hatcheries presently produce a significant proportion of coho migrants, which may average two to three times heavier than natural migrants. Coho salmon spend one year at sea but return later in their second year (fall) than the other species, by which time they average 3 to 4 kilograms. There are few large coho concentrations other than those in Puget Sound and the Columbia River (now primarily from hatcheries). Rather, their abundance seems to be spread over a large area from Oregon to the central Gulf of Alaska. Their abundance in northern coastal areas is difficult to determine because the late-returning coho were not fished intensively. From 1956 to 1977, the high-seas fishery took 64% of the annual coho catch from northern waters.

Chinook Salmon. Chinook salmon (*Oncorhynchus tshawytscha*) are the largest, the oldest at maturity, but the least-abundant species. They also have the most diverse life history and one that has been altered most by human activities (e.g., selective fisheries, dams, and hatcheries). They migrate to sea during their first or second year weighing ~8 to 10 g and commonly return after between two and four years at sea, weighing between 4 and 15 kilograms.

Generalized Life History

The life history of all five species is characterized by juvenile salmon that usually migrate to sea in the spring when water temperature and photoperiod are increasing (Groot 1982). Migrations typically begin abruptly, reach a peak, and then have a long tail-off of stragglers. Since spring comes earlier in the southern portion of their range than it does in the northern portion, the southern stocks migrate to sea about two months earlier than northern stocks. Most northern stocks migrate to sea from mid-May to mid-July. In general, stocks located closer to the coast enter the sea first and those farthest from the coast enter last. This is not only because of the distance they must travel, but also because spring arrives later in the interior of the northern regions where winter ice must melt.

Adult salmon usually return from the sea somewhat earlier than necessary for their fall spawning period. Their arrival in coastal waters usually begins abruptly with large numbers of fish arriving within a few days of the first fish. This is followed by a long tail-off with some fish arriving after spawning is under way. Although the first fish to return may spawn earlier or migrate farther, there are many examples where stocks returned several weeks prior to spawning. In other cases, stocks that returned to the same area at different times spawned at about the same time.

The spawning time for each population must be correlated with the temperature regime of the spawning grounds to ensure that eggs will develop and hatch, and that the fry will emerge at the right time in the spring for feeding and growth. Salmon may spawn later than normal—with their fry emerging in summer—but if they spawn too early and their offspring emerge in winter, the fry will likely not survive (at least not in northern regions).

Each stock, therefore, has a characteristic return and spawning time that is rather precise from year to year. Since fall arrives earlier to the north, northern stocks tend to return earlier than southern stocks. Chinook salmon usually return earliest (June) and coho salmon usually return latest (August–September). The timing of the returns for other species varies among stocks, and can range from mid-June to August. However, sockeye tend to return earlier than pink salmon and the chum salmon returns tend to overlap the return of other species. For example, in Bristol Bay, chum returns overlap with sockeye (in early July) and in Prince William Sound, chum returns overlap with returns for pink salmon (mid-July to mid-August). In southern regions, there is greater variability in timing among stocks—with significant numbers of salmon returning to coastal waters from June through November.

Annual Abundance Estimates

To estimate the number of salmon returning to North America each year (the run), the number of fish caught by a combination of commercial, sport, and subsistence fisheries is added to the number of fish that were not caught (the escapement). Commercial catch statistics are relatively precise, and both sport and subsistence catches have negligible impact on the numbers for the majority of sockeye, chum, and pink salmon stocks. However, reasonably precise escapement estimates are available only for the larger stocks of sockeye salmon (data from weir and tower counts). Less precise estimates are available for pink and chum salmon escapements (data from aerial survey estimates). If the proportion of the run that was caught (rate of exploitation) is known or can be estimated, then the run (catch plus escapement) can be estimated by dividing the catch by the rate of exploitation.

Annual runs (1950–1984) were estimated for the following regions:

- western Alaska—the coastal waters of the Bering Sea from the Yukon River to Unimak Island
- central Alaska—from Unimak Island to the Bering River
- southeastern Alaska/northern British Columbia—from Yakutat to about 51°N
- southern British Columbia to California.

Catch statistics were obtained from Fredin (1980) and INPFC (1979) for the period 1950 to 1977. Regional catch data for recent years were obtained from statistical yearbooks of INPFC (1978–1981), preliminary reports of fishery management agencies such as ADF&G, and Fisheries and Oceans of British Columbia (1982–1984).

Annual escapement estimates for stocks or groups of stocks within the regions were obtained from several summary reports, including INPFC (1974), Beacham (1984), Starr and Petrie (1984), Henderson, Charles, and Starr (1984), Donnelly (1983), and McBride and Wilcock (1983).

Other escapement estimates come from annual agency reports (Yuen 1984; McCurdy 1984; Cross, Bernard, and Marshall 1983; Roos 1984; and ADF&G 1984b).

The regional sockeye runs were estimated by adding the runs of major stocks (for which escapements were known) to the catches of minor stocks, divided by the rate of exploitation on the major stocks. For the interception fishery in the Shumagin–Unimak Islands, the catches in June were added to the western Alaska run, and later catches were added to the central Alaska run. High-seas catches (west of 175°W) were not included in the estimated North American runs because it was unlikely that those salmon were in the Gulf of Alaska in the year of return.

Relationships between rate of exploitation and standardized catch (annual catch minus average catch divided by standard deviation) were estimated for the major pink salmon stocks and some chum salmon stocks (Kodiak, Prince William Sound, British Columbia). Regressions were then used to estimate the rate of exploitation and hence the run for minor stocks and major stocks in years when escapements were unknown (typically prior to 1960). Exploitation

rates for Alaskan pink salmon stocks were generally high (0.7–0.8) when catches were average to above average, but declined to about 0.4 when catches were about one standard deviation below the mean and declined further to 0.2 when they were more than one standard deviation below the mean. Exploitation rates on those chum salmon runs that went to Prince William Sound and Kodiak were between 90 and 94% of the rates on the pink salmon runs.

Escapement figures for coho salmon runs in western and central Alaska were unknown. The annual coho runs to western Alaska were estimated from the catches by assuming an exploitation rate of 0.3 for 1950 to 1972 and an increasing rate of 0.4 to 0.6 from 1973 to 1982. The runs to central Alaska were estimated assuming rates of 0.4 to 0.6 for the period 1950 to 1982. Although escapement estimates were available for some southern stocks (*e.g.*, Columbia River), coho salmon from southern stocks were caught in mixed-stock ocean fisheries from southeastern Alaska to California and it was not feasible to estimate the exploitation rate for individual groups within this region. Annual runs were estimated by assuming a gradually increasing exploitation rate that went from 0.60 (1950) to 0.75 (1982).

Chinook salmon runs to western Alaska since 1965 were estimated by Rogers, Myers, Harris, Knudsen, Walker, and Davis (1984), and the runs in earlier years were estimated using catch data and the average exploitation rates during 1966 to 1975. Runs to central Alaska were estimated from the relatively small catches and an assumed exploitation rate of 0.5. Chinook salmon are fished intensively in mixed-stock fisheries from southeastern Alaska to California, and as with coho salmon, the annual runs were estimated for the combined region. Escapement estimates for the region were available for the period of 1975 to 1982, and the relationship between the catch and exploitation rate for those years was used to estimate the runs in other years.

I estimated the biomass of the annual runs for each species by using the number of fish in the run and the mean weight in the commercial catch—except for Bristol Bay sockeye, where mean weights in the escapement were available. Commercial fisheries, particularly gillnet fisheries, are typically size selective due to the fact that they under-exploit both the smaller individuals (*e.g.*, jacks) and the largest individuals (Ricker 1982). Therefore, the mean weights in the catches may be somewhat biased because mean weight estimates are affected in some areas where a high proportion of the catch is made by gillnets (*e.g.*, western Alaska).

In addition to estimating the annual number and weight of adult salmon that returned from the Gulf of Alaska, I also estimated the approximate number of juvenile salmon (smolts) that annually migrated into the Gulf of Alaska. I divided the estimated number of returning adults (by year of seaward migration) by the marine survival averages reported in the literature (Mathews 1984; Bill 1984; McDonald and Hume 1984; and Peterman 1980). The ocean-age compositions of sockeye salmon runs were available for most major stocks, and when they were not available, ocean-age was estimated from regressions of age composition (*e.g.*, percentage age .3) on mean weight in the catch. A salmon's age is designated according to the number of

winters the fish spent in freshwater and in saltwater. For example, an age of 1.3 indicates that the fish spent one winter in freshwater (excluding winter as an egg or alevin) and three winters at sea; an age of .3 indicates that a fish spent three winters at sea regardless of the number of winters spent in freshwater. Sockeye that ranged from southern British Columbia to Washington were assumed to mature at age .2 and chum and chinook salmon were assumed to mature at age .3 (the average ocean-age at maturity).

Adult Salmon Runs

The annual North American salmon runs from 1950 to 1984 ranged from 9.0×10^7 fish in 1959 to 2.21×10^8 fish in 1980 and from 2.58×10^5 mt in 1959 to 5.48×10^5 mt in 1981. The lowest period of abundance was during 1972 through 1975 when the annual runs averaged 9.9×10^7 fish (2.9×10^5

mt). Then, just three years later, the runs increased and averaged 2.0×10^8 fish (5.03×10^5 mt) from 1978 to 1984. Most of the variation in North American salmon abundance since 1970 was caused by variation in pink and sockeye salmon abundance in central and western Alaska (Tables 15-2 to 15-6).

Central Alaska pink salmon (mostly Kodiak and Prince William Sound stocks) constituted 34% of the North American pink salmon runs during the period from 1950 to 1977, but constituted 46% of the pink salmon runs since 1978. The central Alaskan runs were consistently high in recent years, whereas the runs to the other regions varied considerably from year to year (Table 15-2). The central Alaskan sockeye stocks also increased in the late 1970s; however, the runs were not nearly as large as those from western Alaska (Table 15-3). The western Alaskan sockeye salmon (mostly Bristol Bay stocks) constituted 51% of the North American sockeye runs from 1950 to 1977 (annual range, 13 to 79%), but 65% of

Table 15-2.

Estimates of annual pink salmon (*Oncorhynchus gorbuscha*) runs in millions of fish and thousands of metric tons. Numbers in parentheses are approximate.

YEAR	WESTERN ALASKA		CENTRAL ALASKA		SOUTHEASTERN ALASKA/NORTHERN BRITISH COLUMBIA		SOUTHERN BRITISH COLUMBIA/WASHINGTON		NORTH AMERICA	
	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.
1950	+	+	14	24	24	39	3	4	41	67
51			10	18	40	76	13	33	63	127
52	+	+	16	26	28	51	4	7	48	84
53			14	26	14	27	18	47	47	100
54	+	1	21	35	23	42	1	2	45	80
55			21	37	22	44	15	40	57	121
56	+	1	20	33	30	52	2	3	52	89
57			9	16	20	39	13	31	42	86
58	5	7	20	33	25	47	2	4	52	91
59			7	12	17	33	10	22	34	67
1960	1	1	18	26	12	21	1	1	31	49
61			13	28	27	66	5	14	45	108
62	2	2	39	53	45	81	1	3	87	139
63			19	33	36	56	16	36	70	125
64	3	3	34	52	38	65	1	2	75	122
65			13	20	22	40	4	9	38	69
66	4	6	22	38	45	90	5	8	76	142
67			6	12	9	20	15	37	31	69
68	5	7	22	34	52	74	5	7	84	122
69			24	46	11	22	4	11	40	79
1970	1	1	24	40	31	55	4	7	60	103
71			19	31	21	36	11	24	50	91
72	+	+	5	10	37	49	1	2	43	61
73			5	10	15	25	9	20	30	55
74	2	4	7	14	17	29	3	4	29	51
75			12	21	13	23	7	16	32	60
76	2	3	23	44	20	37	5	18	51	92
77			19	36	31	69	10	24	59	129
78	18	23	36	59	40	58	2	3	95	143
79			46	77	25	46	14	31	85	154
1980	7	9	51	76	33	58	2	3	93	146
81			46	85	37	72	19	41	102	198
82	3	5	45	72	35	52	1	1	84	130
83			29	52	(61)	(115)	(16)	(33)	105	200
84	7	9	59	93	(42)	(64)	(2)	(3)	109	169

+ Indicates less than 1.

Table 15-3.

Estimates of annual sockeye salmon (*Oncorhynchus nerka*) runs in millions of fish and thousands of metric tons. Numbers in parentheses are approximate.

YEAR	WESTERN ALASKA		CENTRAL ALASKA		SOUTHEASTERN ALASKA/NORTHERN BRITISH COLUMBIA		SOUTHERN BRITISH COLUMBIA/WASHINGTON		NORTH AMERICA	
	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.
1950	13	33	10	29	3	8	6	18	32	88
51	11	26	8	21	5	15	4	12	28	74
52	21	42	7	18	6	18	4	10	37	88
53	11	32	6	16	7	19	6	17	30	84
54	9	24	6	16	5	14	13	41	32	95
55	9	21	5	14	4	12	3	8	21	55
56	27	54	6	17	5	15	3	8	40	94
57	12	34	4	11	4	9	5	11	24	65
58	7	18	3	8	6	16	19	52	34	94
59	14	33	4	10	3	8	5	13	26	64
1960	38	76	5	12	3	8	4	9	50	105
61	19	54	5	14	5	14	4	12	34	94
62	11	29	6	16	5	13	3	8	25	66
63	7	20	4	12	3	9	3	8	18	49
64	12	28	5	13	6	17	2	5	25	63
65	54	112	6	16	5	11	3	8	68	147
66	19	52	7	19	5	14	5	14	35	99
67	11	29	5	15	7	17	7	19	30	80
68	9	23	6	16	9	27	4	9	27	75
69	20	48	5	14	4	11	6	14	35	87
1970	42	90	6	17	3	8	6	18	57	133
71	17	46	6	17	4	11	8	23	35	97
72	6	16	5	16	4	12	4	11	20	55
73	3	10	5	16	8	22	7	19	23	67
74	12	28	5	16	5	13	9	27	30	84
75	25	58	4	12	3	7	4	11	36	88
76	13	35	8	25	4	11	6	14	30	85
77	11	32	10	35	6	18	7	20	34	105
78	22	58	9	30	4	11	10	29	44	128
79	44	114	7	21	5	14	7	18	63	167
1980	68	164	8	22	3	9	4	10	83	205
81	40	113	10	30	6	17	9	22	64	182
82	27	79	13	40	6	19	14	41	60	179
83	51	126	14	43	(6)	(16)	(4)	(10)	75	195
84	46	117	13	40	(4)	(10)	(4)	(10)	67	177

the runs since 1978 (annual range, 45 to 82%). The cyclical variation in the large runs to Lake Iliamna (Kvichak stocks) caused most of the year-to-year variation in the western Alaskan runs—with very large runs following very large spawning escapements four or five years earlier. However, since 1978, the other stocks in Bristol Bay increased to a greater extent than the Kvichak stocks and the other stocks are not so cyclical. The large runs to southern British Columbia and Washington State were caused by large Fraser River runs that also followed relatively large escapements four years earlier.

The abundance of North American chum salmon has apparently varied to a lesser extent than abundance of pink and sockeye salmon; however, the abundance estimates for chum salmon are more imprecise. The southeastern Alaska/northern British Columbia region had 38% (range, 20 to 48%) of the North American chum salmon runs during the period of 1950 to 1977, but only 23% of the runs since 1978

(range, 13 to 27%). In recent years, most of the chum salmon runs have been to western and central Alaska where abundances have increased (Table 15-4).

The annual runs of coho and chinook salmon to North America did not vary much between 1950 and 1984; however, in recent years the runs increased in northern areas and decreased slightly in the southern region (Table 15-5). Abundances of coho, chinook, and chum salmon in the southern region were relatively high during the early to mid-1970s when abundances of northern salmon stocks were at a low point. This might indicate either a competitive interaction between southern and northern stocks or an inverse relationship between oceanic conditions favorable for survival—*e.g.*, temperature, food abundance, and predator abundance. To determine plausible interactions among regional stocks of salmon in the Gulf of Alaska, we need to know both the oceanic distributions and the abundances of the stocks.

Table 15-4.

Estimates of annual chum salmon (*Oncorhynchus keta*) runs in millions of fish and thousands of metric tons. Numbers in parentheses are approximate.

YEAR	WESTERN ALASKA		CENTRAL ALASKA		SOUTHEASTERN ALASKA/NORTHERN BRITISH COLUMBIA		SOUTHERN BRITISH COLUMBIA/WASHINGTON		NORTH AMERICA	
	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.
1950	3	9	3	11	13	59	10	52	29	131
51	3	9	3	12	11	51	7	36	24	108
52	3	10	5	17	10	47	5	29	23	103
53	4	11	4	14	12	55	5	29	25	109
54	4	13	5	18	12	55	7	40	28	126
55	3	10	2	8	6	26	2	13	14	57
56	4	12	6	20	7	30	3	13	19	75
57	3	10	7	26	10	45	3	14	23	95
58	3	11	5	18	8	35	5	25	20	89
59	4	12	4	13	3	15	4	20	15	60
1960	6	17	5	17	4	18	3	13	17	65
61	4	12	3	11	5	24	2	9	14	56
62	4	11	6	19	8	38	2	9	19	77
63	3	9	3	11	4	19	2	9	13	48
64	4	12	6	23	7	30	2	11	18	76
65	3	9	2	8	4	17	1	4	10	38
66	3	9	4	12	8	36	2	10	17	67
67	3	10	2	7	6	26	2	9	13	52
68	3	9	4	13	8	39	4	22	18	83
69	3	9	2	7	2	10	3	12	10	38
1970	3	10	4	13	8	32	3	17	19	72
71	3	10	5	16	6	22	2	7	16	55
72	3	10	4	13	9	39	8	39	24	101
73	4	15	4	14	8	38	7	38	23	105
74	5	15	2	6	7	32	3	17	17	70
75	5	14	2	6	3	13	2	10	12	43
76	5	16	3	10	5	26	4	23	17	75
77	7	22	5	20	3	15	2	11	17	68
78	6	19	4	13	3	17	6	30	18	79
79	5	16	4	13	3	15	1	5	13	49
1980	9	27	5	16	6	28	5	26	25	97
81	9	29	9	32	3	15	3	14	23	90
82	5	18	9	34	3	16	6	29	23	97
83	6	20	7	24	(3)	(16)	(2)	(12)	18	72
84	8	25	5	19	(7)	(33)	(6)	(30)	26	107

Salmon Distribution in the Gulf of Alaska

Most of the research sampling conducted in the Gulf of Alaska was done during the period of 1961 to 1967. Gillnets and longlines were used to catch salmon in the offshore waters and purse seines were employed in the coastal waters. Sampling was done primarily in the spring and summer, with no sampling taking place in the early winter. Relatively little sampling was done in late winter, and the sampling that did take place was done entirely by gillnets and longlines. The sampling was insufficient to determine inter-annual variations in either abundance or distribution; however, a general picture of the seasonal distributions and migrations was obtained by combining observations from all years. The regional origins of maturing salmon were largely determined from tags that were returned, augmented by studies of scale patterns and parasites.

Nearly all of the salmon that originate in the area from central Alaska to southern British Columbia spend their

oceanic life within the Gulf of Alaska. However, probably less than half of the coho and chinook salmon originating in the area from Washington to California migrate into the Gulf (*i.e.*, north of 50°N). Stocks from southeastern Alaska and northern British Columbia tend to occupy the eastern and central Gulf and those from central Alaska occupy the central and western Gulf (except chinook salmon, which migrate into the central Pacific).

Salmon from southern British Columbia tend to occupy the more southerly region of the Gulf with sockeye stocks distributed farther to the west and pink salmon stocks concentrated in the eastern region. Chum salmon from western Alaska are centered in the western Gulf but extend from the eastern Gulf to the central Aleutians (180° longitude). Western Alaskan pink salmon are distributed from the western Gulf to the central Aleutians, whereas western Alaskan chinook salmon are found largely in the central Pacific and in the Bering Sea.

Table 15-5.

Estimates of annual coho (*Oncorhynchus kisutch*) and chinook (*O. tshawytscha*) salmon runs in millions of fish and thousands of metric tons. Numbers in parentheses are approximate.

YEAR	COHO						CHINOOK					
	WESTERN ALASKA		CENTRAL ALASKA		SOUTHEASTERN ALASKA/ CALIFORNIA		WESTERN ALASKA		CENTRAL ALASKA		SOUTHEASTERN ALASKA/ CALIFORNIA	
	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.
1950	0.3	1	1.7	6	10.5	41	0.5	5	0.4	5	5.0	34
51	0.3	1	1.6	6	15.5	58	0.5	5	0.4	5	5.1	35
52	0.3	1	1.2	4	12.2	48	0.5	5	0.2	3	5.3	40
53	0.2	1	0.9	3	10.0	38	0.5	5	0.2	3	5.2	38
54	0.3	1	1.8	6	9.3	36	0.5	5	0.2	2	5.2	38
55	0.2	1	1.2	4	10.0	37	0.6	6	0.2	2	5.8	39
56	0.2	1	1.3	5	10.3	38	0.5	5	0.2	2	5.9	36
57	0.4	1	0.8	3	10.8	36	0.6	6	0.1	2	5.0	31
58	0.9	3	1.2	4	9.0	34	0.6	6	0.1	1	4.6	28
59	0.4	1	0.8	3	8.9	28	0.6	6	0.1	1	4.2	28
1960	0.3	1	1.4	5	5.6	19	0.6	6	0.1	1	3.7	24
61	0.2	1	1.0	3	9.4	33	0.6	6	0.1	1	3.9	24
62	0.4	1	1.6	6	10.5	37	0.5	4	0.1	1	3.7	24
63	0.4	1	1.4	5	10.3	35	0.5	5	0.1	1	4.3	27
64	0.4	1	1.9	7	12.3	44	0.7	5	+	+	4.5	29
65	0.2	1	0.9	3	13.7	51	0.5	5	0.1	1	4.3	29
66	0.2	1	1.3	5	15.3	53	0.6	5	+	+	4.5	28
67	0.4	1	1.0	4	11.7	42	0.6	6	0.1	1	4.2	28
68	0.8	2	2.0	7	14.6	44	0.6	6	+	+	4.4	28
69	0.5	1	0.6	2	8.2	27	0.6	6	0.1	1	4.6	27
1970	0.2	+	1.3	5	12.9	49	0.6	6	0.1	1	4.9	30
71	0.1	+	1.0	4	15.8	49	0.6	6	0.1	1	5.2	32
72	0.2	1	0.5	2	11.5	38	0.5	5	0.1	1	5.2	31
73	0.4	1	0.7	3	11.7	39	0.5	5	0.1	1	5.9	35
74	0.4	1	0.6	2	14.5	45	0.5	4	0.1	1	5.3	30
75	0.4	1	0.8	3	10.5	36	0.3	3	0.1	1	5.6	33
76	0.3	1	0.9	3	15.5	41	0.5	5	0.1	1	5.6	32
77	0.9	3	0.9	4	10.5	33	0.6	6	0.1	1	5.8	33
78	0.8	2	1.4	5	10.5	30	0.8	9	0.2	2	5.4	33
79	1.5	5	2.3	8	11.5	35	0.9	8	0.2	2	5.3	31
1980	1.5	5	2.2	7	10.7	32	0.9	9	0.1	1	4.9	29
81	1.4	4	2.4	9	8.5	25	1.2	11	0.2	2	4.6	27
82	2.9	9	3.8	14	10.0	30	1.0	9	0.2	2	4.9	33
83	0.9	3	2.3	8	(8)	(21)	1.0	9	0.3	3	(4)	(24)
84	3.1	10	2.9	10	(9)	(28)	0.8	7	0.2	2	(5)	(27)

+ Indicates less than 100,000 fish or 1,000 mt.

Bristol Bay sockeye often make up the most abundant regional stock at sea because, in addition to the annual run of mature fish, there are two age groups of immature fish in offshore waters. Only one age group of pink salmon is present in offshore waters at any given time. Maturing Bristol Bay sockeye salmon extend from the eastern Gulf of Alaska to the western Aleutians and Bering Sea (Fig. 15-1). To estimate the average proportion of Bristol Bay maturing sockeye in the Gulf (*i.e.*, east of 165°W), the average regional composition of the tag returns was calculated for each 2° × 5° area from data given in Figures 53 to 59 of French *et al.* (1976).

During the period from 1961 to 1967, the average annual catch of sockeye salmon in Bristol Bay (9.3×10^6 fish) was equal to the average sockeye catch in the remainder of North America, so the chance of recovering tags should

have been about equal. The unweighted mean of the percentages of Bristol Bay tags from Gulf of Alaska tagging was 26%, and since the average annual run to North America excluding Bristol Bay was 14.6×10^6 , the average number of Bristol Bay sockeye in the Gulf for the period of 1961 to 1967 was $\sim 5.0 \times 10^6$ fish. This was 26% of the average Bristol Bay inshore run of 1.9×10^7 and 23% of the combined western Alaska sockeye run during those years (Table 15-6). However, the vast majority of the Bristol Bay sockeye in the Gulf were in the western half where they were mixed mainly with central Alaskan stocks, western Alaskan chum salmon, and some unknown proportion of the abundant Asian chum salmon stocks.

I hypothesized that Bristol Bay stocks that migrate to sea late would more likely be in the Gulf of Alaska than those that migrate to sea early. I based the hypothesis on the the-

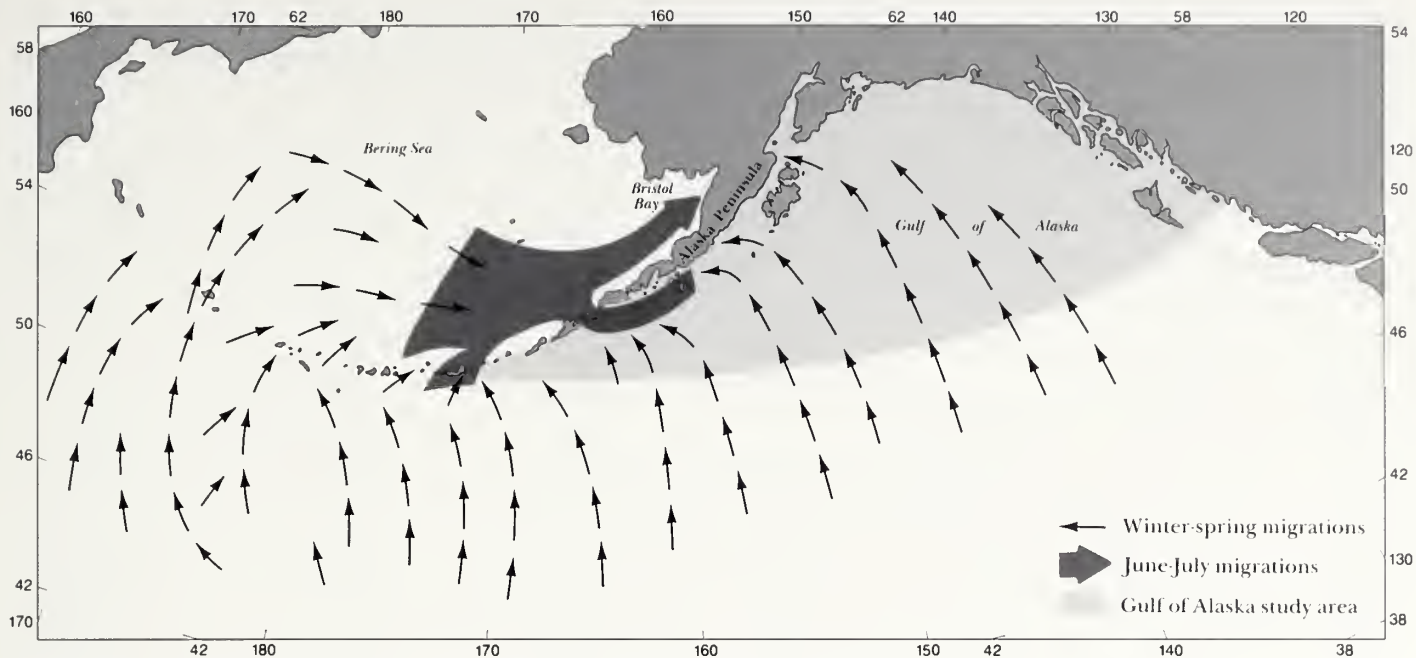


Figure 15-1. Principal migratory routes to Bristol Bay followed by maturing salmon.

ory that salmon return as adults from about the same area where they resided at the end of their first winter at sea. Konovalov (1971) suggested that individual salmon populations have rather precise wintering and feeding grounds at sea; however, the complex of populations from a large river or lake system may occupy a broad area.

Bristol Bay sockeye salmon smolts from the various lake systems migrate to sea each year in about the same order. They migrate seaward in a rather narrow band along the north side of the Alaska Peninsula (Straty 1974). Their migration beyond Unimak Island is undocumented (Fig. 15-2). Although the stocks throughout Bristol Bay contain both early (mid-May to early June) and late (mid-June to late July) migrations, the stocks from the Kvichak River to the Alaska Peninsula generally have earlier migrations and larger and older smolts than stocks from the northwest side of Bristol Bay (Nushagak and Togiak districts). The majority of chum and pink salmon in Bristol Bay are also produced from both the Nushagak and the Togiak systems, and they tend to reside in the western Gulf.

I compared the tag returns to the Kvichak and to north Peninsula fisheries with the returns to the Nushagak/Togiak fisheries. The returns came from maturing sockeye that had been tagged from April to early July in both the Gulf of Alaska and the central Pacific (data on file at the Fisheries Research Institute, University of Washington, Seattle, WA). The expected tag returns were calculated from the commercial catches. For sockeye tagged in the Gulf, there were significantly more tags recovered in the Nushagak/Togiak districts than expected from the number of fish taken in the commercial catches (Table 15-7). An exceptional number of tags (relative to the catches) were recovered in the interception fisheries of the south Peninsula (Unimak/Shumagin Islands). This fishery is particularly effective because sockeye returning from the Gulf are concentrated as they

migrate along the Peninsula and around Unimak Island before heading into Bristol Bay.

Sockeye salmon tagged in the central Pacific tended to return to a lesser extent to the Nushagak/Togiak districts than to the other Bristol Bay systems. The one exception to this pattern occurred in 1962. Most of the sockeye returning to the Nushagak that year had migrated to sea in 1960 and the migration from the Wood River lakes (the major sockeye producer in the district) had an unusually early peak (first week of June) and then a more typical late peak in mid-July. Interannual variation in the timing of smolt migrations from Bristol Bay probably affects the subsequent distribution of the stocks at sea, and thus affects both their abundance in the Gulf and their availability to interception fisheries such as those of the south Peninsula and the high seas.

A comparison was also made between the age compositions from catch estimates of maturing Bristol Bay sockeye in the high-seas fishery (mostly between 175°W and 175°E) given by Fredin and Worlund (1974) and the age compositions in the Bristol Bay runs. The sockeye caught in the high-seas fishery were consistently older in both freshwater and ocean age than the sockeye caught in the Bristol Bay runs. The difference in ocean-age compositions was probably affected by the selectivity of the gillnets, but the freshwater age was probably unaffected. In addition, the freshwater ages of those immature Bristol Bay sockeye that were sampled by the Fisheries Research Institute south of Adak Island were usually older than the ages found in subsequent Bristol Bay returns of mature sockeye. Each year the age composition of immature fish usually shifted from older ages—in late June to early July—to younger ages in late July as the immature salmon moved from east to west on their feeding migration.

Table 15-6.

Estimated annual catches of maturing sockeye salmon (*Oncorhynchus nerka*) of western Alaska origin by both the Japanese high-seas and the Unimak-Shumagin Islands fisheries, and estimated inshore western Alaska sockeye salmon runs for the period 1950 to 1984. Catch and run numbers are expressed in millions of fish.

	JAPANESE FISHERY			UNIMAK- SHUMAGIN FISHERY	WESTERN ALASKA INSHORE RUN	WESTERN ALASKA COMBINED RUN ^b
	TOTAL CATCH	WESTERN ALASKA ^a				
		IMMATURES	MATURES			
1950	0	0	0	1.6	11.2	12.8
51	0	0	0	0.2	10.7	10.9
52	0.7	0	0	0.8	19.9	20.7
53	1.6	0	0	0.9	10.3	11.2
54	3.8	0	0	0.6	8.1	8.7
55	12.5	0	0	0.5	8.6	9.1
56	10.3	0.9	2.4	0.6	26.2	29.2
57	20.1	+	6.4	0.3	11.6	19.2
58	12.9	+	0.4	0.2	6.6	7.2
59	9.9	0.1	0.6	0.2	13.9	14.7
1960	14.5	0.3	3.6	0.2	37.6	41.5
61	14.2	0.1	5.8	0.4	18.8	25.3
62	10.8	0.1	0.8	0.4	10.8	12.1
63	8.9	0.1	0.9	0.2	7.3	8.5
64	7.2	0.8	0.3	0.3	11.3	12.0
65	12.2	0.4	6.1	0.8	53.5	61.2
66	8.0	0.1	1.5	0.6	18.0	20.5
67	10.7	+	0.9	0.3	10.7	12.0
68	9.2	0.8	0.9	0.6	8.4	9.9
69	8.4	0.5	1.2	0.9	19.6	22.5
1970	10.0	1.2	3.5	1.8	39.8	45.6
71	6.6	0.6	0.8	0.7	16.4	19.1
72	6.9	0.2	0.7	0.5	5.7	7.5
73	5.9	0.3	0.6	0.3	2.7	3.8
74	5.4	0.7	0.3	0.1	11.4	12.1
75	5.2	0.2	0.6	0.2	24.6	26.1
76	5.8	0.2	0.8	0.4	12.6	14.0
77	2.8	0.3	0.5	0.3	10.4	11.4
78	3.2	0.2	0.1	0.5	21.4	22.3
79	3.0	0.4	0.1	0.9	43.1	44.3
1980	3.2	0.7	0.2	3.3	64.8	68.7
81	3.1	0.3	0.1	2.0	37.5	40.3
82	2.5	0.2	0.1	2.0	24.6	27.0
83	2.5	0.2	0.1	2.2	49.2	51.7
84	1.9	0.2	0.1	2.1	43.9	46.3

^aFredin and Worlund (1974) and M. L. Dahlburg (NMFS, pers. comm.) estimated the western Alaska catches by the high seas fleet.

^bCombined run includes Unimak-Shumagin catch, Japanese catch of mature sockeye, and the catch of immature sockeye in the preceding year.

+ Indicates less than 100,000 fish.

The Kvichak system usually has the most abundant smolt migration and adult run. Since 1971, the Alaska Department of Fish and Game has made daily estimates of the number of smolts that migrate from Lake Iliamna, although the estimates obtained in 1975 were poor. I calculated the daily adult runs in the fishery by lagging daily escapements back to the catch and comparing the annual timing of the smolt and adult migrations (Fig. 15-3). The timing of the smolt migrations was related to the average April/May air temperature in Bristol Bay, whereas the timing of the adult run related to the average April/May temperature in Womens Bay (Kodiak).

The timings of the smolt and adult migrations were usually correlated, as were the spring air temperatures; however, in 1977 when temperatures were cool in Bristol Bay but

warm in the Gulf, the smolt migration was somewhat late and the adult run was very early. Thus, the interannual variation in both the composition of the stocks migrating from Bristol Bay and in the spring temperature probably affects the abundance of Bristol Bay salmon that can be found in the Gulf of Alaska. A high proportion of late-migrating stocks coupled with a cold spring would probably mean that a high proportion of western Alaskan salmon could be found in the Gulf. On the other hand, a high proportion of early migrating stocks coupled with a warm spring would probably lead to a small proportion of western Alaskan salmon in the Gulf. In addition, cold winters may displace salmon farther to the south, whereas in warm winters they may be more dispersed farther north (Rogers 1984). El Niño events (the unusual extension of southern warm water into

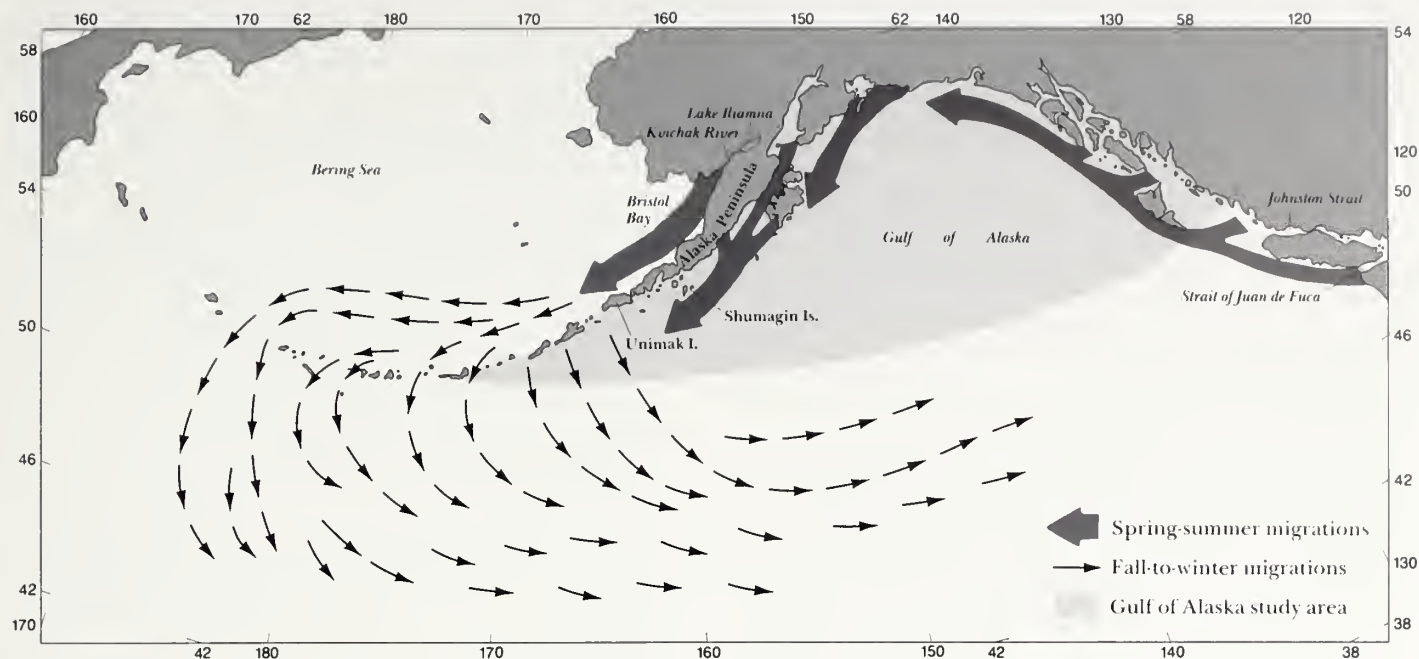


Figure 15-2. Principal spring/summer migratory routes followed by Bristol Bay and Gulf of Alaska salmon stocks (large gray arrows). Hypothetical fall-to-winter migrations of Bristol Bay salmon are shown by small black arrows.

Table 15-7. Tag returns (both observed and expected) from maturing sockeye salmon tagged in the Gulf of Alaska and central Pacific, 1957 through 1967.

YEAR	CATCH (×10 ⁶)			TAGGED IN GULF OF ALASKA (E OF 165° W) AND RETURNED FROM:						TAGGED IN CENTRAL PACIFIC ^a AND RETURNED FROM:			
	SOUTH PENINSULA	KVICHAK-NORTH PENINSULA	NUSHAGAK-TOGIAK	SOUTH PENINSULA	KVICHAK-NORTH PENINSULA		NUSHAGAK-TOGIAK		%d ^b	KVICHAK-NORTH PENINSULA		NUSHAGAK-TOGIAK	
					Observed	Expected	Observed	Expected		Observed	Expected	Observed	Expected
1957	0.34	6.08	0.53	0	4		0			36	33	0	3
58	0.19	2.33	1.13	—	—		—			35	29	8	14
59	0.22	3.41	1.83	0	1		0			18	16	0	2
60	0.38	12.74	1.66	—	—		—			551	508	23	66
61	0.46	11.60	0.70	6	207	210	16	13	+23	525	513	19	31
62	0.41	3.43	1.55	22	27	50	45	22	+105	25	36	27	16
63	0.20	2.06	1.03	5	11	13	8	6	+33	13	13	7	7
64	0.37	4.16	1.67	5	18	24	15	9	+67	8	7	2	3
65	0.88	23.45	1.01	5	114	123	14	5	+180	143	141	4	6
66	0.61	8.19	1.37	13	129	146	31	24	+29	15	15	2	2
67	0.30	3.79	0.76	7	11	14	6	3	+100	17	15	1	3

^aOne tag was recovered in the south peninsula fishery in 1961. Most of the fish were tagged between 165°W and 180°W.

^b $[(\text{Obs.} - \text{Exp.}) \div \text{Exp.}] \times 100$. (Percentage difference between observed and expected).

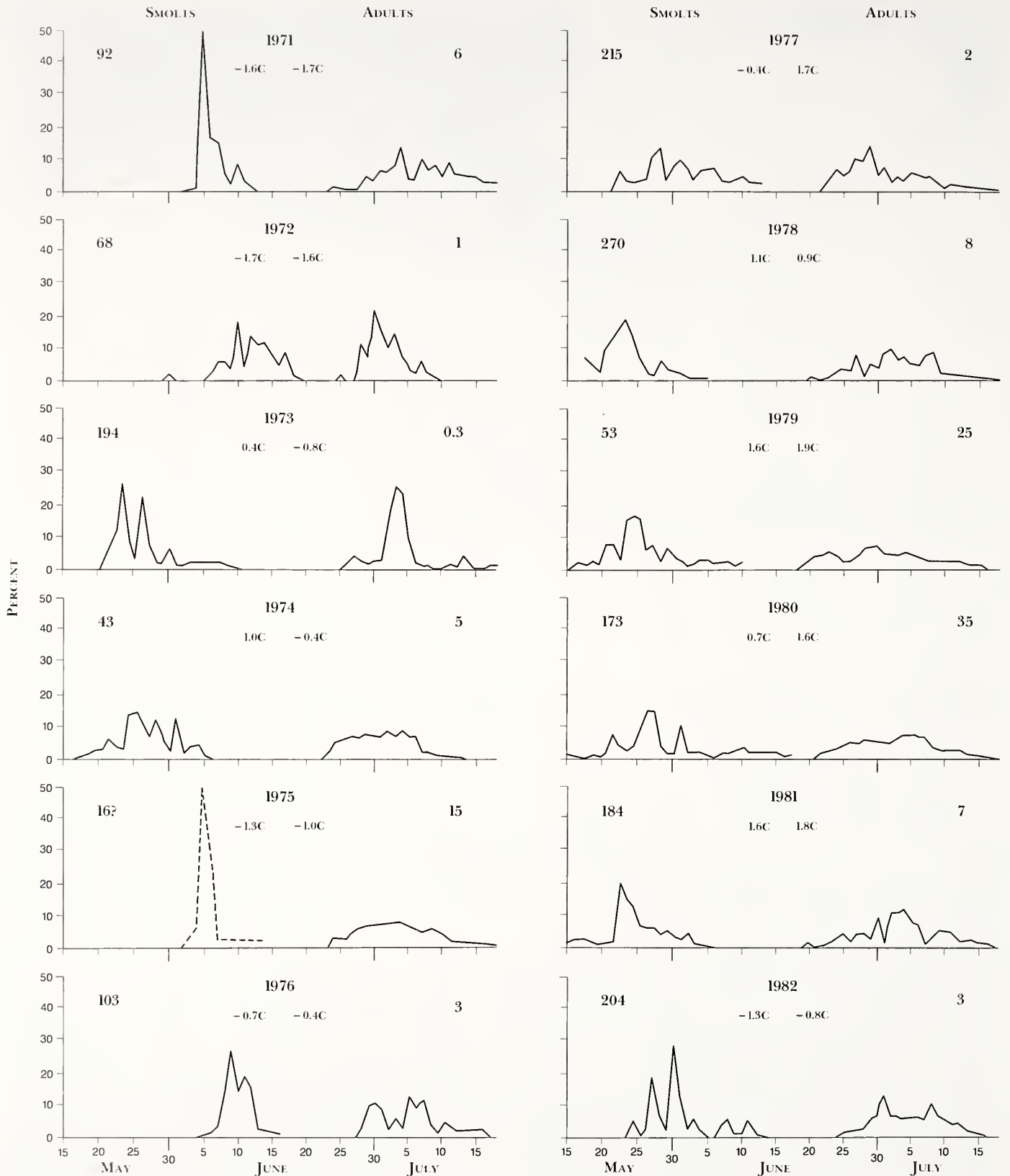


Figure 15-3. Timing of the smolt and adult migrations for Kvichak sockeye salmon (*Oncorhynchus nerka*) during the period 1971 to 1982 in terms of the daily percentage of the annual migration. The number of smolts (millions) is given in the upper left corners and the number of adults (millions) is given in the upper right corners. The deviations from the mean April/May air temperature in Bristol Bay are shown at left center and the deviations from the mean April/May sea surface temperature at Kodiak are shown at right center.

the Gulf) may also cause salmon to locate farther north in the Gulf. Such events occurred in 1958, 1972, and 1983 (McLain 1984).

In 1972, the Kvichak run was earlier than expected based on the sea surface temperature (SST) at Kodiak (Fig. 15-3), so perhaps warmer water from the south moved the fish farther north and thus closer to Bristol Bay. Their migration may even have begun earlier. In warm years, the Fraser River sockeye tend to return around the north end of Vancouver Island (Johnston Strait) rather than taking their usual route through the Strait of Juan de Fuca (McLain 1984). If Fraser River sockeye were concentrated in the upper Gulf, they might be expected to return via Johnston Strait, whereas if they were concentrated in the southern Gulf (as appeared to be the case during the 1961 to 1967 returns), they would probably return via the Strait of Juan de Fuca.

Temperature also affects the growth of sockeye salmon while they are at sea. The growth of Bristol Bay sockeye during their last year at sea (and probably during their last spring) was strongly density-dependent until 1978 (Rogers 1984). After that, they were larger than expected, given the abundance of the runs. I used stepwise multiple regressions to compare the annual variation in the mean lengths for the four main age groups of sockeye salmon in Bristol Bay with 1) the SST in April–May at Kodiak, 2) the western Alaskan run size, and 3) the year (Table 15-8). Ages 1.2 and 1.3 were consistently abundant in the Nushagak runs, whereas ages 2.2 and 2.3 were usually scarce (although they were abundant in the other Bristol Bay systems). The variation in the mean lengths of age 1.2 sockeye was most affected by variation in spring temperature, while the length variation of older sockeye was most affected by the abundance of the run. Very little of the variation in the lengths of age 2.3 fish was explained by the temperature in the Gulf. For the age 2.2 and 2.3 sockeye, lengths were longer in recent years than might be expected, given both the temperatures and abundances of the runs. It was particularly interesting that the

Table 15-8.

Multiple linear regressions of annual mean lengths of Bristol Bay sockeye salmon based on sea surface temperature, western Alaska run size, and year (1959–1983).

REGRESSIONS ^a	PERCENT VARIATION EXPLAINED BY R ²
$L^{b} 1.2 = 0.594 (T)^c - 0.486 (R)^d$	31
$L 1.3 = 0.658 (T) - 0.757 (R)$	53
$L 2.2 = 0.453 (T) - 0.728 (R) + 0.530 (Y)^e$	61
$L 2.3 = 0.274 (T) - 0.826 (R) + 0.386 (Y)$	67

^aAll variables are standardized, $x = \frac{x - \bar{x}}{SD}$ number of standard deviations from the mean for the 25 years, and all coefficients are significant at $P < 0.05$ except 0.274 in the L 2.3 regression.

^bL 1.2 = mean length (mid-eye–tailfork) of Nushagak sockeye, age 1.2; mean = 507 mm, SD = 8.1; L 1.3 = same for Nushagak age 1.3; mean = 571 mm, SD = 7.8; L 2.2 = mean length of Bristol Bay sockeye, age 2.2; mean = 521 mm, SD = 9.9; L 2.3 = same for Bristol Bay age 2.3; mean = 579 mm, SD = 7.2.

^cT = April–May SST at Womens Bay, Kodiak (C); mean = 5.5, SD = 1.3.

^dR = Western Alaskan sockeye run in millions; mean = 23.8, SD = 17.3.

^eY = year; mean = 71, SD = 7.4.

younger freshwater ages (1.2 and 1.3) were more affected by temperatures in the Gulf than were the older freshwater ages, since this seems to agree with the hypothesis that younger smolts are more likely to begin their ocean life in the western Gulf than are the older smolts.

Returns From The Gulf

The abundance, distribution, and size of salmon in the Gulf of Alaska are both seasonally and interannually dynamic. Salmon move from north to south in the fall and from south to north in the spring. The stock compositions vary as both species' abundances and regional stocks change, and fish growth varies as density, temperature, food abundance, and inherent growth rates all vary. Although we lack measurements for these phenomena, we can be reasonably sure that they are occurring. The maximum biomass of salmon in the Gulf of Alaska probably occurs in late May to early June just before the mature fish begin returning to their freshwater spawning streams. If the mortalities from either predation or fisheries (fish that are killed but not caught) equal the growth that occurs between June and October when most fish have returned, then the biomass of runs from the Gulf is nearly equal to the seasonal peak biomass of maturing salmon in the Gulf. I believe this assumption is not unreasonable, although most biologists probably believe that growth exceeds mortality.

Runs from the Gulf of Alaska were estimated by assuming that 1) 26% of the sockeye, coho, and chinook salmon returning to western Alaska were from the Gulf, 2) 75% of chum and pink salmon returning to western Alaska were from the Gulf, and 3) 50% of the southern runs of coho and chinook salmon were also from the Gulf. Annual salmon run estimates for runs from the Gulf and to all of North America are shown in Figure 15-4. The Gulf had an annual peak biomass between 2×10^5 and 3×10^5 mt of maturing salmon from 1950 to 1977, and $\sim 4 \times 10^5$ mt from 1981 to 1984. I did not attempt to estimate the biomass of immature sockeye, chum salmon, or maturing Asian chum salmon,



Figure 15-4. Annual salmon runs from the Gulf of Alaska and to North America for the period 1950 to 1984.

although this can probably be done (Peterman and Wong 1984). The recent salmon returns (1981–1984) valued in terms of prices paid to fishermen would be worth nearly \$500 million/y, based on catch plus escapement. This makes the Gulf of Alaska a valuable resource for North America.

The approximate number of juveniles entering the Gulf of Alaska from the coastal estuaries was estimated based on the number of adult returns and an assumed 10% survival rate. This appeared to be average for 10-cm smolts (~8.5 g)—the size of most salmon when they leave the inshore waters. For the smolt migrations from 1956 to 1976, the annual estimates ranged from 6.30×10^8 to 1.35×10^9 fish, or 5.4×10^3 to 1.15×10^4 metric tons.

The adult returns from those migrations averaged 2.53×10^5 mt—nearly 30 times the average biomass of juveniles that entered the offshore waters of the Gulf during the period of 1956 to 1976. The adult returns from the 1977 to 1981 seaward smolt migrations were 66% higher than the returns from the period 1956 to 1976 migrations. However, most of this increase was probably caused by an increase in marine survival rather than an increase in the number of seaward migrants (Rogers 1984).

The Future

Although in recent years the salmon runs to western and central Alaska were probably as large as they have been since commercial fishing began, the recent abundance of North American salmon was still below the historical peak abundance—mainly because southeastern Alaska and British Columbia stocks were still at a relatively low level. However, based on preliminary catch statistics, the 1985 run may be comparable to the historical peak for this region. It seems likely that North American salmon stocks could produce annual sustained catches of $\sim 3.5 \times 10^5$ mt if it were not for some rather disturbing trends in southern stocks. These trends include a decline in the average size of British Columbia salmon (and probably a decline in their reproductive potential) (Ricker 1982), and a decline in the marine survival rate for some Oregon hatchery stocks (Mathews 1984).

Fishery practices (*e.g.*, selectivity, overexploitation of natural stocks) as well as hatchery practices (*e.g.*, elimination of natural reproduction and the altering of both behavior and natural selection) will probably continue to affect salmon abundance in the southern Gulf of Alaska. However, as long as the freshwater spawning and rearing grounds in British Columbia and Alaska remain as they are, we can look forward to continued bountiful salmon returns from the Gulf of Alaska.

We have yet to determine the causes of natural salmon mortality in offshore waters. It is generally assumed that marine mortality rates are greatest for seaward migrants in coastal estuaries, then decline as the salmon grow to maturity. However, little is known about either the natural mortality for immature salmon at sea or about mortality for maturing salmon on their homeward migration. The ability to predict interannual variation in marine mortality would greatly improve our ability to forecast annual salmon runs.

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Drs. E.S. Salo and S.B. Mathews provided valuable insight regarding both the biology and the interpretations of statistics on salmon stocks from the southern regions of the Gulf. Mr. C.K. Harris provided valuable assistance in interpreting salmon statistics for the high seas.

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ABSTRACT

In this chapter we review existing knowledge of marine birds in the Gulf of Alaska. Three estuarine systems in the Gulf provide critical habitat for migratory shorebirds and waterfowl: 1) the Stikine River Delta, 2) Cook Inlet, and 3) the Copper River Delta. Over 20 million waterbirds are estimated to use the latter system during spring migration. Western sandpipers, dunlin, and northern pintails numerically dominate this migration. Breeding populations of shorebirds and waterfowl in the Gulf are small compared with those elsewhere in Alaska. Of those Gulf regions suitable for nesting waterfowl and shorebirds, the Copper River Delta is the most important. Species diversity and the number of shorebirds wintering in the Gulf are low; however, waterfowl wintering in the Gulf number at least in the low millions. These birds concentrated in sheltered, near-shore regions where their epibenthic and infaunal prey are accessible.

Over nine million seabirds (twenty-six species) nest in the Gulf of Alaska at more than 800 sites. Seabird productivity varies markedly. Food availability seems to have a large influence on reproductive success, especially for surface-feeding species such as the black-legged kittiwake. Seabird densities are highest over shelf and shelf-break habitats during spring migration and in summer. Sooty and short-tailed shearwaters dominate the pelagic avifauna both numerically and in terms of biomass. Seabird densities are generally lower in winter than in summer as a result of both a southward migration of some species and offshore dispersal of others. A variety of prey species are used by seabirds in the Gulf; of these, capelin, sand lance, and euphausiids are of greatest importance. Trophically, seabirds in the Gulf range from near primary consumers to third-order carnivores, ingesting an estimated 1,120,000 mt during the 120-day summer period.

Introduction

Over 147 species of birds use marine or estuarine habitats in the Gulf of Alaska, and overall populations, although not precisely known, number in the millions. Marine bird resources in the Gulf of Alaska are unquestionably some of the largest in the Northern Hemisphere. Our intent in this chapter is to summarize much of the published and unpublished literature on distribution, abundance, migration, breeding biology, and feeding ecology of the waterfowl, shorebirds, and seabirds that spend all or a portion of their lives in coastal or offshore habitats in the Gulf. We concentrate on features that are particularly relevant to each

species group. For waterfowl and shorebirds—many of which breed outside the Gulf of Alaska—migration and wintering are emphasized. For seabirds, many of which spend their entire lives in Alaskan waters, our coverage is more detailed.

Any attempt to understand patterns of bird distribution, variations in migration patterns, nesting phenology, or breeding success depends on an understanding of topography and climate, prey abundance and variability, and factors that affect prey populations. Where possible, we attempt to identify the critical biotic and abiotic factors that affect the lives of marine birds in the Gulf. However, a comprehensive synthesis that relates marine birds to their environment awaits more detailed interdisciplinary studies.

Review Area Boundaries

The Gulf of Alaska, as defined in this volume, includes all marine and coastal waters north of 52°N. Although marine birds are usually confined to geographic regions that have both the appropriate oceanographic conditions and food resources, they may wander widely over that region's marine waters. Indeed, some species found in the Gulf of Alaska are trans-equatorial migrants. The southern boundary of the Gulf of Alaska (*i.e.*, 52°N) is artificial in ornithological terms. Nevertheless, we adhere to 52°N as a southern boundary for estimating at-sea populations of marine birds, ignoring portions of those populations that pass south of that line. For the rest of the chapter, we limit coverage to Alaskan waters between the southern tip of southeastern Alaska and Unimak Pass (Fig. 16-1), where the majority of recent work funded through the Outer Continental Shelf Environmental Assessment Program (OCSEAP) has occurred.

Sources of Information

The biology of marine birds in the Gulf of Alaska was little understood prior to studies initiated in the mid-to-late 1970s. Prior to this time, information on marine birds in the Gulf was limited either to accounts of distribution and abundance or to general information on life histories and feeding (Bent 1919; Gabrielson and Lincoln 1959; Sanger 1972; and Shuntov 1972). Six primary sources provided information on distribution, abundance, and migration of marine birds:

- 1) Gabrielson and Lincoln (1959)
- 2) Isleib and Kessel (1973)
- 3) Kessel and Gibson (1978)
- 4) SOWLS, Hatch, and Lensink (1978)
- 5) Gould, Forsell, and Lensink (1982)
- 6) the frequently updated seabird-colony database of the U.S. Fish and Wildlife Service.

Information on specific sites and species was gleaned from numerous sources. Data on shorebird and waterfowl migration are primarily from:

- Isleib and Kessel (1973)
- Senner (1979)
- Murphy (1981)
- Senner, West, and Norton (1981)
- Hawkings (1982).

Similar information from southeastern Alaska is from Petersen, Greulich, and Harrison (1981) and Heglund and Rosenberg (1985).

For seabirds, we have summarized data primarily collected by personnel of the U.S. Fish and Wildlife Service or subcontractors to the Fish and Wildlife Service. Most of these data are from colony studies that took place in the following locations: Forrester Island in southeastern Alaska; Middleton Island; Wooded Islands and the Barren Islands in the northern Gulf; Chisik Island in Cook Inlet; Sitkalidak Island and Chiniak Bay at Kodiak Island; and Semidi Islands, Ugaiushak Island, and the Shumagin Islands west of Kodiak Island (Fig. 16-1). Much of the data on seabird breeding biology is summarized in Baird and Gould (1983), and we draw heavily from that report. The broad scope of this chapter, and particularly the limited amount of data from some sites, does not permit a detailed analysis of the between-year and the between-colony differences in reproductive success and nesting phenology. These differences were sometimes profound. Instead, we summarize these data and present averages for several reproductive parameters.

Information on the pelagic distribution and abundance of seabirds is primarily from Gould *et al.* (1982). Most information is for nearshore and continental shelf waters in spring, summer, and fall.

Data on feeding ecology of seabirds come primarily from studies by the U.S. Fish and Wildlife Service. Nestling diets were studied at several colony sites in the Gulf, and pelagic

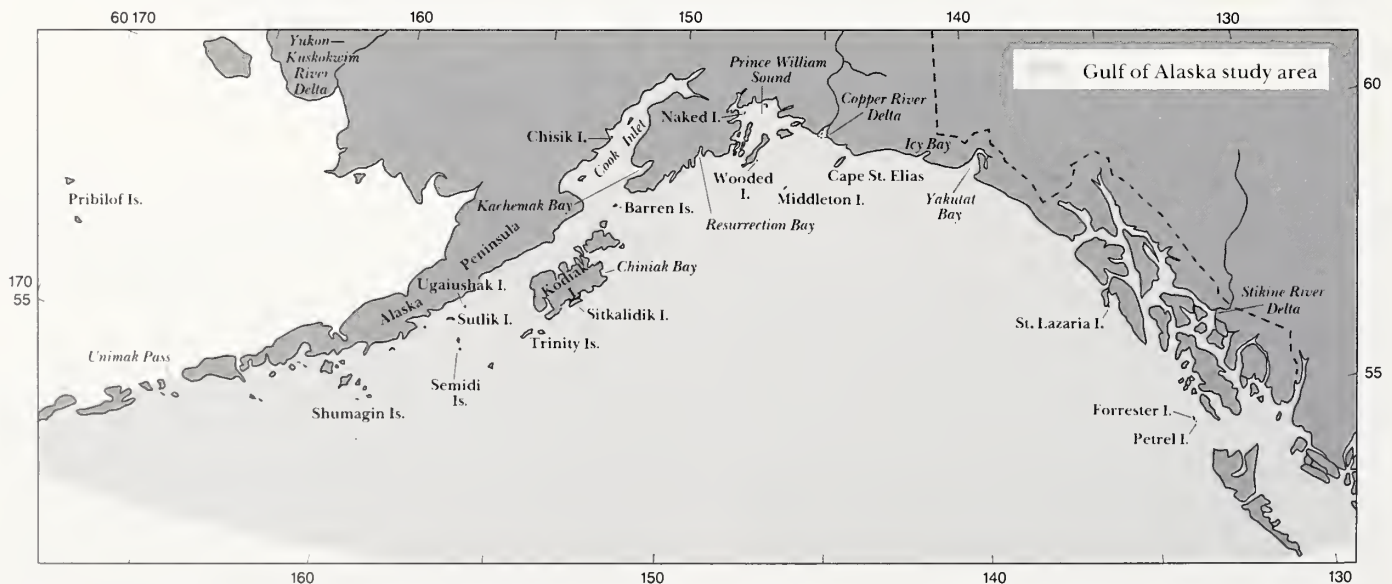


Figure 16-1. Gulf of Alaska and principal locations referred to in the text.

studies of older birds were focused in nearshore waters of the continental shelf off Kodiak Island in summer, and in protected bays at Kodiak Island and in Kachemak Bay in winter (Sanger and Jones 1982, 1984; Krasnow and Sanger 1982; Sanger, in press; and Sanger and Ainley, in press). Little work was done in oceanic areas.

Waterfowl

Several geographic factors make the coastal fringe of the Gulf of Alaska important for waterfowl. The open Gulf of Alaska and the extensive mountain ranges to the east and north both restrict the movements of many species to a narrow coastal corridor. Estuarine meadows and intertidal mudflats—important as feeding and resting areas—are limited in number and widely spaced. In addition, several of these wetlands, particularly on the west side of Cook Inlet and in the Copper River Delta, provide crucial nesting habitat for waterfowl, including several subspecies of Canada geese (*Branta canadensis*) with limited breeding distributions.

In contrast to the shorebirds that winter in Alaska in relatively low numbers, waterfowl (particularly diving ducks) are abundant. These birds forage in shallow water along a coastline that remains essentially ice-free. Also, the coastline of the Gulf of Alaska, especially in southeastern Alaska and Prince William Sound, is dissected by numerous bays and fjords. This not only increases the linear extent of coastline and the habitat available to wintering waterfowl, but also provides birds with sheltered waters for feeding and resting (Fig. 16-1).

Fifty-two species of waterfowl have been recorded in the coastal fringe of the Gulf of Alaska (Table 16-1) including 39 species recorded in winter. Twenty-eight species are known to breed along the coast, although ten of these are uncommon or rare.

We know little about the waterfowl populations in the Gulf of Alaska, despite their abundance and variety. The timing of migration and the migratory corridors to and from Alaska are well known for most species (Bellrose 1976), but the relative importance of the inland, coastal, or over-water routes is unclear. Waterfowl nesting studies have emphasized highly visible species such as swans and geese at only a few sites such as the Copper River Delta. In contrast, heavily forested regions where waterfowl nest in low densities have been largely ignored. Populations of wintering waterfowl, like shorebirds, are poorly known because of the difficulties of undertaking field work in winter.

Loons and Grebes

Five species of loons and four species of grebes are known from the Gulf of Alaska (Table 16-1). All five loon species nest in Alaska, but only the common loon (*Gavia immer*), red-throated loon (*G. stellata*), and Pacific loon (*G. pacifica*) nest along the Gulf coast. All loons are migratory, and all five species are found in winter in the Gulf of Alaska (Gabrielson and Lincoln 1959; Isleib and Kessel 1973).

Loons are most abundant in the Gulf during spring and fall migration (Hogan and Murk 1982). Spring loon migra-

tions extend from late March to early June. Migrating loons appear to follow the coastline and can be seen from prominent points of land. Arneson (1980) estimated upwards of 10,000 loons per day flew past Cape St. Elias during the 1978 migration peak (between 8 and 20 May). Fall migration in the north Gulf coast region occurs from early September

Table 16-1.
Status and relative abundance of waterfowl in coastal regions of the Gulf of Alaska by seasons.

SPECIES	SEASONAL STATUS ^a			
	SPRING	SUMMER	FALL	WINTER
Red-throated loon	CM	CB	CM	C
Arctic loon	Ra		Ra	Ra
Pacific loon	CM	B	CM	C
Common loon	CM	CB	CM	C
Yellow-billed loon		UV		Fc
Pied-billed grebe			RaM	Ra
Horned grebe	CM	UB	CM	C
Red-necked grebe	CM	B	CM	C
Western grebe				Ra
Tundra swan	CM	CaV	CM	Ca
Whooper swan			A	
Trumpeter swan	UM	B	CM	U
White-fronted goose	CM		CM	
Snow goose	CM		CM	
Ross' goose	RaM			
Emperor goose	RaM		RaM	Ra
Brant	FcM	RaV	RaM	Ca
Canada goose	CM	CB	CM	U
Wood duck	CaM	CaV		
Green-winged teal	CM	CB	CM	Ra
American black duck			Ca	Ra
Mallard	CM	CB	CM	C
Spot-billed duck			A	
Northern pintail	CM	CB	CM	U
Garganey			A	
Blue-winged teal	UM	RaB	RaM	
Cinammon teal	CaM			
Northern shoveler	FcM	CB	FcM	Ca
Gadwall	FcM	FcB	FcM	C
Eurasian widgeon	CaM		CaM	Ca
American widgeon	CM	CB	CM	U
Canvasback	UM	B	UM	Ca
Redhead	CaM	RaB	CaM	
Ring-necked duck	RaM	RaB	RaM	Ra
Tufted duck			RaM	Ra
Greater scaup	CM	CB	CM	C
Lesser scaup	UM		RaM	Ra
Common eider		CB		C
King eider				U
Steller's eider				U
Harlequin duck		CB		C
Oldsquaw	CM	RaB	CM	C
Black scoter	FcM	UV	FcM	C
Surf scoter	CM	UB	CM	C
White-winged scoter	CM	UB	CM	C
Common goldeneye	CM	UB	CM	C
Barrow's goldeneye	CM	CB	CM	C
Bufflehead	CM	UB	CM	C
Smew	RaM			Ca
Hooded merganser	RaV	UB	RaV	Ra
Common merganser	CM	CB	CM	C
Red-breasted merganser	CM	UB	CM	C
Ruddy duck			CaM	Ca

^a A = accidental; B = breeding; Ca = casual; C = common; Fc = fairly common; M = migrant; Ra = Rare; U = uncommon; V = visitant.

Sources: Gabrielson and Lincoln 1959; Isleib and Kessel 1973; Kessel and Gibson 1978; and Gibson 1982.

through November (Isleib and Kessel 1973). The limited data on wintering birds suggest that common loons and Pacific loons are more abundant than the other three species (Forsell and Gould 1981; Trapp 1982).

Of the four species of grebes found in Alaska, only the red-necked grebe (*Podiceps grisegena*) and the horned grebe (*P. auritus*) are abundant. Both species also breed in the Gulf coast and are common during the winter in coastal waters (Table 16-1). Spring migration occurs from late April through mid-May and fall migration from late August to early November (Isleib and Kessel 1973). Red-necked grebes and horned grebes are almost equally abundant in winter at Frederick Sound in southeastern Alaska (Trapp 1982) and at Valdez Arm in Prince William Sound (Sangster 1978). Farther west, however, red-necked grebes appear to be the more abundant of the two species (Forsell and Gould 1981; R.H. Day, University of Alaska, pers. comm., 1985).

Swans

Two species of swans are commonly observed along the coast of the Gulf of Alaska, the trumpeter swan (*Cygnus buccinator*) and the tundra swan (*C. columbianus*). Important breeding locations of trumpeter swans are found in freshwater habitats along the north Gulf coast from Prince William Sound to Yakutat, along the margins of Cook Inlet, and in the Susitna River Drainage (Hansen, Shepard, King, and Troyer 1971; King and Conant 1981). During the fall, trumpeter swans concentrate both at Yakutat and at the Stikine River Delta (Petersen *et al.* 1981; Heglund and Rosenberg 1985). However, on the wintering grounds, these birds are widely dispersed (King 1981; R.J. King, U.S. Fish and Wildlife Service, pers. comm., 1985). Some trumpeter swans remain in the northern Gulf of Alaska in winter (Isleib and Kessel 1973), but most migrate to wintering grounds in southeastern Alaska, British Columbia, and Washington State.

Tundra swans are abundant migrants and are casual summer breeders and winter visitors to the coastal Gulf of Alaska. It appears that most of the tundra swans migrating along the Gulf coast nest on the Alaska Peninsula (Bellrose 1976), although small numbers of birds also nest on Kodiak Island. The tundra swans' spring migration can be impressive. During the migration peak on 27 and 28 April 1971 for example, M.E. Isleib counted 500 swans per hour passing one location on the east side of Prince William Sound (Isleib and Kessel 1973). Fall migrants pass through the Copper River Delta from mid-September to early November, with the peak migration at Yakutat on 11 and 12 October in 1981 (Petersen *et al.* 1981). Most tundra swans migrating through the Gulf of Alaska winter between southern British Columbia and central California (Bellrose 1976).

Geese

Five goose species are common in coastal regions of the Gulf of Alaska (Table 16-1), but only two species breed there, the Canada goose and the white-fronted goose (*Anser albifrons*). At least four subspecies of Canada geese nest on the coast of the Gulf of Alaska:

- 1) the Vancouver Canada goose (*Branta canadensis fulva*) in southeastern Alaska (Lebeda and Ratti 1983)
- 2) the dusky Canada goose (*B.c. occidentalis*) on the north Gulf coast, primarily in the Copper River Delta (Bromley 1985)
- 3) the lesser Canada goose (*B.c. parvipes*) in the Cook Inlet region (C.J. Lensink, U.S. Fish and Wildlife Service, pers. comm., 1985)
- 4) the Aleutian Canada goose (*B.c. leucopareia*) in the Semidi Islands (Hatch and Hatch 1983).

A fifth group of birds, similar in behavior and appearance to *B.c. fulva*, is resident in Prince William Sound and may be distinct from the other subspecies of Canada geese (D.V. Derksen, U.S. Fish and Wildlife Service, pers. comm., 1985).

At least half of the known population of tule geese (*Anser albifrons gambelli*) nest on the west side of Cook Inlet (Timm, Wege, and Gilmer 1982).

Estimated populations of these geese are small:

- Vancouver Canada geese, 40,000 – 50,000 (J.G. King, U.S. Fish and Wildlife Service, pers. comm., 1985)
- dusky Canada geese, 10,000 – 15,000 (Corneley and Jarvis 1986)
- lesser Canada geese, 2,000 (Pacific Flyway Management Plan)
- Aleutian Canada geese, 60 to 85 (Hatch and Hatch 1983)
- tule geese, 5,000 (Wege 1985).

The coastal fringe of the Gulf provides important migratory habitat for these and other populations of geese. The spring migration of geese in the Gulf of Alaska occurs from early April through mid-May. Data from the Copper River Delta suggest that subspecies of Canada geese migrate in waves in spring (Hawkings 1982). In 1979, dusky Canada geese were the earliest to reach the Copper River Delta, with migration peaking in mid-April. They were followed by Taverner's geese (*B.c. taverneri*) in late April and cackling Canada geese (*B.c. minima*) in early May.

Snow geese (*Chen caerulescens*), which winter in California and nest on Wrangel Island in Siberia, are a common migrant in the Gulf of Alaska. Snow geese were present on the Stikine River Delta from early April to late May (Heglund and Rosenberg 1985). They usually bypass Yakutat and the Copper River Delta, and appear next in Cook Inlet. More than 18,000 snow geese staged on wetlands in Cook Inlet in early May 1982 (Petersen and Handel 1982).

White-fronted geese have been observed at the Stikine River (Heglund and Rosenberg 1985), Yakutat (Petersen *et al.* 1981), the Copper River Delta (Isleib and Kessel 1973; Hawkings 1982), and Cook Inlet (Petersen and Handel 1982; Handel and Gill 1983). Most of the white-fronted geese that are observed migrating in the Gulf of Alaska probably nest on the Yukon-Kuskokwim River Delta; the small numbers observed in Cook Inlet (Petersen and Handel 1982; Handel and Gill 1983) may have been locally breeding tule geese. A few brant (*Branta bernicla nigricans*) migrate past the Copper River Delta in mid-April to mid-May (Hawkings 1982) with a larger movement occurring offshore from Kayak Island (Arneson 1980).

The fall goose migration in the Gulf lasts longer than the spring migration, and several populations appear to bypass much of the coast in favor of long, direct migrations to wintering grounds. Dusky Canada geese begin leaving the Copper River Delta in early August, and most are gone by early October (Isleib and Kessel 1973; Hawkings 1982). The lack of dusky Canada geese sightings in southeastern Alaska suggests that they fly directly to their wintering grounds in Oregon. Taverner's Canada geese pass through the Copper River Delta from 15 September to early November and also appear to bypass southeastern Alaska (Heglund and Rosenberg 1985). Cackling Canada geese from the Yukon Delta stage at the base of the Alaska Peninsula (J.S. Sedinger, University of Alaska, pers. comm., 1985) and fly directly to wintering grounds in California. The same is true of brant that stage on the Alaska Peninsula (Bellrose 1976). Snow geese make heavy use of estuarine areas in the Gulf of Alaska in fall, with some birds stopping briefly at the Copper River Delta (Hawkings 1982), at Yakutat (Petersen *et al.* 1981), and at the Stikine River Delta (Heglund and Rosenberg 1985). In the Gulf, the peak fall migration for snow geese occurs from early to mid-October.

Few geese winter in the Gulf, with the exception of Vancouver Canada geese in southeastern Alaska (Ratti and Timm 1979), Vancouver-like Canada geese in Prince William Sound, and emperor geese (*Chen canagica*) in the western Gulf and Kodiak region (Forsell and Gould 1981; Gabrielson and Lincoln 1959). Canada geese occasionally winter on the Copper River Delta (Isleib and Kessel 1973) and have been recorded during winter surveys on Kodiak Island (Forsell and Gould 1981). Brant occasionally winter at Izembek Lagoon on the north side of the Alaska Peninsula and may occasionally move to the Gulf side of the peninsula during freeze-ups (D.V. Derksen, U.S. Fish and Wildlife Service, pers. comm., 1985).

The emperor goose, the only goose that commonly winters in the Gulf of Alaska, is fairly common in spring and fall in protected lagoons on the south side of the Alaska Peninsula (Dau 1984; King and Derksen 1983) and is presumed to winter there also. Forsell and Gould (1981) estimated that 1,650 emperor geese wintered on Kodiak Island in 1980. Emperor geese have occasionally been recorded both on the Copper River Delta and on Middleton Island in winter (Isleib and Kessel 1973).

Ducks

Thirty-five duck species have been recorded in the Gulf of Alaska (Table 16-1) and 22 of those species are known to breed there. Breeding populations of ducks in the coastal Gulf are locally abundant, but overall numbers pale in comparison to populations elsewhere in Alaska. The ducks migrating through the Gulf probably number in the low millions (Isleib and Kessel 1973). The spring migration for ducks occurs from late March through early June. Divers, such as goldeneyes (*Bucephala clangula*, *B. islandica*), buffleheads (*B. albeola*) and mergansers (*Mergus* spp.) are the earliest migrants, arriving in the Copper River system in late March. Northern pintails (*Anas acuta*) are the most numerous of all migrant ducks in the Gulf of Alaska and have the most protracted spring migration at the Copper River Delta,

with arrivals extending from early April to early June (Isleib and Kessel 1973). Isleib and Kessel estimate the spring flight of pintails through the Copper River Delta in the low millions. On 27 April 1971, they observed 5,500 pintails per hour passing through one part of the estuary.

The fall duck migration in the Gulf occurs from mid-August through November (Isleib and Kessel 1973). Although Bellrose (1976) suggested an over-water migration of pintail that stages on the Alaska Peninsula, the few data collected to date on duck migration suggest that most species follow coastal routes.

There have been comprehensive surveys of breeding ducks conducted at only a few sites in the Gulf of Alaska (Table 16-2). In the northern Gulf, the northern pintail is the most common breeding duck in estuarine habitats. Greater scaup (*Aythya marila*), mallard (*Anas platyrhynchos*), American widgeon (*A. americana*), and green-winged teal (*A. crecca*) are also abundant at Cook Inlet and the Copper River Delta. Breeding mallards, green-winged teal, and common mergansers (*Mergus merganser*) were common to both Yakutat (Petersen *et al.* 1981) and the Stikine River Delta (Heglund and Rosenberg 1985) in southeastern Alaska (Table 16-2). Mallards, harlequin ducks (*Histrionicus histrionicus*), Barrow's goldeneyes, and common mergansers were recorded breeding in the forested regions of Prince William Sound (Sangster, Benz, and Kurhajec 1978). On offshore islands, mallards, green-winged teal, northern pintails, gadwalls (*Anas strepera*), and common eiders (*Somateria mollissima*) have been recorded breeding (Gabrielson and Lincoln 1959; Nysewander and Barbour 1979; and Gould, Nysewander, Trapp, and Schaffer 1983).

Summer surveys in the Gulf of Alaska have revealed large numbers of non-breeding sea ducks (Arneson 1980; Hogan and Murk 1982; and Nelson and Lehnhausen 1983). More than 11,000 scoters were counted in Prince William Sound in summer, accounting for almost 50% of all ducks recorded in that season (Hogan and Murk 1982). Sangster (1978) and Hogan and Colgate (1980) found white-winged scoters (*Melanitta fusca*) and surf scoters (*M. perspicillata*) to be the dominant non-breeding ducks in summer at Valdez Arm, Prince William Sound. Large numbers of non-breeding sea ducks, primarily scoters, have been observed in lower Cook Inlet and in Kachemak and Icy Bays (Arneson 1980), and sea ducks were among the most abundant birds observed during small-boat transects in southeastern Alaska (Nelson and Lehnhausen 1983).

Large numbers of ducks also winter throughout the Gulf of Alaska, although estimates of wintering populations are available for only a few areas. An estimated 1,000,000 ducks winter in southeastern Alaska each year (Conant, King, Trapp, and Hodges, in press). More than 80,000 ducks winter in the Kodiak Island area (Forsell and Gould 1981), and another 50,000 are estimated to winter in Prince William Sound (Hogan and Murk 1982). Unfortunately, estimates of wintering populations are unavailable for other regions in the Gulf of Alaska.

The species composition of wintering ducks varies geographically in the Gulf (Table 16-3). In the Kodiak Archipelago, oldsquaws (*Clangula hyemalis*) and black scoters (*Melanitta nigra*) apparently constitute a larger percentage of

Table 16-2.
Composition of breeding waterfowl populations at four locations along the coast in the Gulf of Alaska.

SPECIES	COOK INLET ^a		COPPER RIVER ^b		YAKUTAT ^c		STIKINE ^d	
	NO. BIRDS COUNTED	PERCENT OF TOTAL	NO. BIRDS COUNTED	PERCENT OF TOTAL	NO. BIRDS COUNTED	PERCENT OF TOTAL	NO. BIRDS COUNTED	PERCENT OF TOTAL
Green-winged teal	74	17.9	2,564	13.2		present		present
Mallard	78	18.8	2,456	12.6		present		present
Northern pintail	100	24.2	6,216	31.9				
Blue-winged teal								present
Northern shoveler	55	13.3	1,337	6.9				
Gadwall	9	2.2	71	0.4				
American widgeon	20	4.8	2,501	12.8				
Canvasback			140	0.7				
Redhead	6	1.4						
Greater scaup	42	10.1	3,357	17.2				
Oldsquaw			113	0.6				
Goldeneyes	14	3.4	622	3.2		present		
Bufflehead			117	0.6		?		
Mergansers	6	1.4				present		

^a From Sellers 1979.

^b Average for the period 1974 to 1976 Alaska Department of Fish and Game data in Bucaria (1979).

^c From Petersen *et al.* 1981.

^d From Heglund and Rosenberg 1985.

Table 16-3.
Species composition of ducks wintering at five locations in the Gulf of Alaska.

Species	KODIAK ^a	PRINCE WILLIAM ^b	VALDEZ ^c	SOUTHEASTERN ^d	PORT ^e
	ISLAND	SOUND	ARM	ALASKA	FREDERICK
	PERCENT OF ESTIMATED TOTAL N = 188,800	PERCENT OF TOTAL COUNTED N = 30,960	PERCENT OF TOTAL COUNTED N = 1,476	PERCENT OF TOTAL COUNTED N = 144,690	PERCENT OF TOTAL COUNTED N = 11,065
Green-winged teal	0.2	tr ^f			0.1
Mallard	5.3	9.2	25.9	16.5	26.4
Northern pintail	0.3	0.1			0.2
Northern shoveler	tr				
Gadwall	tr				
American widgeon	0.1	tr			
Scaup	1.9	2.8	3.8	0.2	3.4
Common eider	0.2				
King eider	6.9				
Steller's eider	0.6				
Harlequin duck	5.1	9.8	6.5	8.9	5.7
Oldsquaw	34.4	2.8	5.3	4.4	1.6
Black scoter	15.9	9.7			0.2
Surf scoter	2.6	9.9	7.7		19.0
White-winged scoter	18.5	3.9	3.4		5.8
Unidentified scoter		15.7		35.4	10.4
Goldeneyes	4.6	23.2	33.1	22.1	17.9
Bufflehead	2.4	3.4	12.3	5.4	5.8
Hooded merganser					tr
Common merganser	0.3		1.9		0.7
Red-breasted merganser	0.5				0.4
Unidentified merganser		9.5		7.1	0.6

^a Kodiak Archipelago less northern Afognak Island and the Trinity Islands (from Forsell and Gould 1981).

^b From Hogan and Murk (1982).

^c Northeastern part of Prince William Sound (from Sangster 1978).

^d Northern part of southeastern Alaska from aerial surveys of Conant *et al.* (in press).

^e In northern part of southeastern Alaska (from Trapp 1982).

^f tr = trace (<0.1%).

total waterfowl than they do in other regions, whereas mallards and goldeneyes are less common in Kodiak than they are elsewhere. In contrast, the percentage of surf- and white-winged scoters was consistent among areas. King eiders (*Somateria spectabilis*) and Steller's eiders (*Polysticta stelleri*) are apparently rare east of Kodiak Island (Isleib and Kessel 1973; Arneson 1980).

Feeding Ecology. Few detailed studies of waterfowl food habits are available from the Gulf of Alaska, although sufficient information is available to allow us to make a few generalizations. Geese are known to graze on plants (Bellrose 1976), and studies of geese in the Gulf of Alaska support this view. For example, dusky Canada geese on the Copper River Delta take a variety of plant foods including the leaves and seeds of sedges (*Carex* spp.), horsetails (*Equisetum*), willows (*Salix*), and arrowgrass (*Triglochin*) (Hawkings 1982; Bromley 1985). Vancouver Canada geese in southeastern Alaska feed on American yellow-skunk cabbage (*Lysichitum americanum*) and a variety of other plants and berries (Lebeda and Ratti 1983). Emperor geese frequently feed in the intertidal zone (Petersen 1983) and are known to feed on small bivalves, notably *Mytilus* and *Macoma* (M.R. Petersen, U.S. Fish and Wildlife Service, pers. comm., 1985), and marine algae (Cottam and Knappen 1939).

The diets of dabbling ducks in coastal regions of the Gulf are poorly known, although seeds, various plants, and invertebrates are the most frequently taken foods elsewhere in North America (Bellrose 1976).

Diets of diving ducks in the Gulf of Alaska are better known, although only a few species have been studied and in only a few locations. The limited data available suggest that near-shore, benthic organisms are a critical food resource. The diet of oldsquaw wintering in Kachemak Bay was composed of a minimum of 61 species (Sanger and Jones 1984). Pacific sand lance (*Ammodytes hexapterus*), Alaska surf clam (*Spisula polynyma*), blue mussel (*Mytilus edulis*), small gastropods, and other small bivalves were the most important prey species. Observations of feeding birds and the life histories of their major prey indicated that oldsquaws fed primarily over mud and mud-sand substrates and that they took largely epibenthic or infaunal prey in Kachemak Bay. Similarly, oldsquaws on the east side of Kodiak Island ate a variety of prey (Krasnow and Sanger, in press). Prey species varied greatly depending on the date and the locality, but the most important were the gastropods *Lacuna variegata* and *Alvinia compacta*, blue mussels, Pacific little neck clams (*Protothaca staminea*), gammarid amphipods, mysids, and Pacific sand lance. Three Steller's eiders, also collected at Kodiak Island in winter, had mainly eaten the bivalve *Hiatella* sp. and sea cucumbers (*Cucumaria*) (Krasnow and Sanger, in press).

White-winged scoters that wintered in Kachemak Bay fed primarily on the blue mussel, the Pacific littleneck clam, and the puppet margarite (*Margarita pupillus*). White-winged scoters in Kachemak Bay fed most frequently over shell debris and boulder-cobble substrates (Sanger and Jones 1984).

Foods of wintering Barrow's goldeneyes were examined in southeastern Alaska (Koehl, Rothe, and Derksen 1984). Five taxa constituted the majority of food items taken:

- 1) blue mussel (*Mytilus edulis*)
- 2) discord mussel (*Musculus discors*)
- 3) the puppet margarite (*Margarita pupillus*)
- 4) a barnacle (*Balanus glandula*)
- 5) a hermit crab (*Pagurus hirsutiunculus*).

Summer diets of harlequin ducks have been studied in Prince William Sound (Dzinbal and Jarvis 1984). Stomachs of harlequin ducks in this region contained mostly small crabs and snails (*Littorina* sp.). As the summer progressed and salmon became more abundant in the streams, harlequin ducks shifted their primary foraging areas from the intertidal zones to the streams—probably to exploit drifts of salmon eggs and invertebrates. Common mergansers in Prince William Sound in summer fed primarily on sculpins (Cottidae) and shrimp (*Spirontocaris* sp.) (Fritsch and Buss 1958).

Estimated Food Consumption. The lack of population estimates of diving ducks in the Gulf of Alaska makes it difficult to determine overall food consumption by this group. Nevertheless, in order to provide a crude approximation of the importance of this group in the coastal ecology of the Gulf, we calculated food consumption for the duck population wintering along the coast in southeastern Alaska—a population estimated at one million birds (Conant *et al.*, in press). Based on the species composition of ducks wintering in southeastern Alaska as determined in that study (Table 16-3), we estimated the biomass of ducks wintering in that region at about 1,039 mt (Table 16-4). To estimate biomass of prey consumed by ducks, we assume that birds weighing between 200 and 600 g eat the equivalent of 30% of their

Table 16-4.
Estimates of biomass and prey ingestion by waterfowl in Southeastern Alaska in winter (December to March).^a

SPECIES	ESTIMATED POPULATION	ESTIMATED WEIGHT (kg) ^b	ESTIMATED BIOMASS (mt)	PREY BIOMASS EATEN (mt/d) ^c
Mallard	250,000	1.16	290.0	58.0
Northern pintail	10,000	1.01	10.1	2.0
Scaup	20,000	1.05	21.0	4.2
Scoters	380,000	1.15	437.0	87.4
Harlequin duck	30,000	0.61	18.3	3.7
Oldsquaw	20,000	0.89	17.8	3.6
Goldeneyes	230,000	0.90	207.0	41.4
Bufflehead	40,000	0.45	18.2	5.5
			Totals	209.8

^a Excluding loons and grebes. Population estimates derived from Conant *et al.* (in press).

^b Weights taken from Palmer (1976).

^c Assumed ingestion rates as a percent of body weight. For birds 0 to 200 g estimate was 40%; for birds 200 to 600 g, 30%; for birds greater than 600 g, 20%.

body weight per day and those weighing over 600 g eat 20% per day. Thus ~209.8 mt of food per day are eaten by ducks in southeastern Alaska (Table 16-4). Over a 120-day winter season, ~25,176 mt of food are consumed.

Distribution and Abundance. Water depth and food availability are probably the most important factors influencing the distribution and abundance of diving ducks in the Gulf of Alaska. Ice cover also limits waterfowl distribution, but its effects in the Gulf of Alaska are local and confined primarily to the heads of bays. The western side of Cook Inlet is an exception, however, as it frequently fills with ice in winter, forcing waterfowl to move elsewhere.

Diving ducks are restricted to a narrow coastal band in the Gulf of Alaska. Many species, such as eiders, scoters, goldeneyes, and scaup, usually feed in less than 20 m of water (Palmer 1976; Johnson 1984; and Sanger and Jones 1984), although many are probably capable of diving deeper. For example, oldsquaws have been caught in fishing gear as deep as 68 m (Ellarson 1956). The diving ability of ducks excludes them from feeding on the bottom in deep water, and may partially explain why the number of ducks wintering in Resurrection Bay, a deep-water fjord, are few compared to Kachemak Bay, which has large areas of shallow water.

Existing data do not permit a rigorous comparison of waterfowl densities from various localities in the Gulf of Alaska. Consequently, we are unable to assess the importance to waterfowl of various localities in the Gulf, despite the information now available on those regions' intertidal and benthic faunas (O'Clair and Zimmerman, Ch. 11, this volume; Feder and Jewett, Ch. 12, this volume). It seems intuitive that waterfowl will concentrate in sheltered waters where food is most abundant and available. Circumstantial evidence for this exists from at least one area, Kachemak Bay.

Densities of diving ducks in Kachemak Bay were among the highest in the coastal Gulf for all seasons, exceeding 100 birds/km² in spring and summer (Arneson 1980). Kachemak Bay is also one of the most productive regions in the Gulf of Alaska (Larrance and Chester 1979) as a result of an extended phytoplankton bloom that contributes over 60 g C/m² to the bottom during the summer. Organic material derived from macrophytes, terrestrial sources, and from the Alaska Coastal Current further increases the supply of organic detritus (Sanger and Jones 1984). The input of large amounts of material to the bottom of Kachemak Bay results in a rich benthic fauna (Lees and Driskell 1981; Feder and Jewett, Ch. 12, this volume), and a complex, detritus-based food web of which the numerous diving ducks of Kachemak Bay are a part (Sanger and Jones 1984).

Shorebirds

Three points are crucial to understanding shorebird ecology in the Gulf of Alaska. First, only a small part of the coastal fringe is suitable for nesting by many species of

shorebirds. Second, only a handful of species winter in Alaska, the remainder undertaking long migrations to wintering grounds elsewhere in Asia, the Americas, and the Pacific islands. Third, millions of migrant shorebirds depend upon widely spaced, littoral, habitat 'islands' in the Gulf of Alaska. Four sites in the Gulf coast region are particularly important:

- 1) the Stikine River Delta in southeastern Alaska (Heglund and Rosenberg 1985)
- 2) the Copper-Bering River Delta complex (Senner 1979)
- 3) the flats of Kachemak Bay (Senner 1979; Senner *et al.* 1979)
- 4) western Cook Inlet in south central Alaska (Senner 1979; Senner *et al.* 1981).

Nesting Patterns

Forty-two species of shorebirds have been identified in the Gulf of Alaska, of which fifteen species breed in coastal areas (Table 16-5). Overall breeding populations are unknown, although they are undoubtedly smaller than in other regions in Alaska, such as the Yukon-Kuskokwim River Delta (Gill and Handel 1981). Nevertheless, for species such as the semipalmated plover (*Charadrius semipalmatus*), American black oystercatcher (*Haematopus bachmani*), spotted sandpiper (*Actitis macularia*), least sandpiper (*Calidris minutilla*), and red-necked phalarope (*Phalaropus lobatus*), suitable nesting habitat is widespread and populations are abundant (Isleib and Kessel 1973).

American black oystercatchers nest exclusively on rocky shorelines of both the mainland coast and offshore islands throughout the Gulf of Alaska. Semipalmated plovers nest in sandy habitats primarily along the coastal fringe and on offshore islands, but also nest inland from the coast. Least sandpipers and red-necked phalaropes both nest in wetlands, including small freshwater marshes.

The 650 km² of wetlands of the Copper River Delta provide the single largest shorebird nesting area in the region. Least sandpipers and red-necked phalaropes are the most abundant breeding shorebirds there, but common snipe (*Gallinago gallinago*), short-billed dowitchers (*Limnodromus griseus*), semipalmated plovers, and dunlin (*Calidris alpina*) nest there as well (Murphy 1981). Petersen *et al.* (1981) found short-billed dowitchers nesting in Sitka spruce bogs, in mixed scrub-sphagnum bogs, and in sedge-marsh wetlands at Yakutat. This suggests that the species could be a more widespread breeder in the Gulf-coast region than previously believed.

Surfbirds (*Aphriza virgata*), wandering tattlers (*Heteroscelus incanus*), and rock sandpipers (*Calidris ptilocnemis*) also breed peripherally in the Gulf-coast region. The first two species nest in small numbers in the alpine zone of surrounding mountain ranges (Isleib and Kessel 1973; Kessel and Gibson 1978). Rock sandpipers nest on the Alaska Peninsula (Gill and Jorgensen 1979; Gill, Petersen, and Jorgensen 1981) and are suspected to breed on islands from the western Gulf of Alaska east to Kodiak Island (R.H. Day, University of Alaska, pers. comm., 1985).

Table 16-5.
Status and relative abundance of shorebirds in coastal regions of the Gulf of Alaska by season.

SPECIES	SEASONAL STATUS ^a			
	SPRING	SUMMER	FALL	WINTER
Black-bellied plover	CM	UV	CM	
Lesser golden plover	CM	UV	CM	
Mongolian plover	A			
Semipalmated plover	CM	CB	CM	
Killdeer	UM	UB	UM	
American black oystercatcher	R	RB	R	R
Greater yellowlegs	CM	CB	CM	
Lesser yellowlegs	CM	UB	CM	
Solitary sandpiper	UM	UB	UM	
Wandering tattler	FCM	FCB	FCM	
Grey-tailed tattler			AM	
Spotted sandpiper	CM	CB	CM	
Upland sandpiper	RaM		CaM	
Whimbrel	CM	UB	CM	
Bristle-thighed curlew	RaM			
Hudsonian godwit	FcM	UB	FcM	
Bar-tailed godwit	UM			
Marbled godwit	RaM	UV	CaM	
Ruddy turnstone	CM	UV	CM	
Black turnstone	CM	UV	CM	U
Surfbird	CM	UB	CM	U
Red knot	CM		RaM	
Sanderling	CM	CV	CM	Ra
Semipalmated sandpiper	UM	UV	UM	
Western sandpiper	CM	CV	CM	
Rufous-necked stint			RaM	
Least sandpiper	CM	CB	CM	
White-rumped sandpiper	RaM		RaM	
Baird's sandpiper	UM		UM	
Pectoral sandpiper	CM		CM	
Sharp-tailed sandpiper			UM	
Rock sandpiper	CM	UB	CM	C
Dunlin	CM	UB	CM	Ra
Stilt sandpiper			RaM	
Buff-breasted sandpiper			RaM	
Ruff	RaM			
Short-billed dowitcher	CM	CB	CM	
Long-billed dowitcher	CM		CM	
Common snipe	CM	CB	CM	Ra
Wilson's phalarope	CaM	CaV		
Red-necked phalarope	CM	CB	CM	
Red phalarope	CM	UV	CM	

^a A = accidental; B = breeding; Ca = casual; C = common; FC = fairly common; M = migrant; R = resident; Ra = rare; U = uncommon; V = visitant.

Sources: Gabrielson and Lincoln 1959; Isleib and Kessel 1973; Kessel and Gibson 1978; and Gibson 1982.

Wintering Habits

Shorebirds that winter in the Gulf of Alaska are even more poorly known than shorebird breeding populations. Of the six species that winter in the Gulf (*i.e.*, the black oystercatcher, black turnstone [*Arenaria melanocephala*], rock sandpiper, surfbird, dunlin, and sanderling), only the first three occur regularly. Most wintering shorebirds in the Gulf prefer rocky intertidal habitats for foraging, although sanderlings and dunlins are found more frequently on sand or mud (Gill and Handel 1981). American black oystercatchers are considered resident throughout much of their range (Gabrielson and Lincoln 1959; Hartwick and Blaylock 1979),

although in the northern Gulf of Alaska they disappear from breeding areas in winter (D.W. Nysewander, U.S. Fish and Wildlife Service, pers. comm., 1985).

Sanderlings, dunlins, and surfbirds include Alaska on the northern periphery of their extensive winter ranges. If the black oystercatchers are excluded, the black turnstones and rock sandpipers are probably the most abundant shorebirds wintering in the Gulf of Alaska, although many individuals of these species also migrate south along the Pacific coast of North America (Gill 1979; American Ornithologists Union 1983; and Gill, Handel, and Shelton 1983).

Migration

The Gulf of Alaska is an important region for waterbird migration because it is located between the major Arctic and subarctic breeding grounds and the temperate wintering areas. Peaks of migration at various study sites in spring were not directly comparable because of the different years of study, but most shorebirds moved through the Gulf from late April through mid-May (Petersen *et al.* 1981; Senner *et al.* 1981; and Heglund and Rosenberg 1985). The average peak migration occurred from 2 through 10 May at the Copper River Delta in 1976 to 1979, and on 6 May 1977 at Kachemak Bay in lower Cook Inlet (Senner *et al.* 1981) (Fig. 16-2).

Of the four sites, the Copper River Delta supports the greatest number of migrants, with between 10- and 12 million shorebirds using the Delta each spring (Isleib 1979; Senner *et al.* 1981). The second most important site in terms of total numbers of birds is lower Cook Inlet—Kachemak Bay and the western side of the Inlet in particular. Over 625,000 shorebirds were present in Kachemak Bay on 6 May 1977 (Senner *et al.* 1981). The total number of shorebirds passing through that system in spring was undoubtedly larger than the peak count. Petersen *et al.* (1981) considered the Yakutat area to be relatively inconsequential to shorebirds, with fewer than 10,000 birds passing through. In contrast, at the Stikine River Delta, well over 100,000 shorebirds were estimated to have migrated through during the peak of the 1982 migration (Heglund and Rosenberg 1985).

Western sandpipers (*Calidris mauri*) and dunlins were the most abundant migrants using intertidal mudflats in the Gulf of Alaska during spring migration, although the two species differed markedly in their use of individual sites. Western sandpipers were the most abundant spring migrants at the Stikine River Delta, at Yakutat, and at Kachemak Bay. Dunlins were infrequently seen at the first two sites and were outnumbered at Kachemak Bay by western sandpipers by a ratio of 42 to 1 (Senner 1979).

Western sandpipers and dunlins were both abundant at the Copper River Delta, and together constituted between 83% (Murphy 1981) and 94% (Senner 1979) of the more than 10 million shorebirds that passed through that system. The Copper River Delta was the only region in the Gulf of Alaska where dunlins were observed in large numbers. Compared to dunlins and western sandpipers, the relative migration strengths of other shorebird species are less well known.

Because spring shorebird migration is temporally compressed, the turnover rates at feeding sites in the Gulf of Alaska are high. On the Copper River Delta, dunlins and

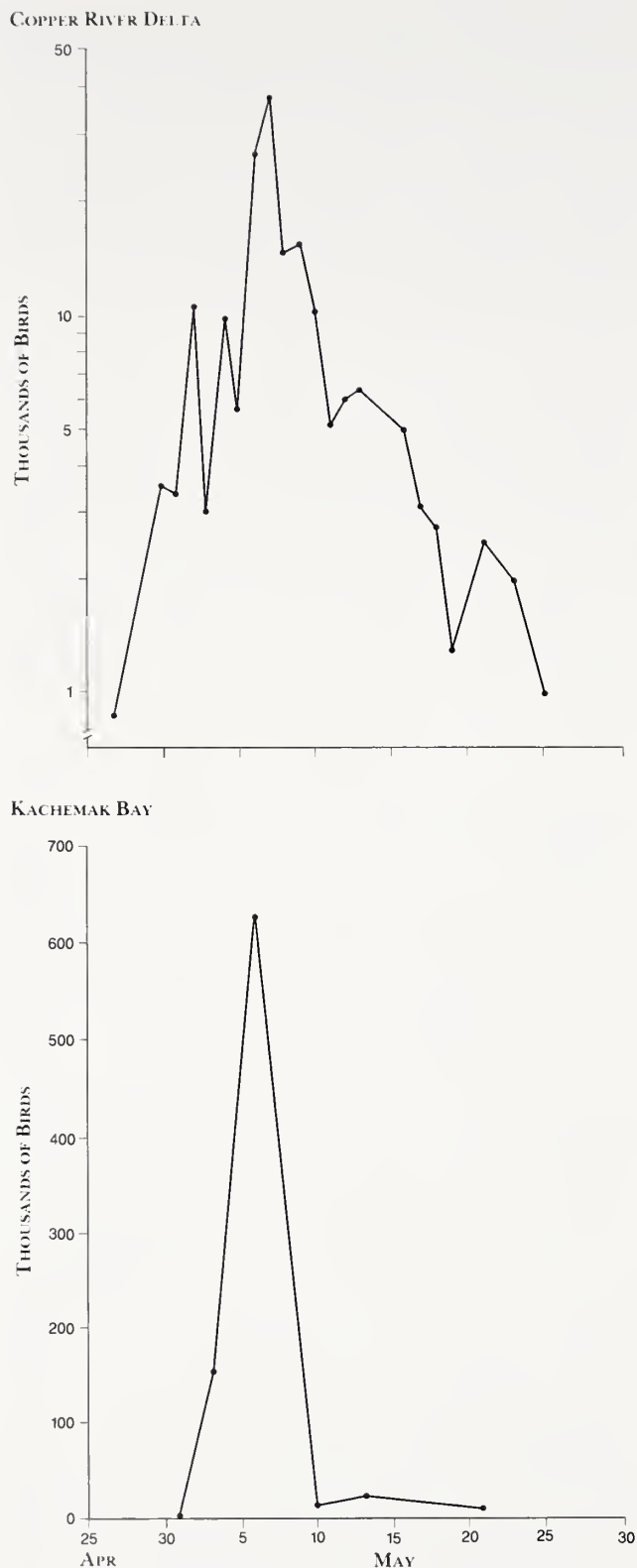


Figure 16-2. Average peak of shorebird migration at the Copper River Delta, from the period during April and May, 1976 to 1979, and peak of shorebird migration at Kachemak Bay in May 1977.

western sandpipers were estimated to stay from one to six days (Senner *et al.* 1981).

Weights of dunlin during spring migration on the Pacific coast were highest at the Fraser River Delta in southern British Columbia and lowest on the Copper River Delta. This suggests that dunlins undergo a highly synchronous over-water migration direct from southern British Columbia to the Copper River Delta (Senner 1979; Senner *et al.* 1981). The lack of large spring dunlin concentrations on the limited suitable habitat between the two locations (primarily the Stikine River Delta) lends credence to this hypothesis. Once on the Copper River Delta, dunlins feed heavily and fatten enough to make another long flight to their breeding grounds in western Alaska, thus bypassing lower Cook Inlet. A long over-water migration is also suspected for the 100,000 red knots (*Calidris canutus*) that appear on the Copper River Delta each spring (Isleib 1979).

Western sandpipers have less fat than dunlins in spring, and consequently have a lower estimated flight range. Senner (1979) suggested that some western sandpipers in southern British Columbia have enough fat to make non-stop flights to the Copper River Delta or Kachemak Bay. Evidence from the Stikine River and from Yakutat, however, indicates that for a portion of the western sandpiper population, additional stops along the way are necessary. In contrast to dunlins, western sandpipers did not show a gain in mean weight as they migrated east to west across the Copper River Delta. Predictably then, large numbers of western sandpipers—lacking sufficient fat to make long, non-stop flights—briefly stop in Kachemak Bay and western Cook Inlet to feed before proceeding to their breeding grounds in western Alaska.

The fall migration of shorebirds through the Gulf of Alaska differs markedly from the spring migration in two respects. First, the overall flight of shorebirds is less synchronous than in spring and lasts about four months (Murphy 1981). Second, at least one of the principal species of the spring migration—the dunlin—uses intertidal mudflats much less in fall than in spring.

Contrasting the fall flights of shorebirds among species in the Gulf of Alaska is difficult because of their temporal differences in migration. Some species such as the western sandpiper, the least sandpiper, and both the long-billed (*Limnodromus scolopaceus*) and the short-billed dowitchers migrate over extended periods of time. For example, in 1978, western sandpipers were present on the Copper River Delta for three months during fall migration (Murphy 1981). In contrast, ruddy turnstones (*Arenaria interpres*) were present for slightly more than one month in 1978. A lack of information on shorebird turnover rates on the Copper River Delta during the fall makes it difficult to assess the magnitude of fall flights through that area.

There is evidence that some species bypass the Gulf of Alaska almost totally in fall. This is particularly true for the red knot, which was uncommon on the Copper River Delta in fall (Isleib and Kessel 1973) and unobserved at either Yakutat or at the Stikine flats (Petersen *et al.* 1981; Heglund and Rosenberg 1985). Fall migration data for dunlin are conflicting, although the most recent data suggest that many

birds migrate to the west coast of southern British Columbia and the United States via a direct over-water flight from staging areas on the Bering Sea side of the Alaska Peninsula (Gill and Jorgensen 1979). There may also be some variation in dunlin flight patterns between years. Dunlins have been abundant on the Copper River Delta in late July and common through mid-September (Isleib and Kessel 1973). However, dunlins were not seen on the Copper River Delta in 1978 and 1979 until mid-October (Murphy 1981)—about the same time dunlins leave staging areas on both the Alaska Peninsula and on the Yukon-Kuskokwim Delta (Gill and Jorgensen 1979).

Although migratory patterns have not been elucidated for most of the species using littoral habitats in the Gulf of Alaska, it appears that overall shorebird use of these areas is less in fall as reflected by the absence of red knots and dunlins. The importance of these wetlands in fall is not diminished, however. Numerous species of waders depend upon them entirely, and, in contrast to red knots and dunlins, the waders may occur in higher numbers during fall than in spring as newly hatched birds join older birds in the south-bound migration (Murphy 1981).

Feeding Ecology

Food habit information is available for only four shorebird species in the Gulf of Alaska:

- 1) American black oystercatcher
- 2) common snipe
- 3) dunlin
- 4) western sandpiper.

American black oystercatchers feed almost entirely in intertidal habitats along the coast. Bivalves, primarily *Mytilus edulis*, limpets, small gastropods, and small crabs form the mainstay of their diet (Webster 1941; Hartwick 1976). Common snipe on the Copper River Delta feed heavily on invertebrates—primarily crane fly—and beetle larvae (Senner and Mickelson 1979). Dunlins on the Copper River Delta during spring migration feed heavily on small bivalves (*Macoma balthica*, *Mytilus edulis*) and to a lesser extent on amphipods and other invertebrates. Western sandpipers on the Copper River Delta feed to a lesser degree on bivalves and consume more dipteran larvae than dunlins (Senner 1979).

Seabirds

Seabirds dominate the avifauna on the outer coast of the Gulf of Alaska. Fifty-one species of seabirds have been identified in the Gulf and twenty-six of these species nest there (Table 16-6). We estimate that nesting populations of seabirds in the Gulf may exceed nine million individuals (Table 16-7). Many seabirds do not breed until several years of age; hence, large populations of pre-breeders are also found in nearshore and offshore waters. These already large populations of seabirds are increased still further in summer with

Table 16-6.
Status and relative abundance of seabirds in the Gulf of Alaska by seasons.

SPECIES	SEASONAL STATUS ^a			
	SPRING	SUMMER	FALL	WINTER
Short-tailed albatross		RV	RV	
Black-footed albatross	CaV	CV	CV	UV
Laysan albatross	CaV	CV	CV	UV
Northern fulmar	R	CB	R	R
Mottled petrel	V	CV	V	
Pink-footed shearwater	UV	UV	UV	
Flesh-footed shearwater	CaV	CaV	CaV	
Buller's shearwater	UV	UV	UV	
Sooty shearwater	CV	CV	CV	RV
Short-tailed shearwater	CV	CV	CV	UV
Manx shearwater		CaV		
Fork-tailed storm-petrel	R	CB	R	R
Leach's storm-petrel	CM	CB	CM	
Double-crested cormorant	R	CB	R	R
Brandt's cormorant		RaB		
Pelagic cormorant	R	CB	R	R
Red-faced cormorant	R	CB	R	R
Pomarine jaeger	CM	CM	CM	
Parasitic jaeger	CM	CB	CM	
Long-tailed jaeger	UM	UM	UM	
South polar skua	RaV	RaV	RaV	
Franklin's gull	CaV	CaV		
Common black-headed gull		CaV		
Bonaparte's gull	CM	CB	CM	
Mew gull	R	CB	R	R
Ring-billed gull	RaV	RaV	RaV	RaV
California gull		RaV		
Herring gull	R	B	R	R
Thayer's gull	UV	UV	UV	UV
Glaucous-winged gull	R	CB	R	R
Glaucous gull	UV	UV	UV	UV
Ivory gull		CaV	CaV	CaV
Black-legged kittiwake	R	CB	R	R
Red-legged kittiwake	UV	UV	UV	UV
Sabine's gull	M	UV	M	UM
Caspian tern		UV	RaV	
Arctic tern		CM	CB	CM
Aleutian tern	M	B	M	
Black tern		V	A	
Common murre	R	CB	R	R
Thick-billed murre	R	CB	R	R
Pigeon guillemot	R	CB	R	R
Marbled murrelet	R	CB	R	R
Kittlitz's murrelet	R	B	R	R
Ancient murrelet	R	CB	R	R
Cassin's auklet	C	B	C	?
Parakeet auklet	U	B	U	?
Least auklet	Ra	UB	Ra	Ra
Crested auklet	R	B	R	R
Rhinoceros auklet	R	B	R	R
Tufted puffin	R	CB	R	R
Horned puffin	R	CB	R	R

^aA = accidental; B = breeding; Ca = casual; C = common; FC = fairly common; M = migrant; R = resident; Ra = rare; U = uncommon; V = visitant.

Sources: Gabrielson and Lincoln 1959; Isleib and Kessel 1973; Kessel and Gibson 1978; and Gould *et al.* 1982.

the arrival of 11 species of migrants. These migrants, particularly the sooty- and short-tailed shearwaters (*Puffinus griseus* and *P. tenuirostris*), number in the millions.

Table 16-7.
Estimated populations of seabirds breeding in the Gulf of Alaska.^a

SPECIES	TOTAL NUMBER OF BIRDS	COLONY SIZE		NUMBER OF KNOWN SITES
		MINIMUM	MAXIMUM	
Northern fulmar	441,000	40	90,000	11
Fork-tailed storm-petrel	1,000,000	300	200,000	38
Leach's storm-petrel	1,200,000	100	575,700	31
Unidentified cormorant	22,000	2	6,000	90
Double-crested cormorant	3,500	2	770	55
Brandt's cormorant	80	40	46	2
Pelagic cormorant	18,000	2	4,682	197
Red-faced cormorant	30,000	2	5,000	127
Mew gull	20,000	2	3,800	69
Herring gull	1,000	2	200	13
Glaucous-winged gull	200,000	2	11,000	465
Glaucous-winged × herring gull	5,000	2	2,050	17
Black-legged kittiwake	700,000	4	150,494	177
Arctic tern	22,000 ¹	2	2,000	106
Aleutian tern	16,000	10	3,000	22
Unidentified murre	1,300,000	300	441,000	19
Common murre	450,000	8	195,555	65
Thick-billed murre	50,000	2	24,444	27
Pigeon guillemot	54,000	2	3,000	338
Marbled murrelet	?	2	?	?
Kittlitz's murrelet	?	2	?	?
Ancient murrelet	200,000	2	60,000	27
Cassin's auklet	400,000	50	100,000	24
Parakeet auklet	100,000	2	15,000	81
Least auklet	100	20	20	2
Crested auklet	400,000	20	300,000	7
Rhinoceros auklet	120,000	2	108,000	13
Tufted puffin	1,500,000	2	100,000	382
Horned puffin	1,000,000	2	250,000	304

^a Coastal colonies only.

Nesting Patterns

The overall densities of nesting seabirds in the Gulf of Alaska are depicted in Figure 16-3. Although nesting seabirds are found throughout the Gulf, the largest numbers of both birds and colonies are found west of Kodiak Island. The presence of a few large, diverse seabird colonies in the northern Gulf and in southeastern Alaska, however, suggests that favorable food resources are at least locally abundant elsewhere. Thus, other factors may be limiting the distribution of nesting seabirds.

The northeastern Gulf of Alaska is conspicuous in its paucity of breeding seabirds. This is easily explained by the lack of suitable offshore nesting habitat. Relatively few seabird species nest at colonies in Cook Inlet or near the Copper River Delta. The turbid waters of these major estuarine systems may limit prey abundance and diversity. Gulls, which feed on a variety of prey, are the most common seabirds in these areas. Seabird diversity and abundance are also low in the inland waterways of southeastern Alaska. Lack of suitable nesting habitat and easy access for mammalian predators are important limiting factors in this region.

Most seabirds nesting in southeastern Alaska are concentrated along the outer coast, and, with the exception of St. Lazaria Island and the Forrester Island complex, most colonies are small. Numerous islands on the outer coast of southeastern Alaska are unused because of the lack of suitable cliffs and grassy slopes that are used by many species for nesting. The presence of small rodents and other predators on these islands may also limit the distribution of seabird breeding colonies.

Several studies have documented the deleterious effects of river otters (*Lutra canadensis*), bears, foxes, and rodents on seabirds (Verbeek and Morgan 1978; Jones and Byrd 1979; Sealy 1982; Quinlan 1983; and Bailey and Faust 1984). The introduction of both red and Arctic foxes (*Vulpes fulva* and *Alopex lagopus*) on Gulf of Alaska islands in the late 1800s and early 1900s reduced or eliminated nesting seabirds, particu-

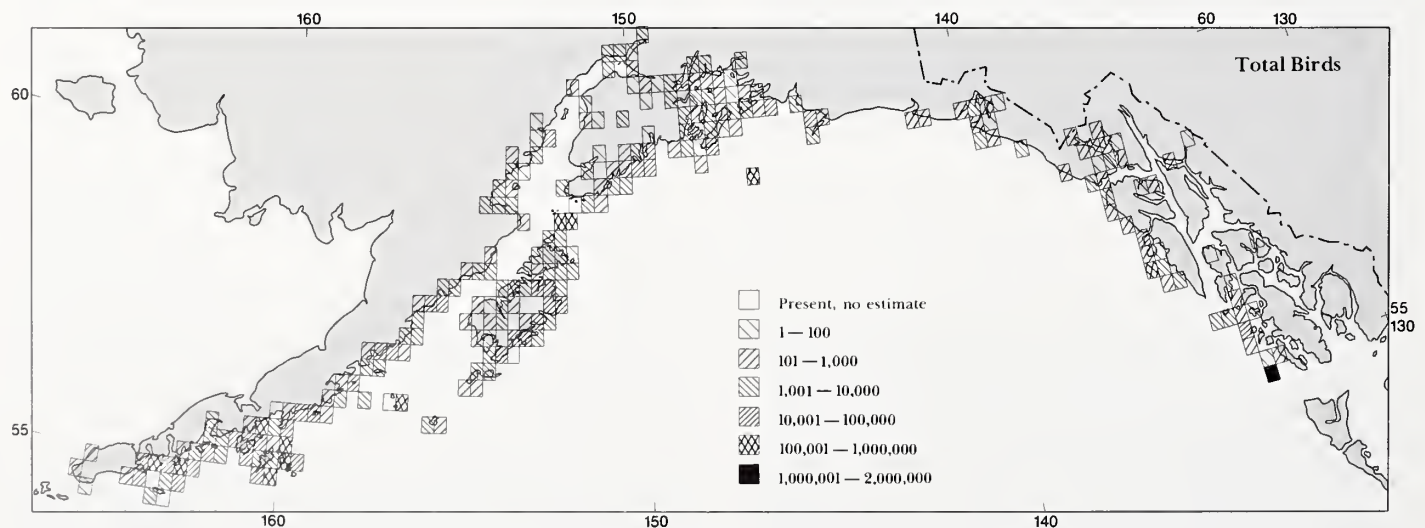


Figure 16-3. Overall breeding densities for seabirds in the Gulf of Alaska. Rectangles on this and Figures 16-5 to 16-24 represent USGS 1:63,360 quadrangle maps.

larly on islands south of the Alaska Peninsula. Foxes persist on numerous islands today.

Along with foxes, trappers introduced voles (*Microtus* spp.) and Arctic ground squirrels (*Citellus parryi*) as sources of food for foxes. Where foxes have disappeared, rodent populations have exploded, and have partially destroyed the habitat for burrow-nesting seabirds on at least 24 islands south of the Alaska Peninsula (E.P. Bailey, U.S. Fish and Wildlife Service, pers. comm., 1985). Feral cattle on four islands in the Gulf have altered considerable amounts of natural habitat that presumably was used in the past by nesting waterbirds.

Brown bears (*Ursus arctos*) are an important predator of burrow and surface nesting seabirds on islands adjacent to the Alaska Peninsula (Bailey and Faust 1984). They have been observed on islands that contain seabird colonies as far as 13 km from the mainland (Wehle 1978).

Breeding Distribution and Reproductive Biology

Seabirds in the Gulf of Alaska sometimes vary widely in their breeding distributions, nesting habitat, nesting phenology, clutch size, and reproductive success. Breeding population and colony estimates, data on the timing of egg laying, the length of incubation and nestling periods, and reproductive success are summarized in Tables 16-7, 16-8, 16-9, and 16-10, respectively. Summaries of seabird breeding distributions in the Gulf of Alaska, their nesting phe-

Table 16-8.
Summary of timing of egg-laying for 21 seabird species breeding in the Gulf of Alaska.^a

	DATE OF FIRST EGG			PERIOD OF EGG-LAYING ^b		
	MONTH			N ^a	DAYS	SD
	N ^a	-DAY	SD(d)			
Northern fulmar	7	5-30	2.9	7	25	5.1
Fork-tailed storm-petrel	8	5-4	11.4	8	34	8.0
Leach's storm-petrel	5	5-27	20.3	—	—	—
Double-crested cormorant	4	6-9	18.9	2	19	3.5
Pelagic cormorant	9	5-29	4.5	8	26	8.3
Red-faced cormorant	8	5-27	10.8	5	22	4.3
Mew gull	3	5-17	7.6	3	23	2.1
Glaucous-winged gull	22	5-29	6.0	14	28	8.2
Black-legged kittiwake	22	6-6	11.5	19	25	9.7
Arctic tern	7	5-22	5.9	3	30	5.3
Aleutian tern	4	5-28	3.7	4	29	6.1
Common murre	16	6-17	12.6	12	32	8.8
Thick-billed murre	5	6-6	5.6	5	27	5.2
Pigeon guillemot	2	5-25	5.0	2	33	7.8
Ancient murrelet	2	5-3	35.4	2	31	21.2
Cassin's auklet	3	4-24	13.1	3	53	15.7
Parakeet auklet	3	5-17	9.5	3	31	12.1
Crested auklet	1	6-6	—	1	20	—
Rhinoceros auklet	5	5-10	12.9	5	34	6.0
Tufted puffin	17	5-25	5.1	13	28	6.8
Horned puffin	14	6-12	4.1	13	22	5.9

^a Sample size (N) is the number of colony years on which estimate is based.

^b Mean range (in days) of a colony-year.

nology, and breeding distributions for select species are included in Figures 16-3, 16-4, and 16-5 through 16-24.

Fulmars and storm-petrels. Three members of the order Procellariiformes breed in Alaska: the northern fulmar (*Fulmarus glacialis*), the fork-tailed storm-petrel (*Oceanodroma furcata*), and the Leach's storm-petrel (*O. leucorhoa*).

Northern fulmars breed in both the North Atlantic and North Pacific Oceans. They occur in both light and dark color phases, with the latter predominating in the Gulf of Alaska. The northern fulmar is a cliff-nesting bird throughout its range. Little overlap in nesting habitat occurs between fulmars and other cliff nesters such as murres and

Table 16-9.
Mean incubation and nestling periods (days) used in calculating laying, hatching, and fledging dates.

SPECIES	INCUBATION PERIOD ^a	NESTLING PERIOD	REFERENCES
Northern fulmar	48 (46-51)	53 (49-58)	Hatch 1979
Fork-tailed storm-petrel	50 (37-68)	60 (51-65)	Boersma and Wheelwright 1979; Quinlan 1979
Leach's storm-petrel	42 —	66 (63-70)	Palmer 1962; Quinlan 1979
Double-crested cormorant	28 (25-29)	50 (40-50)	van Tets 1959; Palmer 1962
Pelagic cormorant	31 (28-32)	49 (42-58)	Drent, van Tets, Tompa, and Vermeer 1964
Red-faced cormorant	33 —	50 —	Baird and Gould 1985
Mew gull	26 (?)	35 (?)	Barth 1955
Glaucous-winged gull	27 (26-29)	40 (40-45)	Drent <i>et al.</i> 1964
Black-legged kittiwake	27 (25-31)	42 (36-53)	Coulson and White 1958; Maunder and Threlfall 1972
Arctic tern	21 —	28 (25-31)	Baird and Gould 1985
Aleutian tern	22	28 (25-31)	Baird and Gould 1985
Common murre	33 (32-34)	23 (16-30)	Tuck 1960
Thick-billed murre	33 (32-34)	23 (16-30)	Tuck 1960
Pigeon guillemot	30 (28-32)	35 (29-39)	Drent <i>et al.</i> 1964
Ancient murrelet	35 (33-47)	2 (2-4)	Sealy 1976
Cassin's auklet	38 (37-42)	41 (35-46)	Manuwal 1974c
Parakeet auklet	35 (35-36)	35 (34-37)	Sealy and Bedard 1973
Crested auklet	37 (?)	34 (?)	Sealy 1968
Rhinoceros auklet	46 (42-49)	52 (42-62)	Leschner 1976
Tufted puffin	40 (38-43)	40 (37-46)	Wehle 1980
Horned puffin	46 (43-53)	46 (43-48)	Sealy 1973; Baird and Gould 1985

^a Values expressed as means (ranges).

Table 16-10.
Productivity of seabirds in the Gulf of Alaska.^a

SPECIES		FLEDGLINGS/ NEST ATTEMPT	FLEDGLINGS/ NEST WITH EGGS	NEST WITH EGGS/ NEST ATTEMPT	CLUTCH SIZE	HATCHING SUCCESS	FLEDGLING SUCCESS
Northern fulmar	\bar{x}	0.45	0.49	0.85	1	0.63	0.81
	Range	0.12-0.63	0.15-0.72	0.80-0.87		0.23-0.79	0.66-0.91
	N ^b	5	7	5		5	5
	n ^b	2,086	1,761	1,913		1,778	1,196
Fork-tailed storm- petrel	\bar{x}	0.30	0.42	0.69	1	0.62	0.67
	Range	0.21-0.40	0.24-0.68	0.68-0.69		0.35-0.84	0.52-0.94
	N	2	6	2		6	6
	n	255	519	367		519	319
Double-crested cormorant	\bar{x}	0.77	1.31	0.81	3.17	0.49	0.93
	Range		0.95-1.67		2.67-3.67		
	N	1	2	1	2	1	1
	n	26	36	26		55	27
Pelagic cormorant	\bar{x}	0.83	1.14	0.94	3.08	0.54	0.75
	Range	0.00-1.96	0.14-2.05	0.75-0.96	2.17-3.64	0.29-0.68	0.47-0.93
	N	17	9	7	11	6	6
	n	1,052	274	191		795	421
Red-faced cormorant	\bar{x}	0.86	1.24	0.97	2.60	0.36	0.86
	Range	0.00-2.33	0.32-2.33	0.90-1.00	2.12-3.08	0.24-0.48	0.81-0.90
	N	11	5	4	2	2	2
	n	690	304	272		219	89
Glaucous- winged gull	\bar{x}		1.08		2.46	0.69	0.61
	Range		0.16-1.58		1.98-2.93	0.35-0.86	0.18-0.89
	N		11		22	13	11
	n		761		1,628	2,283	1,331
Mew gull	\bar{x}		0.83		2.69	0.82	0.38
	Range	0.70-0.97		2.51-2.88	0.72-0.87	0.33-0.42	
	N		3		3	3	3
	n		104		104	276	228
Black-legged kittiwake	\bar{x}	0.33	0.41	0.71	1.63	0.49	0.50
	Range	0.00-1.23	0.00-1.45	0.02-0.91	1.26-1.98	0.00-0.85	0.06-0.90
	N	39	26	20	29	18	16
	n	15,305	2,859	3,458		2,840	1,568
Arctic tern	\bar{x}				2.06	0.68	0.77
	Range				1.79-2.29	0.32-0.91	
	N				8	7	1
	n				417	861	17
Aleutian tern	\bar{x}				1.66	0.53	
	Range				1.35-1.89	0.16-0.65	
	N				4	4	
	n				215	373	
Common murre	\bar{x}	0.32	0.50	0.78	1	0.50	0.73
	Range	0.07-0.47	0.29-0.64	0.71-0.87		0.15-0.70	0.54-0.86
	N	5	4	4		7	4
	n	386	273	356		894	187
Thick-billed murre	\bar{x}	0.38	0.50	0.74	1	0.61	0.77
	Range	0.24-0.52	0.43-0.63	0.56-0.82		0.54-0.97	0.68-0.85
	N	4	4	4		4	4
	n	425	330	425		351	221
Tufted puffin	\bar{x}		0.78 ^c	0.64	1	0.86	0.75
	Range		0.76-0.80	0.44-0.90		0.85-0.88	0.46-0.91
	N		2	9		3	11
	n		71	801		99	340
Horned puffin	\bar{x}		0.60		1	0.79	0.74
	Range		0.29-0.77			0.64-0.93	0.36-0.91
	N		8			10	9
	n		361			375	243

^a Sources: Snarski (1971); Baird and Gould (1985); Hatch (1985); Gould *et al.* (1983); Nysewander and Irons (U.S. Fish and Wildlife Service, pers. comm., 1985); G. Mulberg (U.S. Fish and Wildlife Service, pers. comm., 1984).

^b Sample sizes are number of colony years (N) and total nests, eggs, or chicks (n) on which estimate is based.

^c Hatching success (0.86) × fledging success (0.75) = 0.65, probably a better estimate of breeding success for tufted puffins.

kittiwakes because fulmars prefer the higher, more vegetated portions of the cliffs (Hatch and Hatch 1983; Squibb and Hunt 1983).

Approximately two million northern fulmars breed in Alaska, of which 96% occur at four sites: the Pribilof Islands, the St. Matthew Island complex, Chagulak Island in the Aleutian Islands, and the Semidi Islands in the Gulf of Alaska. An estimated 440,000 fulmars nest in the Gulf of Alaska at 11 sites, but with the exception of the Semidi Islands, the colonies are of little significance (Fig. 16-5).

Nesting by fulmars in Alaska has been studied on the Semidi Islands (Hatch 1979, 1983, and 1985) and the Pribilof

Islands (Hunt, Eppley, and Drury 1981). The nesting season is long. Northern fulmars at the Semidi Islands usually arrive at their colonies in March or early April and most chicks depart sometime in September or early October (Fig. 16-4). On average, about 85% of the pairs that attend nesting sites lay eggs and about 50% of the pairs that lay eggs successfully produce a fledged chick (Table 16-10). With the exception of 1976, reproductive success—defined as the number of chicks fledged per nest with eggs—was generally high for fulmars on the Semidi Islands. Hatch (1985) suggests that food availability is the primary factor affecting reproductive success.



Figure 16-4. Nesting phenologies of seabirds in the Gulf of Alaska. Thin horizontal lines indicate the extreme dates on which each event occurred and bars indicate the mean first and last dates of occurrence. Sample sizes (colony-years) are as in Table 16-8. Frequently, only one or two of the three distributions were observed per species. In those instances, the timing of the other events was calculated using the mean incubation and fledging periods given in Table 16-9.

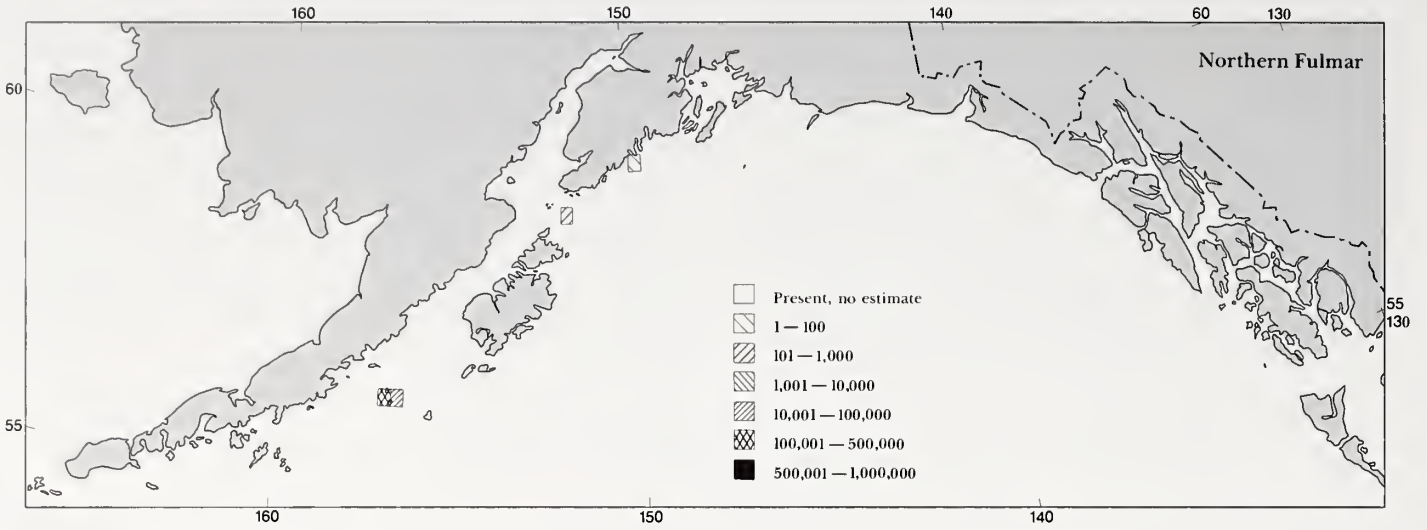


Figure 16-5. Northern fulmar breeding densities for the Gulf of Alaska.

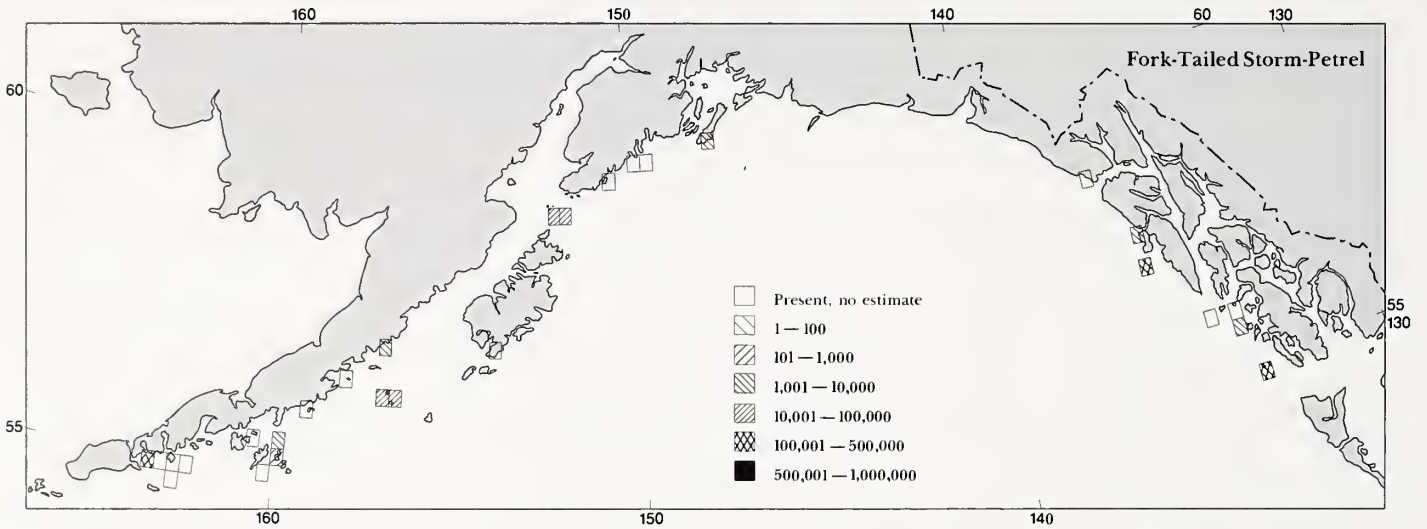


Figure 16-6. Fork-tailed storm-petrel breeding densities for the Gulf of Alaska.

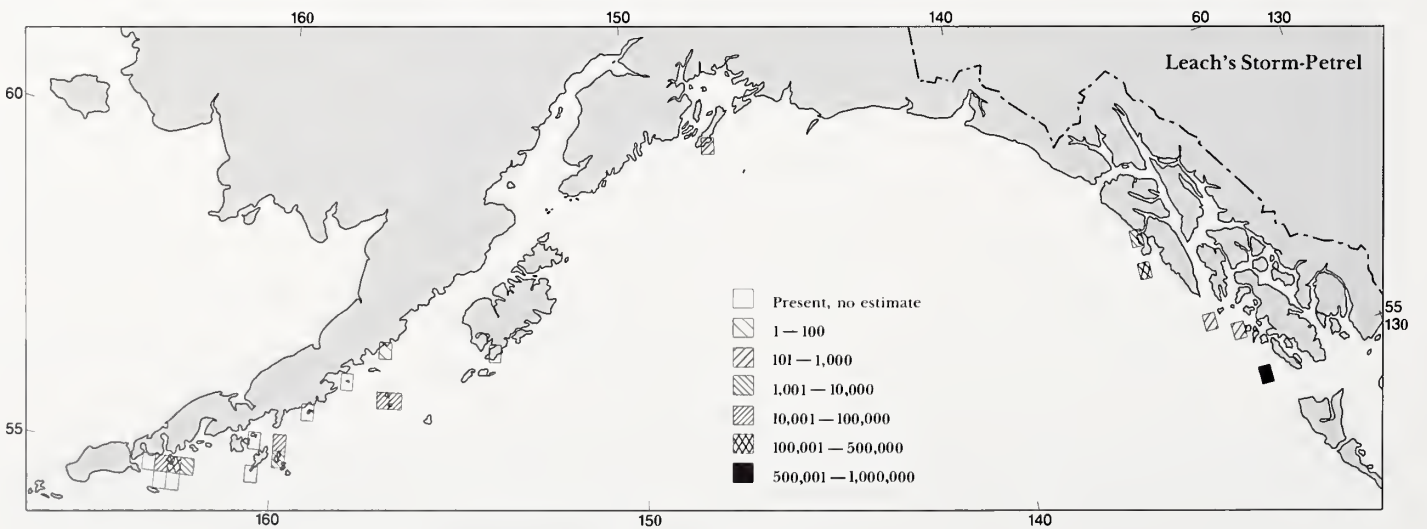


Figure 16-7. Leach's storm-petrel breeding densities for the Gulf of Alaska.

Storm-petrels are small, abundant oceanic birds. Fork-tailed storm-petrels are restricted to the North Pacific, and Leach's storm-petrels are found on both sides of the North Atlantic and North Pacific Oceans. In Alaska, the breeding distributions of both species extend from Petrel Island at the tip of southeastern Alaska to the westernmost Aleutian Islands (Figs. 16-6, 16-7). The breeding populations of fork-tailed storm-petrels and Leach's storm-petrels are estimated at one million and 1.2 million birds, respectively. The nocturnal habits of storm-petrels and their preferences for nesting in isolated areas have discouraged censusing efforts, so population data are often either crude or lacking.

Both fork-tailed and Leach's storm-petrels commonly nest in burrows dug in the soil on both forested and treeless islands. Fork-tailed storm-petrels also frequently nest in crevices in rocky habitats. The breeding season for storm-petrels is the longest of all Alaskan seabirds (Fig. 16-4). Fork-tailed storm-petrels commence egg laying as early as late April in the Gulf of Alaska. Leach's storm-petrels, on average, breed about 20 days later than fork-tailed storm-petrels, and the nestling period may extend into November at some colonies. Incubation periods and nestling periods are long for both species (Table 16-9), and interrupted incubation is common at least for fork-tailed storm-petrels (Boersma, Wheelwright, Nerini, and Wheelwright 1980).

Boersma and Wheelwright (1979) found that hatched eggs on the Barren Islands were neglected an average of 11 days each in 1977. Interrupted incubation probably occurs in many Procellariiformes (Boersma 1982). At colonies in the Gulf of Alaska, ~69% of the active fork-tailed storm-petrel burrows contained eggs. Hatching success averaged 62%, and about 42% of the pairs producing eggs fledged a chick (Table 16-10). Similar data on the reproductive performance of Leach's storm-petrels are unavailable.

Cormorants. Four species of cormorants occur in Alaska, of which three species, the double-crested (*Phalacrocorax auritus*), pelagic (*P. pelagicus*), and red-faced

cormorants (*P. urile*), are common in the Gulf of Alaska. The fourth species, Brandt's cormorant (*P. penicillatus*), is uncommon but is possibly increasing its range in southeastern Alaska (U.S. Fish and Wildlife Service, unpubl. data). Double-crested cormorants are widespread throughout much of North America, but the other three species are restricted to the North Pacific basin. The red-faced cormorant is endemic to the subarctic North Pacific and Bering Sea (American Ornithologists' Union 1983).

In the Gulf of Alaska, double-crested and pelagic cormorants are widespread (Figs. 16-8, 16-9), but red-faced cormorants nest exclusively west of Cape St. Elias (Fig. 16-10). A small population of Brandt's cormorants nested in Prince William Sound in 1972 (Isleib and Kessel 1973), but they are now known to occur only at two sites in southeastern Alaska. The size of various breeding populations is only crudely known. Most cormorants were not identified to species during censuses, hence population estimates must be considered minimal and their distributions, as depicted here, incomplete.

Double-crested cormorants place their nests on flat islets, on wide cliff ledges, on gradual slopes of islands, and in trees. In contrast, the pelagic and red-faced cormorants nest almost exclusively on narrow cliff ledges (Sowls *et al.* 1978). On average, the nesting season of cormorants in the Gulf of Alaska extends from the end of May to mid- to late-September (Fig. 16-4). Cormorants lay multi-egg clutches, with double-crested and pelagic cormorants averaging slightly greater than three eggs per nest, compared with ~2.6 eggs per nest for red-faced cormorants (Table 16-10).

Reproductive success was highly variable for all species, averaging slightly more than one chick per nest (Table 16-10). Hatching success was uniformly low for all these species, indicating that most mortality occurred during incubation. Egg predation by glaucous-winged gulls (*Larus glaucescens*), bald eagles (*Haliaeetus leucocephalus*), common ravens (*Corvus corax*) or northwestern crows (*Corvus caurimus*) was important at most study sites.

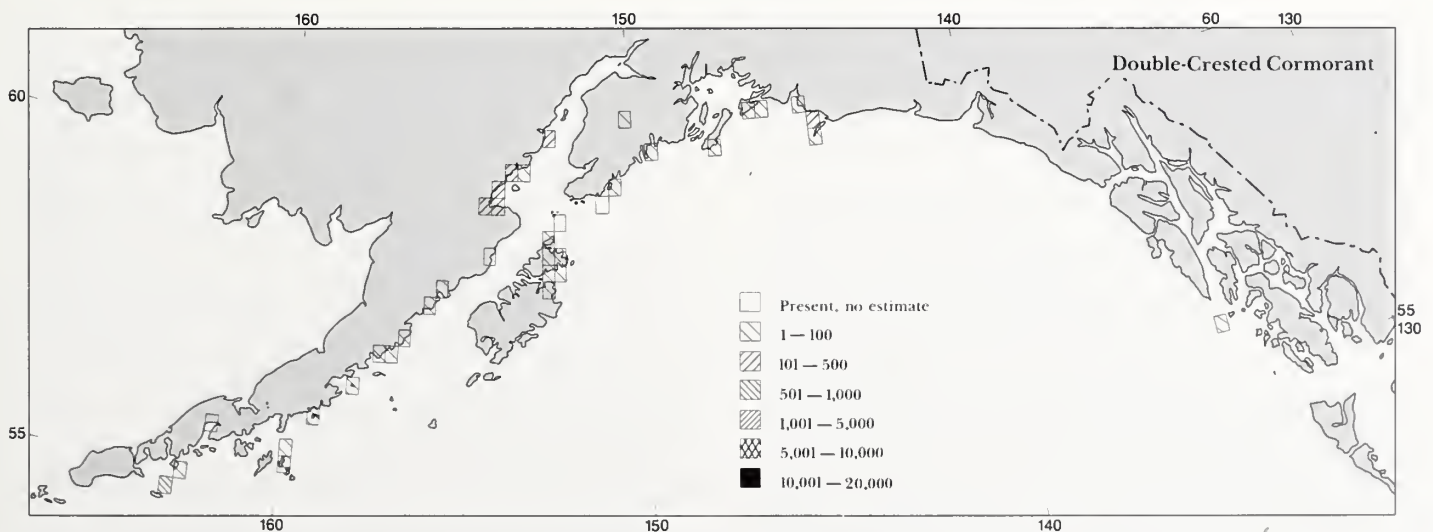


Figure 16-8. Double-crested cormorant breeding densities for the Gulf of Alaska.

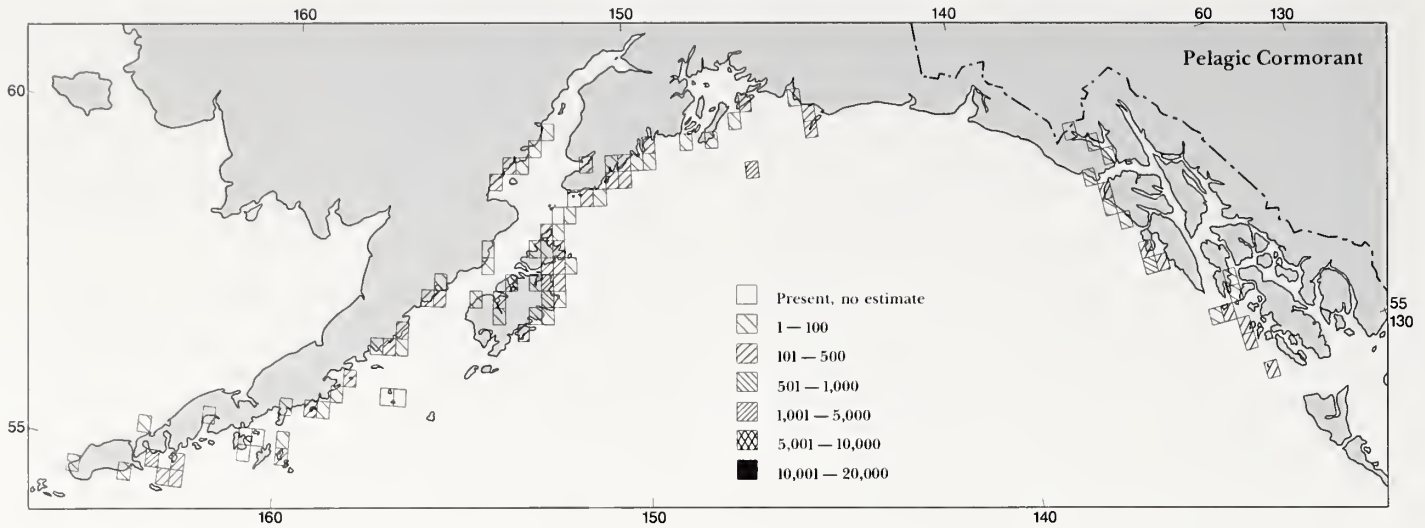


Figure 16-9. Pelagic cormorant breeding densities for the Gulf of Alaska.

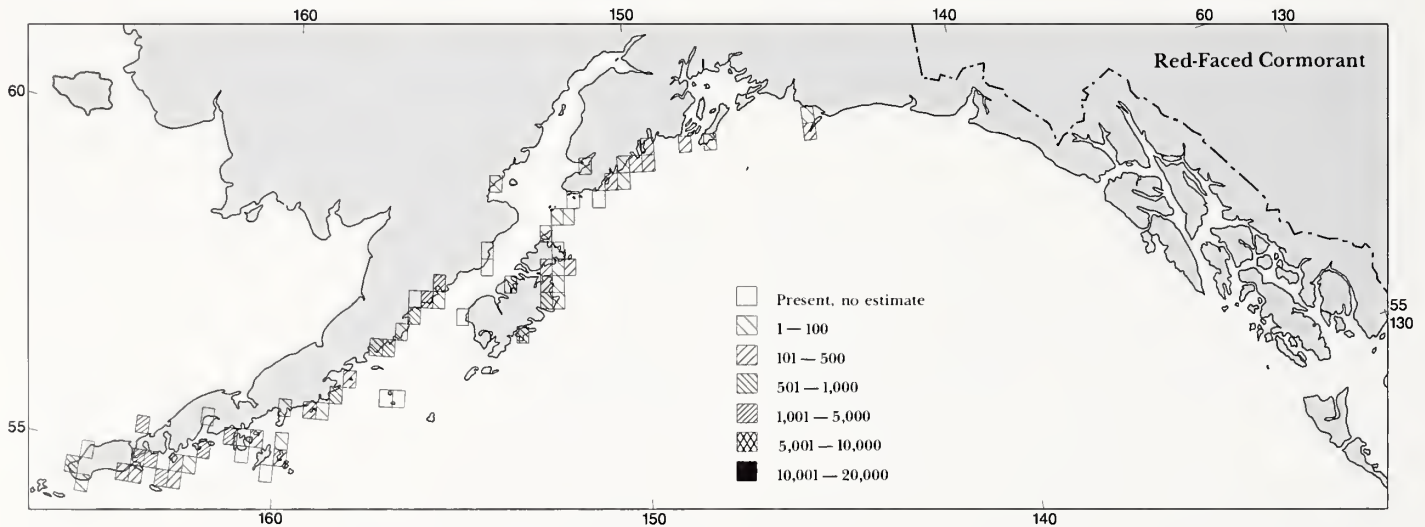


Figure 16-10. Red-faced cormorant breeding densities for the Gulf of Alaska.

Gulls. Gulls are probably the most familiar of seabirds to people along the Gulf coast of Alaska. Four species breed in the Gulf of Alaska:

- 1) mew gull (*Larus canus*)
- 2) herring gull (*L. argentatus*)
- 3) glaucous-winged gull (*L. glaucescens*)
- 4) black-legged kittiwake (*Rissa tridactyla*).

All four species are widely distributed. The mew gull is found across Eurasia and northwestern North America. The herring gull is circumpolar. The glaucous-winged gull occurs from Washington State to Nunivak Island, and west to the Commander Islands (Sowls *et al.* 1978), and the black-legged kittiwake is found in both the North Atlantic and North Pacific Oceans.

Mew gulls are much less abundant than glaucous-winged gulls in the Gulf of Alaska, but are nevertheless widespread (Fig. 16-11)—occurring at 69 nesting sites (Table 16-7). They

nest in a variety of habitats, including moist maritime meadows, crowberry tundra, sandy beaches, the grassy tops of islands, and in trees (Baird and Gould 1985). In Anchorage, mew gulls have been found nesting on fill sites, on truck trailers, and on industrial debris (C.I. Adamson, Anchorage, AK, pers. comm., 1984). Mew gulls usually lay two to three eggs per nest. Hatching success was relatively high, but fledging success was low (Table 16-10). Overall reproductive success averaged 0.83 fledglings per nest with eggs. Baird and Gould (1985) list starvation, exposure, predation, and eggging as the principal factors affecting reproductive success.

Breeding herring gulls are uncommon in the Gulf of Alaska. They frequently hybridize with glaucous-winged gulls in the northern Gulf (Patten 1980).

Colonies of glaucous-winged gulls vary in size from two birds to 11,000 birds. More than 460 colonies have been located in the Gulf of Alaska, and the breeding population probably exceeds 200,000 individuals. The majority of the

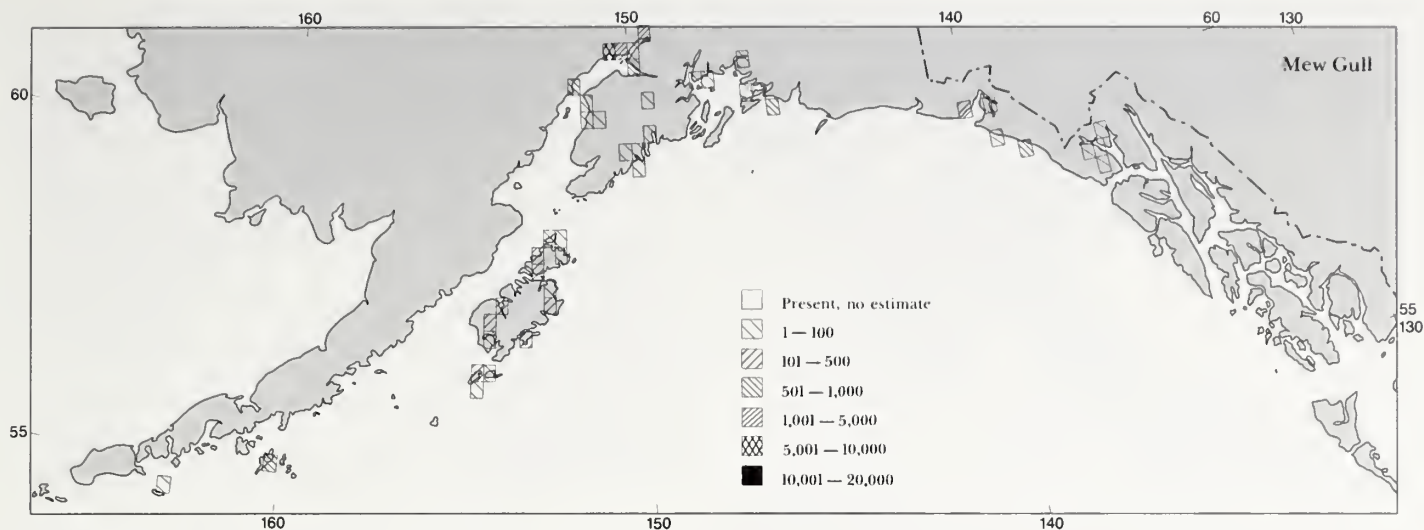


Figure 16-11. Mew gull breeding densities for the Gulf of Alaska.

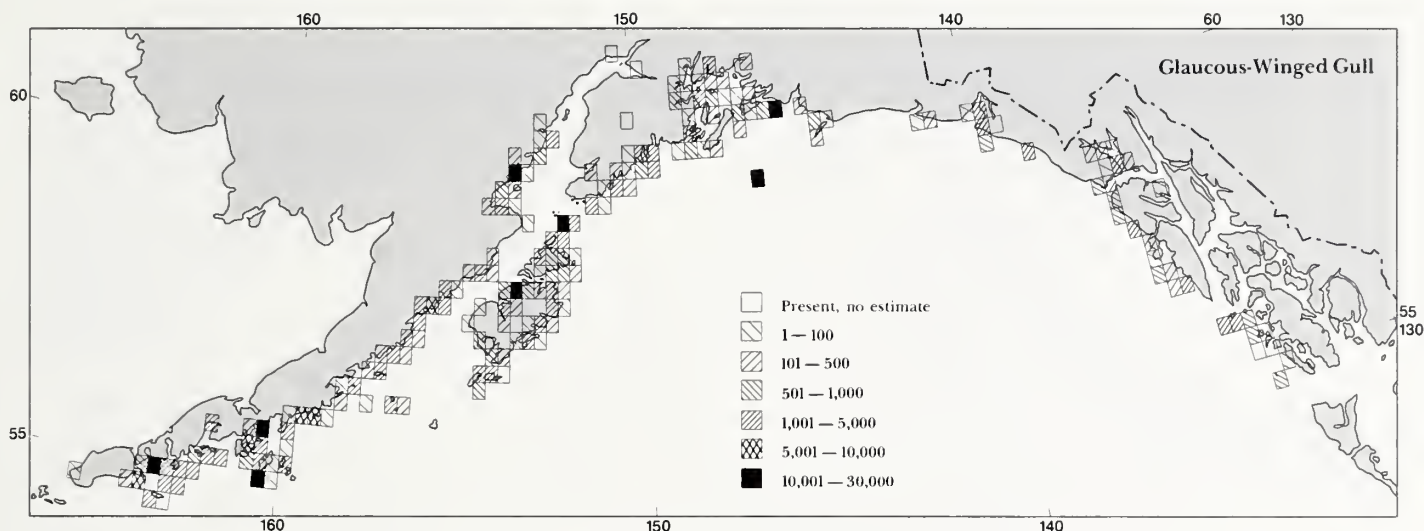


Figure 16-12. Glaucous-winged gull breeding densities for the Gulf of Alaska.

colonies are located west of Cape St. Elias (Fig. 16-12). Nests are almost always situated on offshore rocks or islands, and nests are placed on sandbars, along beaches, on the flat tops and gentle slopes of islands, and occasionally on cliffs. Overall reproductive success for gulls is difficult to determine because the cryptically colored chicks leave the nest shortly after hatching and are difficult to find.

Our best estimates indicate that about one chick is fledged per nest with eggs, which is similar to the productivity of the species in British Columbia (Vermeer 1963). The availability of food during the incubation period, predation by other birds and river otters, and egging by humans were important factors affecting reproductive success of glaucous-winged gulls in the Gulf of Alaska (Baird and Gould 1985).

Black-legged kittiwake colonies occur at 177 sites in the Gulf of Alaska, mostly west of Cape St. Elias (Fig. 16-13). The estimated population of breeding birds exceeds 700,000 individuals (Table 16-7). Although long-term population

data are not available for most sites in the Gulf of Alaska, at Middleton Island, breeding populations have increased from ~14,000 birds in 1956 to ~144,000 birds in 1974 (Baird and Gould 1985). Increases have also occurred at Chiniak Bay on Kodiak Island.

Black-legged kittiwakes most commonly nest on the narrow ledges of steep cliffs. On Middleton Island, black-legged kittiwakes colonized steep, soil-covered slopes after the entire island was uplifted during the Great Alaskan Earthquake of 1964. Kittiwakes also nested on an old shipwreck and on boulders protruding from a meadow on Middleton Island.

Kittiwakes first arrive at their colonies in March and the peak of egg laying occurs from early June to early July (Baird and Gould 1985). Very early nesting on Middleton Island in 1978 was responsible for a wider range of egg dates than for any other seabird (Fig. 16-4). About 71% of the kittiwake pairs that built nests laid eggs. The average clutch size for 3,328 nests was 1.63 eggs per clutch, but hatching success was

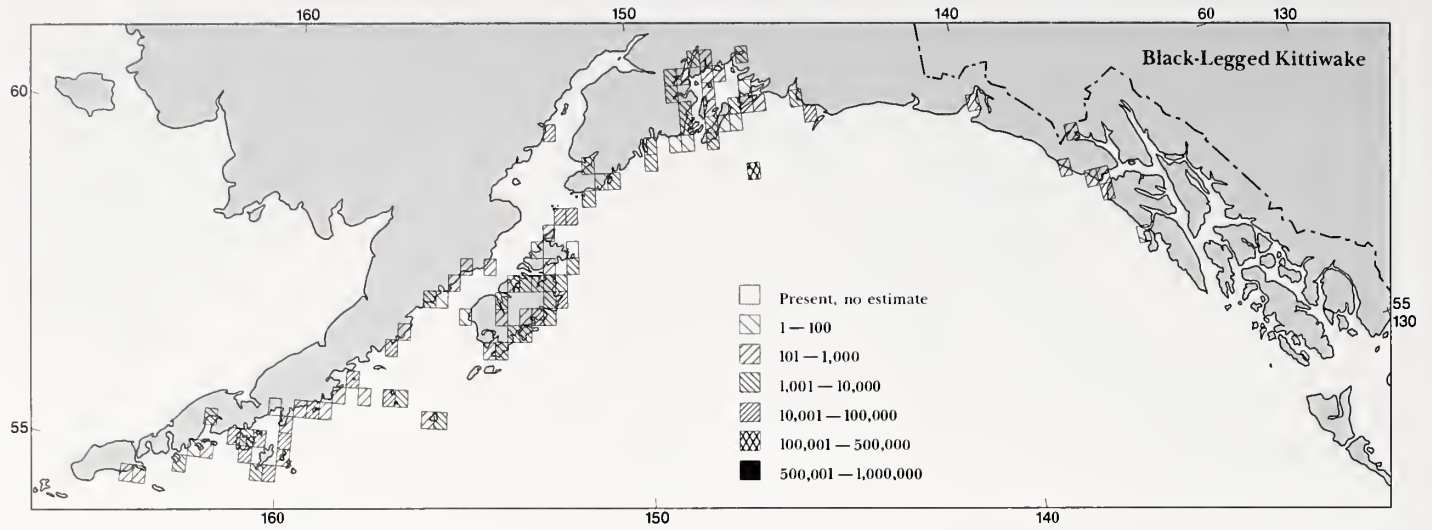


Figure 16-13. Black-legged kittiwake breeding densities for the Gulf of Alaska.

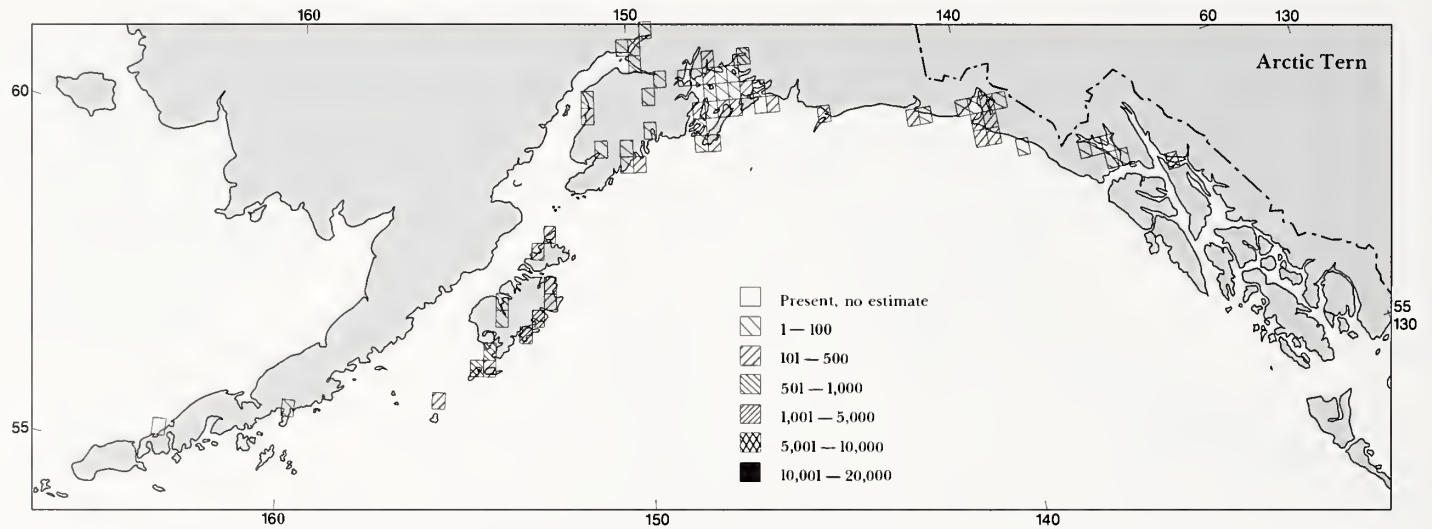


Figure 16-14. Arctic tern breeding densities for the Gulf of Alaska.

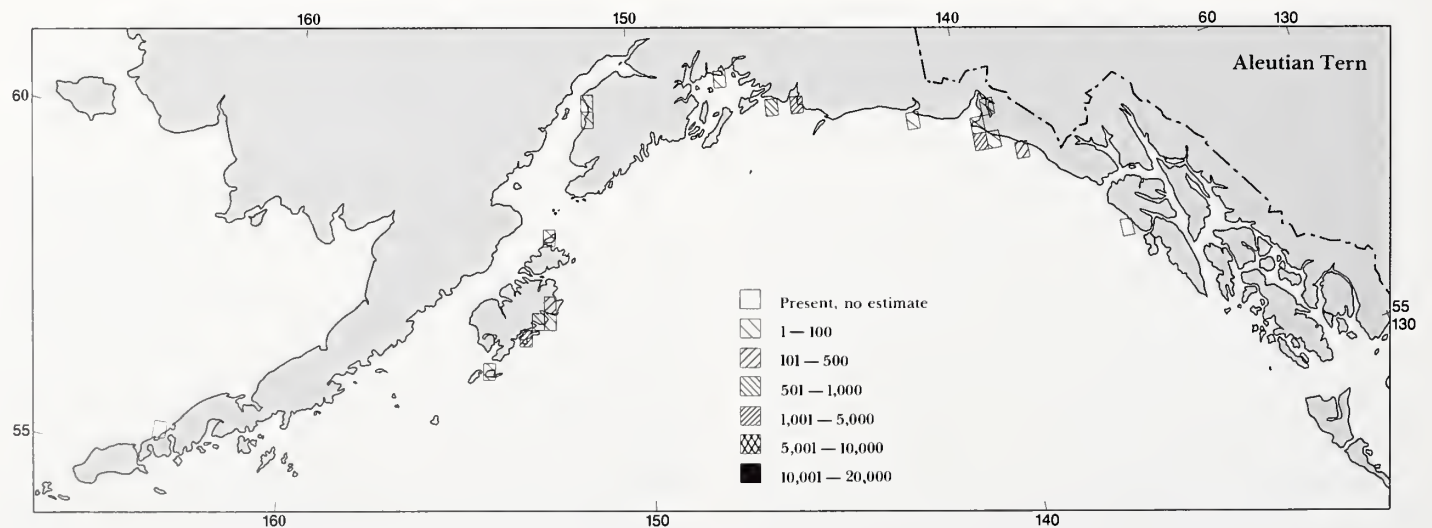


Figure 16-15. Aleutian tern breeding densities for the Gulf of Alaska.

low compared with other gulls (Table 16-10). Approximately 0.41 chicks fledged per nest with eggs.

An important feature of kittiwake biology in the Gulf is the great variation in reproductive success among years and colonies. This variation was manifest during all phases of the nesting cycle including: 1) the proportion of nest-building pairs that laid eggs, 2) the clutch sizes, 3) the hatching success, and 4) the fledging success. Black-legged kittiwakes at some colonies such as Middleton Island and Chisik Island had consistently low reproductive success (Baird and Gould 1985), while those at most other sites raised chicks in some years and failed completely in others. Reproductive success of kittiwakes elsewhere in Alaska is similarly variable (Hunt, Eppley, and Drury 1981; Springer, Roseneau, Murphy, and Springer 1984), which is in marked contrast to high kittiwake productivity in the North Atlantic (Coulson 1972; Maunder and Threlfall 1972; and Wooller and Coulson 1977).

Terns. Arctic terns (*Sterna paradisaea*) are circumpolar-breeding seabirds and are abundant in both the Arctic and the subarctic regions of the North Pacific. Aleutian terns (*S. aleutica*), on the other hand, are found only in the North Pacific. Breeding Arctic terns occur at 106 colonies in the Gulf (Fig. 16-14); Prince William Sound and the Kodiak Archipelago contain the largest number of colonies. Aleutian terns are much less abundant and more local than Arctic terns, occurring at 22 sites in the Gulf (Table 16-7, Fig. 16-15).

Terns nest primarily in open areas such as on low grassy islands, in flat areas with low vegetation, and on gravel or sandy beaches (Baird and Gould 1985). The breeding season of both species extends from mid-May to mid-August (Fig. 16-4). Most individuals of both species have departed the breeding grounds by late August (Baird and Gould 1985).

Both Arctic and Aleutian terns lay from one to three eggs per nest and hatching success varies considerably from year to year for both species. Field investigators both at Sitkalidak Strait and at Chiniak Bay on Kodiak Island were unable to determine estimates of overall productivity. Human disturbance, predation of both eggs and chicks, and exposure of both eggs and chicks to poor weather were the most important factors affecting productivity. Egging by humans near Sitkalidak Strait greatly reduced the value of studies undertaken there.

Murres. Both common (*Uria aalge*) and thick-billed murres (*U. lomvia*) are widely distributed in the North Pacific and the North Atlantic Oceans (Tuck 1960). Approximately five million birds of each species nest in Alaska (Sowls *et al.* 1978). Both species are widespread in the Gulf of Alaska (Figs. 16-16, 16-17), although common murres are considerably more abundant than thick-billed murres. The latter species appears to be expanding its range into southeastern Alaska (J.W. Nelson, U.S. Fish and Wildlife Service, pers. comm., 1984) and British Columbia (Vallee and Cannings 1983). Because murres are difficult to distinguish on their crowded nesting ledges, they frequently were not identified to species, so there are no precise population estimates for each species and their known breeding distributions are imprecise.

Murres typically nest on the steep cliffs of offshore islands and mainland promontories where they typically lay one egg on bare rock or soil. Some segregation between the two species occurs, with common murres preferring to nest in dense aggregations on wide cliff ledges or on the tops of sea stacks, and thick-billed murres preferring to nest in single lines on long, narrow ledges (Squibb and Hunt 1983; Baird and Gould 1985). Less frequently, common murres can be found nesting in crevices, in the entrances to puffin burrows, in dense grass and umbels, and on vegetated and unvegetated talus slopes (Baird and Gould 1985). The predilection of murres for steep, inaccessible cliffs greatly limits their vulnerability to terrestrial predators (Petersen 1982).

On average, the breeding schedule of thick-billed murres precedes that of common murres by about two weeks (Fig. 16-4). Murre chicks jump from their nesting ledges before they are fully grown—usually about 23 days after hatching. Most chicks have departed the colony by mid-September. Approximately 50% of the pairs that produced eggs fledged a chick (Table 16-10). During the mid- to late 1970s, productivity of murres on the Pribilof Islands and in Norton Sound was generally higher than in the Gulf of Alaska (Hunt, Eppley, and Drury 1981).

Pigeon Guillemot. Pigeon guillemots are among the few alcids to lay two eggs. Colonies, which are frequently nothing more than loosely scattered pairs, are found throughout the Gulf, but are concentrated west of Cape St. Elias (Fig. 16-18). Rock crevices, boulder beaches, and talus slopes are favorite natural nesting places, but this species has also adapted well to man-made structures such as boat piers, rock jetties, and even the tires used for bumpers on boat piers (Sowls, DeGange, Nelson, and Lester 1980).

The nesting season extends from late May to late August. There are few estimates of the reproductive success for pigeon guillemots in Alaska. The most intensive study occurred at Naked Island in Prince William Sound where the number of chicks fledged per nest ranged from 0.68 to 1.16 ($\bar{x} = 0.86$) (Kuletz 1983).

Small Alcids. Seven species of small alcids nest in the Gulf of Alaska:

- 1) marbled murrelet (*Brachyramphus marmoratus*)
- 2) Kittlitz's murrelet (*B. brevirostris*)
- 3) ancient murrelet (*Synthliboramphus antiquus*)
- 4) Cassin's auklet (*Ptychoramphus aleuticus*)
- 5) parakeet auklet (*Cyclorhynchus psittacula*)
- 6) least auklet (*Aethia pusilla*)
- 7) crested auklet (*Aethia cristatella*).

Little is known of the first two species (marbled murrelet and Kittlitz's murrelet). Both are widespread in the Gulf of Alaska in coastal waters, but their solitary and largely undiscovered nesting habits have all but precluded their study. Marbled murrelets nest on branches of trees in old growth coastal forests (Binford, Elliott, and Singer 1975), on the ground on treeless islands (Simon 1980; Hirsch, Woodby, and Astheimer 1981), or on the mainland (Day, Oakley, and Barnard 1983). Kittlitz's murrelets nest on rocky substrates in the alpine zone of coastal mountain ranges

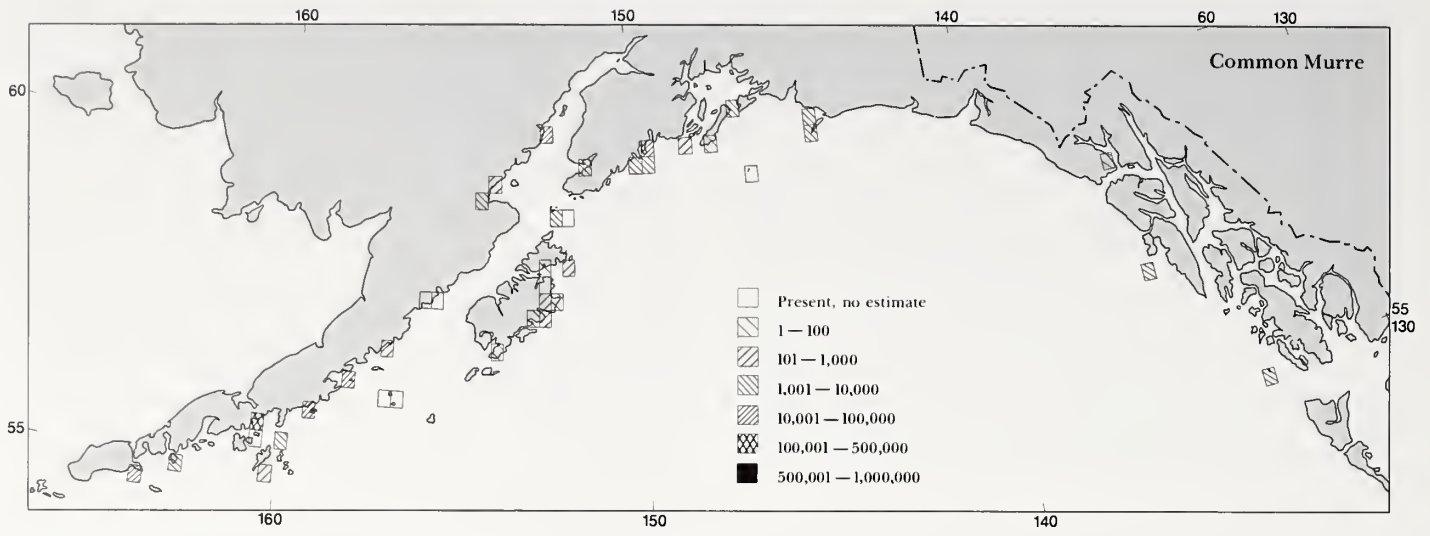


Figure 16-16. Common murre breeding densities for the Gulf of Alaska.

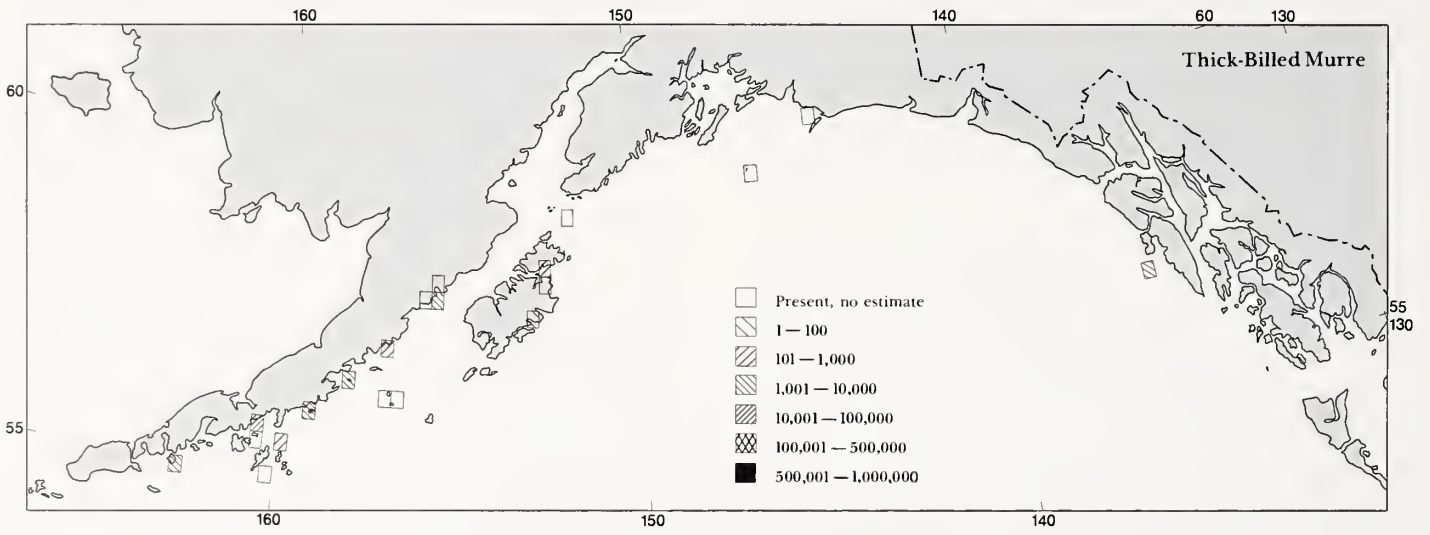


Figure 16-17. Thick-billed murre breeding densities for the Gulf of Alaska.

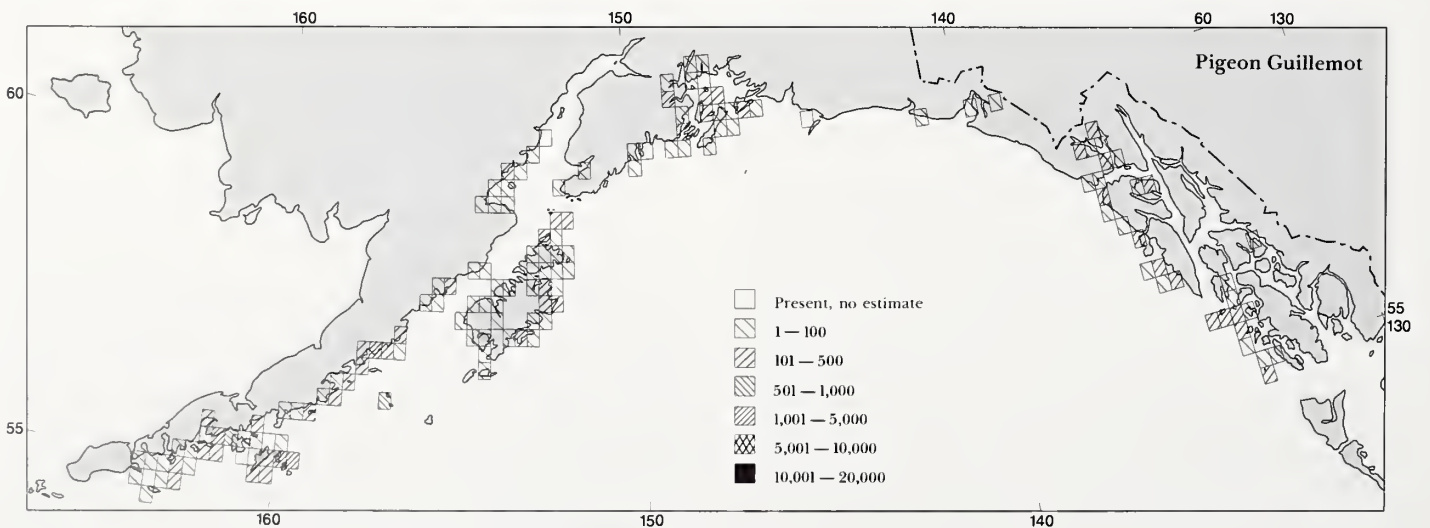


Figure 16-18. Pigeon guillemot breeding densities for the Gulf of Alaska.

(Bailey 1973; Day *et al.* 1983). What little is known of their biology is summarized in these papers and in Sealy (1974, 1975a) and Kiff (1981).

Ancient murrelets nest from British Columbia through the Aleutian Islands and south to Korea (Sowls *et al.* 1978). Their nocturnal nesting habits may limit the northern extent of their range. Colonies of ancient murrelets are difficult to find, not only because of their nocturnal, burrow-nesting habit, but also because of the limited time they spend on land each breeding season. Nests are found in burrows, under tree roots, in rock crevices, and under shoreline debris. In southeastern Alaska, ancient murrelets may nest in forests, but they also are at home on treeless islands. Presently, 27 widespread colonies of ancient murrelets have been identified in the Gulf (Fig. 16-19). The largest of these colonies—on Forrester Island in southeastern Alaska—has a population of 60,000 birds.

The breeding biology of this species is summarized by Sealy (1976). Among the small alcids nesting in the Gulf of

Alaska, ancient murrelets have a unique breeding strategy. After an incubation period of about 35 days, the precocial chicks hatch and, at between two and four days of age, go to sea with their parents. This arrangement relieves the parents of costly long-distance flights with food to colonies, and probably enables the parents to occasionally raise two chicks—provided the chicks survive their extraordinary journey to sea. Ancient murrelets are one of the earliest-nesting species in southeastern Alaska (Fig. 16-4), and most adults and chicks have usually departed the colonies by late June.

Cassin's auklet is another small burrow-nesting seabird of the North Pacific. Colonies extend from Baja California north through the Aleutian Islands (American Ornithologists' Union 1983). Nearly two dozen Cassin's auklet colonies have been found in the Gulf of Alaska, most of which are concentrated south of the Alaska Peninsula (Fig. 16-20). Population estimates are available for only a few of these colonies.

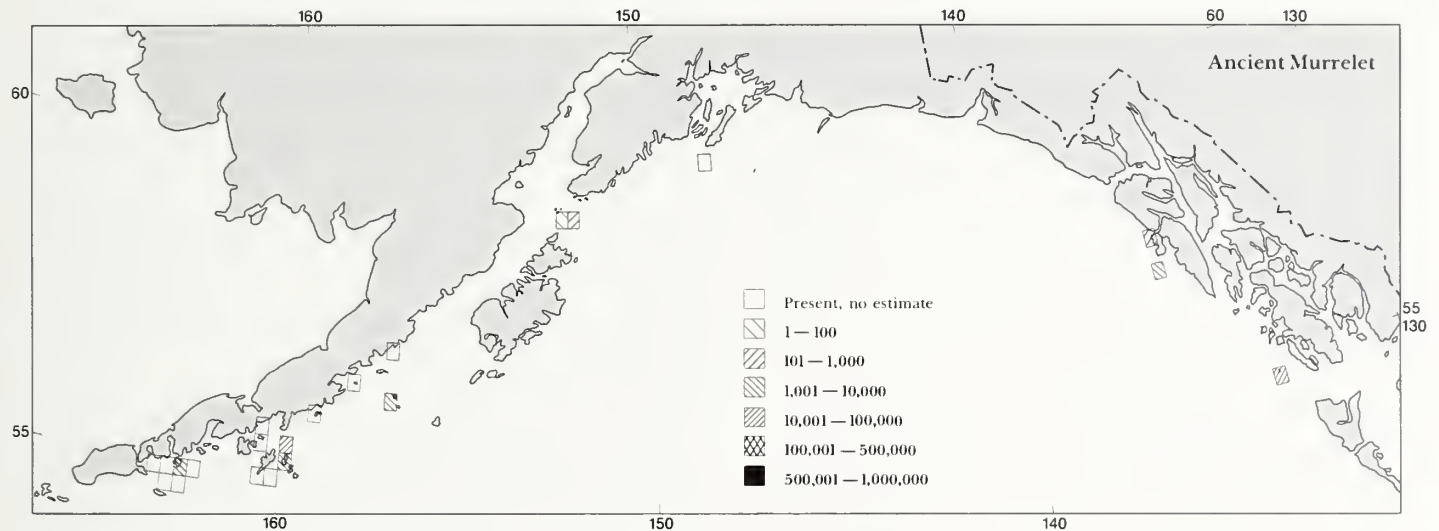


Figure 16-19. Ancient murrelet breeding densities for the Gulf of Alaska.

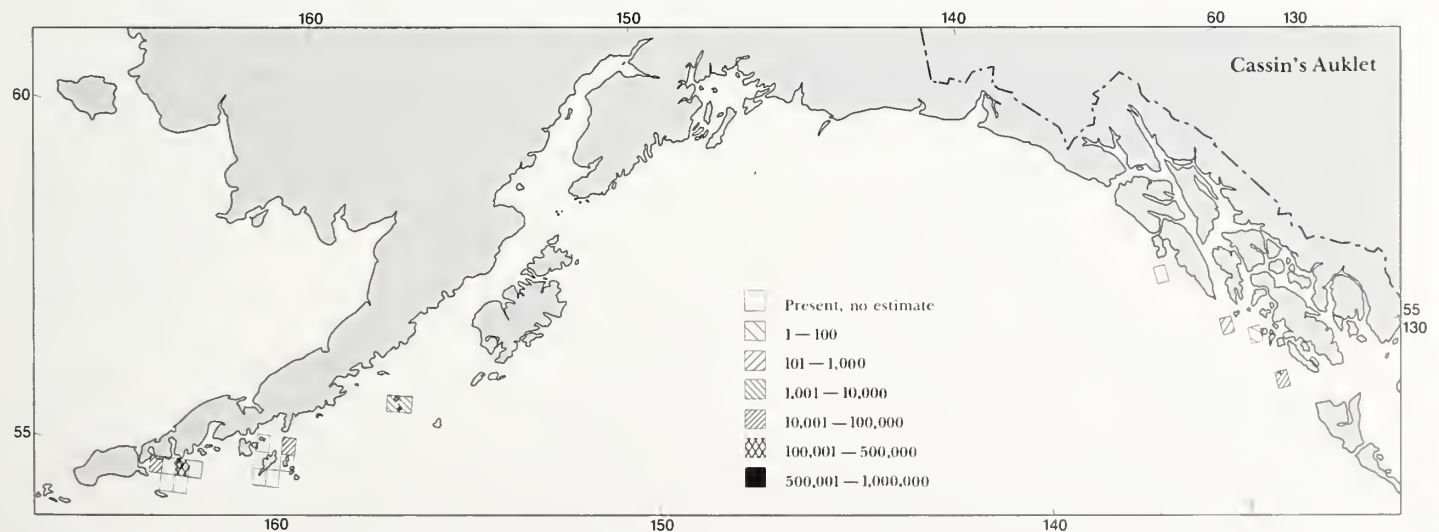


Figure 16-20. Cassin's auklet breeding densities for the Gulf of Alaska.

Cassin's auklets are one of the earliest breeding seabirds in Alaska (Fig. 16-4). There have been no detailed studies of this species in Alaska, but they have been studied both in California (Thoresen 1964; Manuwal 1974a, b, c; Manuwal 1979; and Speich and Manuwal 1974) and in British Columbia (Vermeer, Vermeer, Summers, and Billings 1979; Vermeer 1981, 1984).

Parakeet auklets are common breeding seabirds in the western Gulf of Alaska, in the Aleutian Islands, and in the Bering Sea (Sowls *et al.* 1978). They are widespread west of Kodiak Island, but are absent east of Cape St. Elias (Fig. 16-21). They prefer nesting habitats that include talus slopes, boulder beaches, and crevices in cliffs. Parakeet auklets are not as gregarious as other auklets, usually nesting as solitary pairs or in small colonies. Little work has been done on the biology of this auklet in the Gulf of Alaska, but it has been studied on St. Lawrence Island in the Bering Sea (Bedard 1969a, b; Sealy and Bedard 1973).

Both least- and crested auklets are birds of the Bering Sea and the Aleutian Islands (Sowls *et al.* 1978). Small numbers of least auklets are found at two sites in the Gulf of Alaska: the Shumagin Islands and the Semidi Islands. Twenty birds were counted at these sites, although we feel that 100 birds is a more reliable estimate. Breeding crested auklets are comparatively abundant in the Gulf of Alaska, numbering over 40,000 birds. All seven breeding sites are located in the Shumagin Islands.

Elsewhere in Alaska, least and crested auklets nest together in huge colonies. They prefer nest sites that include talus slopes, boulder beaches, and cracks in cliff faces. Competition between the two species for nest sites is minimized by their size difference (Bedard 1969a; Knudtson and Byrd 1982). Few data from the Gulf of Alaska are available on these species, but considerable information on their reproductive biology is available from colonies both in the Bering Sea (Bedard 1969a, b; Sealy 1968, 1972,) and on the Aleutian Islands (Knudtson and Byrd 1982; Byrd, Day, and Knudtson 1983).

Puffins. Three puffin species occur in the Gulf of Alaska:

- 1) rhinoceros auklet (*Cerorhinca monocerata*)
- 2) tufted puffin (*Fratercula cirrhata*)
- 3) horned puffin (*F. corniculata*).

Rhinoceros auklets are the largest of the burrow-nesting nocturnal alcids. They are widely distributed in the North Pacific, with colonies found from California to the Aleutian Islands and Japan (American Ornithologists' Union 1983). Forrester Island in southeastern Alaska—with an estimated population of more than 100,000 birds—is the only large colony in Alaska. The remaining 12 colonies in the Gulf are small and widely dispersed (Fig. 16-22). Detailed studies of this species have occurred at Middleton Island (Hatch 1984), in British Columbia (Vermeer 1978; Vermeer and Cullen 1979; Vermeer, Cullen and Porter 1979; and Vermeer and Westheim 1984), and in Washington State (Richardson 1961; Leschner 1976; and Wilson 1977).

Tufted puffins are among the most abundant and widespread of Alaskan seabirds. Some 382 colonies are located in the Gulf of Alaska and the breeding population may exceed 1.5 million individuals (Table 16-7, Fig. 16-23). The center of this species' abundance is in the western Gulf of Alaska and the eastern Aleutian Islands (Sowls *et al.* 1978). Tufted puffins primarily nest in earthen burrows, but will occasionally nest in rocky habitats. The most typical colony sites are either on steep grassy slopes or on the grassy shoulders of cliffs. Tufted puffins return to their colonies in the central Gulf of Alaska in early May, and the breeding season extends to early September (Baird and Gould 1985). Like most alcids, tufted puffins lay one egg per season, but there is evidence that suggests that some birds may re-lay following loss of their first egg (Wehle 1980).

Aspects of the breeding biology of tufted puffins are summarized in Baird and Gould (1985), Burrell (1980), and Wehle (1976, 1980, 1982a, b, 1983). In studies conducted by the U.S. Fish and Wildlife Service, approximately 64% of

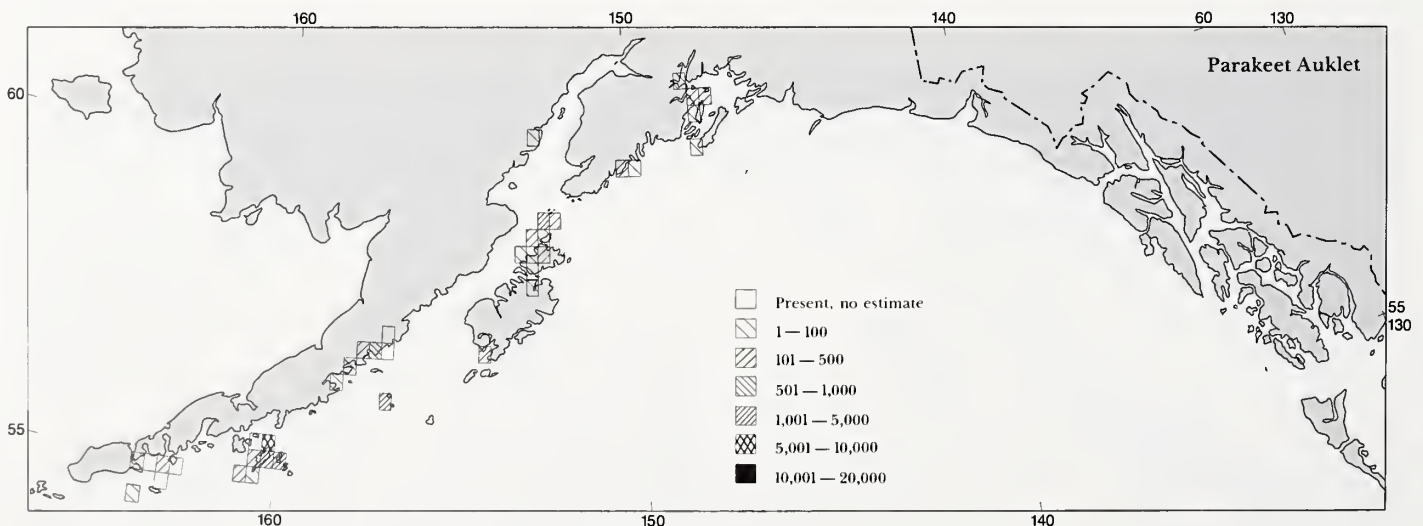


Figure 16-21. Parakeet auklet breeding densities for the Gulf of Alaska.

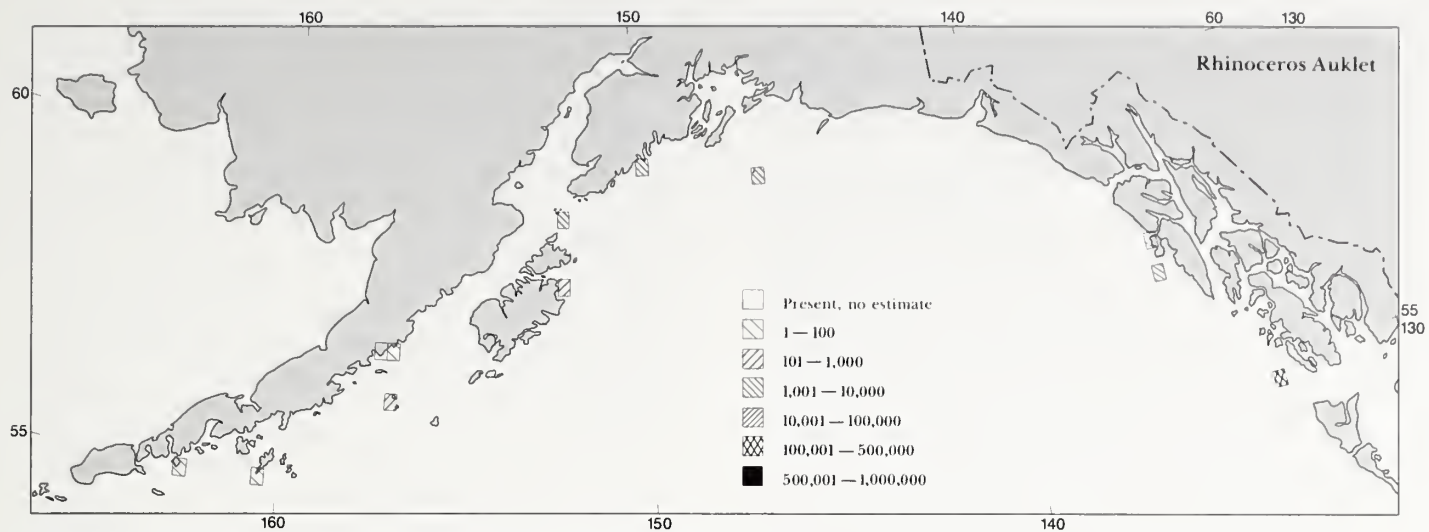


Figure 16-22. Rhinoceros auklet breeding densities for the Gulf of Alaska.

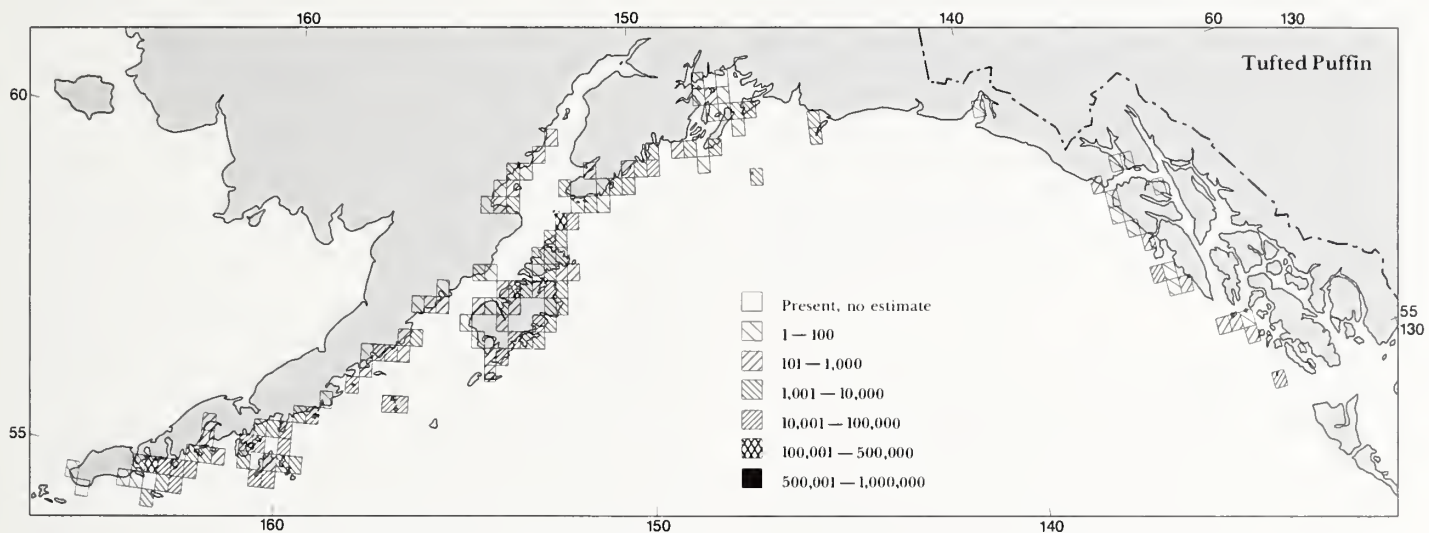


Figure 16-23. Tufted puffin breeding densities for the Gulf of Alaska.

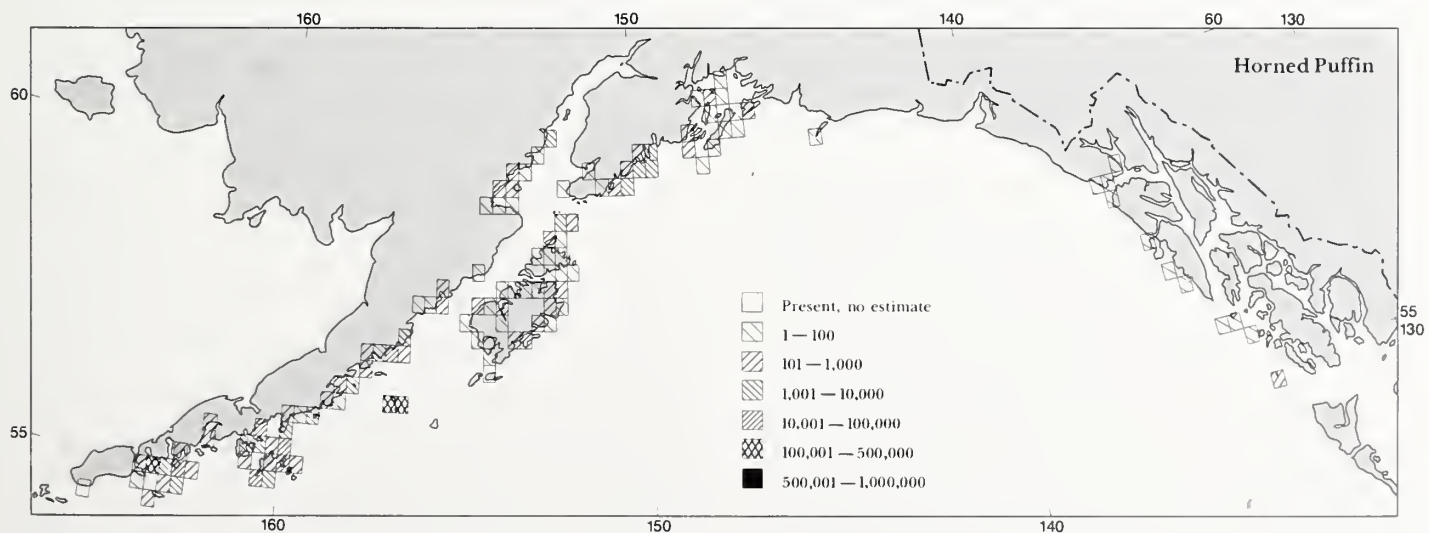


Figure 16-24. Horned puffin breeding densities for the Gulf of Alaska.

the burrows that showed some activity by tufted puffins contained eggs. Because tufted puffins frequently desert their nests if disturbed during the incubation period, their reproductive success varied markedly between disturbed and undisturbed areas within the colonies. Between 1976 and 1978, reproductive success of tufted puffins that were frequently disturbed during the incubation and nestling periods averaged 0.34 chicks fledged per nest with eggs, compared with 0.74 chicks fledged per undisturbed nest with eggs. Overall reproductive success for tufted puffins for all years of study was about 65% for those colonies where there was a minimum of disturbance (Table 16-10).

Horned puffins are common in the Gulf of Alaska, although their abundance does not equal that of the tufted puffins. Approximately 304 colonies of horned puffins are located in the Gulf, ranging from southeastern Alaska to Unimak Pass (Fig. 16-24). The breeding population may exceed one million individuals. The western Gulf of Alaska is unquestionably the center of this species' breeding distribution.

Horned puffins prefer to nest in boulder rubble, in talus slopes, and in rock crevices, although the population nesting on Sutlik Island in the Semidi Islands uses burrows almost exclusively (Hatch and Hatch 1983). Horned puffins arrive at their colonies in the central Gulf of Alaska in early May, and the nesting season extends through early October (Fig. 16-4). Overall reproductive success, in terms of fledglings per nest with eggs, was 60% (Table 16-10). The natural history of horned puffins is summarized in both Sealy (1973) and Wehle (1980).

Pelagic Distribution

Physical properties of Gulf waters, such as surface water temperature and salinity, affect the distribution and abundance of seabirds by directly affecting the species composition, quantity, and availability of food organisms. The three topographic features that most obviously influence the distribution and abundance of seabirds in the Gulf of Alaska include 1) a deep ocean basin studded with seamounts, 2) a wide continental shelf with a wealth of small and large islands, and 3) extremely rocky coastal areas with many deep fjords and bays. In general, seabirds are found wherever physical conditions are appropriate, and within such areas, seabirds become distributed in response to food availability and breeding sites.

Water circulation in the Gulf is dominated by the North Pacific Current, which flows eastward from Japan before it bifurcates into two currents off North America. The first branch curves northward to form the Alaska Current (Favorite 1967), which flows westward along the shelf break, occasionally sending branches southward to complete the Alaskan Gyre (see Reed and Schumacher, Ch. 3, this volume). The second branch curves southward to form the California Current. In the northern Gulf and along the Alaska Peninsula, there is also a distinctly narrow, dilute current called the Alaska Coastal Current, which also flows westward (Royer 1981).

The Transition Domain and Subarctic Boundary, which occur across the North Pacific between 35°N and 45°N,

mark the boundary between subtropical and subarctic water masses (Favorite, Dodimead, and Nasu 1976). These water masses are characterized by distinctly different avifaunas (Gould 1983, R. H. Day, University of Alaska, pers. comm., 1985). In the eastern Pacific, the separation of distinct faunas becomes less structured where the North Pacific Current bifurcates to form part of the Alaskan Gyre and California Current systems.

Pelagic surveys of seabirds indicate that large seasonal differences in seabird abundance occur across all habitats in the Gulf of Alaska (Gould *et al.* 1982). Seabird populations in the Gulf are both least numerous and least diverse in winter. During spring, however, profound changes occur in seabird numbers and diversity as returning breeders and summer visitors appear and birds begin concentrating over the deeper waters of the continental shelf and in oceanic regions. As summer approaches, increasing numbers of birds move onto the continental shelf and into nearshore waters. Overall bird densities in shelf, shelf-break, and oceanic habitats in spring are higher than at any other time of the year (Table 16-11). Overall bird densities in spring are highest over the continental shelf and shelf break, reflecting the preference for this habitat by the millions of short-tailed and sooty shearwaters that spend the austral winter in the North Pacific and Bering Sea (Table 16-11).

During mid-summer, seabird populations in the Gulf of Alaska may exceed 40 million individuals (Gould *et al.* 1982). Densities of seabirds in bays and fjords are higher at this time of year, reflecting the large number of nesting seabirds. Some species such as cormorants, guillemots, and *Brachyramphus* murrelets remain near shore. Others, including kittiwakes, puffins, fulmars, and storm-petrels, are capable of foraging far from colonies.

The continental shelf contains, by far, the largest densities of seabirds in summer (Table 16-11). Shearwaters—particularly short-tailed shearwaters—make up the majority of birds on the shelf. Alcid densities over the shelf decrease markedly from their densities in nearshore habitats. Shelf-break waters contain similar densities of seabirds as do nearshore habitats, and shearwaters again are the dominant group in this region. Tubenose populations such as albatrosses, fulmars, and storm-petrels are more dense over shelf-break waters than they are over the continental shelf.

Table 16-11. Total densities of seabirds (birds/km²) in the Gulf of Alaska by season and habitat (from Gould *et al.* 1982).

SEASON	BAY	HABITAT		OCEANIC
		SHELF	SHELF-BREAK	
Spring (Mar–May)	29.0	158.2	57.2	43.8
Summer (Jun–Aug)	56.7	134.1	55.8	14.7
Fall (Sep–Nov)	35.6	59.9	22.4	6.7
Winter (Dec–Feb)	18.2	13.7	22.0	3.2

The lowest seabird densities in the Gulf in summer occur in oceanic waters where sooty shearwaters and other tubenoses predominate (Gould *et al.* 1982; Sanger and Ainley, in press). Immature tufted and horned puffins were found to be an important component of the avifauna in oceanic waters south of the western Aleutian islands (A.R. DeGange and D.J. Forsell, U.S. Fish and Wildlife Service, unpubl. data), and it is likely that many of the puffins summering over deep oceanic water in the Gulf of Alaska are also immature.

In the fall, seabird densities in the Gulf decrease over all habitats (Table 16–11). This is particularly true on the continental shelf as the shearwaters depart for their breeding grounds in the Southern Hemisphere. Alcids also disperse from coastal waters, resulting in lower densities of these birds in nearshore areas. Seabird densities decrease even further in winter (Table 16–11), especially in nearshore, shelf, and oceanic habitats. Seabird densities over shelf-break habitats are similar to densities in the fall, reflecting the importance of this area to wintering fulmars, fork-tailed storm-petrels, kittiwakes, and murres.

More precise information on temporal and spatial distribution is available for some Gulf species. Both black-footed and Laysan albatrosses are non-breeding visitors to the Gulf of Alaska, reaching their peak abundance in late summer and early fall (Gould *et al.* 1982). The striking concentration of albatrosses along the shelf-break front (Gould *et al.* 1982) suggests that there is ample food there. Of the two species, black-footed albatrosses were the more numerous—particularly in the northeastern Gulf—indicating a more easterly distribution of this species in the North Pacific during the non-breeding season than the distribution of Laysan albatrosses (see also Shuntov 1972; Fisher and Fisher 1972; and Sanger 1974). Northern fulmars were similarly concentrated along the Gulf shelf break during both summer and winter (Fig. 16–25).

It is estimated that more than 26 million short-tailed and sooty shearwaters occur in the Gulf of Alaska in summer, 68% of which are sooty shearwaters (Gould *et al.* 1982). There is some geographical separation between the two shearwater species. In the northern Gulf, sooty shearwaters appear to outnumber short-tails by a ratio of nearly nine to one; west of Kodiak Island, the two species are found in approximately equal abundance (Gould *et al.* 1982).

Gould *et al.* (1982) also suggested that some habitat separation occurs between the two species. Short-tailed shearwaters were more abundant than sooty shearwaters over the continental shelf, but were uncommon over shelf-break and oceanic habitats (Fig. 16–25). Sooty shearwaters, in contrast, were about equally abundant over shelf and shelf-break habitats and were more abundant than were short-tailed shearwaters over oceanic waters (Fig. 16–25) (see also Sanger and Ainley, in press). Most shearwaters depart for the Southern Hemisphere in fall, but small numbers of over-wintering birds have been observed both west of the Queen Charlotte Islands in British Columbia and south of Kodiak Island (Gould *et al.* 1982).

Both Leach's storm-petrels and fork-tailed storm-petrels were common in the Gulf of Alaska in summer, and were most frequently associated with shelf-break and oceanic

habitats (Fig. 16–25). Fork-tailed storm-petrels were frequently observed on the continental shelf, particularly near breeding colonies. Leach's storm-petrels, however, are more pelagic than fork-tailed storm-petrels, and were only occasionally observed on the shelf. In winter fork-tailed storm-petrels were uncommon and were found principally outside the shelf break. Leach's storm-petrels disperse southward to tropical waters (Palmer 1962).

Several species attained their highest summer densities in nearshore waters, coinciding with the concentration of breeding birds near colonies. These species included cormorants, glaucous-winged gulls, black-legged kittiwakes, pigeon guillemots, marbled murrelets, and tufted puffins. Apparently, the life histories of cormorants, pigeon guillemots, and marbled murrelets are closely tied to the nearshore zone. These species were rarely seen far offshore, and at least in the case of cormorants and marbled murrelets, densities in winter were also higher in nearshore habitats when compared to offshore areas (Fig. 16–25).

In contrast, densities of glaucous-winged gulls, black-legged kittiwakes, and tufted puffins decreased in nearshore habitats following the breeding season. In winter, densities of glaucous-winged gulls were highest over the shelf and the shelf break (Fig. 16–25). An unknown percentage of the glaucous-winged gull population migrates southward far offshore and along the coast as far south as California (Sanger 1973; Harrington 1975), and some also concentrate around coastal communities in Alaska at this time. Densities of black-legged kittiwakes in winter were highest over the shelf-break (Fig. 16–25). They are uncommon along the coast of Alaska in winter.

Tufted puffins dispersed widely to sea following the breeding season (Shuntov 1972) and were rarely encountered during surveys over the shelf of the Gulf of Alaska during winter (Gould *et al.* 1982). Tufted puffins are one of the main components of the winter seabird community across the entire oceanic subarctic Pacific (Shuntov 1972; Sanger and Ainley, in press), although they are widely dispersed.

Common murres were most abundant near shore, especially in winter when they attained their highest densities (Fig. 16–25). Common murres were an especially important component of the wintering avifauna around Kodiak Island (Forsell and Gould 1981). Thick-billed murres—although less abundant in the Gulf of Alaska than common murres—were relatively more abundant over oceanic water than in nearshore or continental shelf habitats (Gould *et al.* 1982).

We were unable to make comparisons of summer versus winter densities for additional species. During winter, few surveys were undertaken, and several of the species were not observed with any frequency. There is some evidence that shelf and shelf-break habitats are important for Arctic terns, ancient murrelets, Cassin's auklets, and horned puffins during summer (Fig. 16–25).

Feeding Ecology

Seabirds differ not only in terms of the geographic areas where they forage, but in terms of the way they use different depth strata in the water column, the maximum depths to

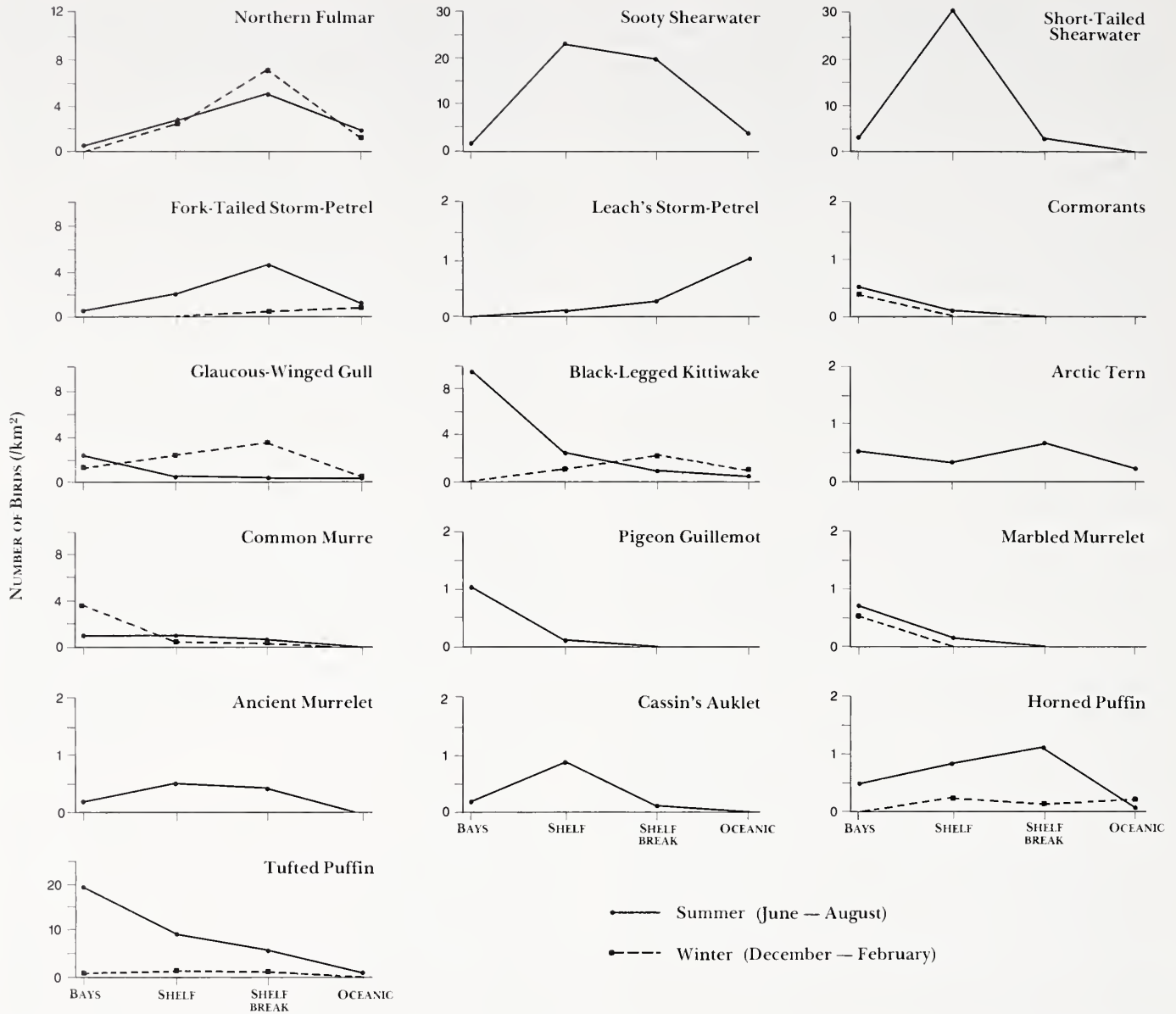


Figure 16-25. Winter and summer seabird densities in four pelagic habitats in the Gulf of Alaska. (Modified from Gould *et al.* 1982.)

which they descend to feed, and (in shallower waters) their tendencies to forage on or near the bottom. Besides those instances where birds are caught in fishing gear at known depths (Piatt and Nettleship 1985), foraging depths can often be deduced by a careful evaluation of the habits of prey species and a knowledge of water depth where birds were collected (Croxall and Prince 1980; Ainley, Anderson, and Kelley 1981; and Sanger and Jones 1982).

For purposes of comparing foraging behavior and diets, seabirds in the Gulf may be divided into four groups—based on information in Table 16-12:

- 1) surface-feeders that are restricted to feeding in 0.5 m depths in either coastal or oceanic habitats
- 2) shallow divers that regularly forage down to ~ 20 m in either coastal or oceanic habitats
- 3) coastal foragers that regularly forage down to at least 40 m either in mid-water or on the bottom

- 4) pelagic foragers that descend from at least 40 m to well over 100 m depending on species, and which may include benthic foraging in shallower depths.

Since diving depths for some species are much better known than others, there may well be more overlap in foraging strata than suggested in Table 16-12. In general, however, those species feeding on the surface (to 0.5m) include albatrosses, northern fulmar, storm petrels, gulls, kittiwakes, terns, and phalaropes. The shallow divers include the shearwaters. Cormorants and the smaller alcids appear to forage regularly to at least 40 m, either in mid-water or to the bottom, while murres and puffins are deep-diving pelagic foragers. Common murres have been caught in crab pots at 125 m at Kodiak Island (Forsell and Gould 1981), and in trammel nets at 180 m in the Atlantic (Piatt and Nettleship 1985). The latter study shows that the larger alcids routinely dive to far greater depths than has been generally believed.

Table 16-12.
Known and estimated foraging depths of seabirds in the Gulf of Alaska.

SPECIES	USE OF DEPTH STRATA IN WATER COLUMN ^a					MAXIMUM DIVE DEPTH (m)	REFERENCES
	0-0.5 m	0.5-10 m	MID-WATER 10 m	DEMERSAL	EPIBENTHIC		
Black-footed albatross	1	3	0	0	0	1	
Laysan albatross	1	3	0	0	0	1	
Northern fulmar	1	3	0	0	0	1	
Mottled petrel	1	3?	0	0	0	0.5?	
Sooty shearwater	3	1	3?	0	0	5	Brown, Bourne, and Wahl 1978
Short-tailed shearwater	3	1	2?	0	0	20	Morgan 1982
Fork-tailed storm-petrel	1	0	0	0	0	cm's	
Leach's storm-petrel	1	0	0	0	0	cm's	
Double-crested cormorant	0	3?	3?	1	2?	20?	
Pelagic cormorant	0	3?	2?	1	1	36	Scheffer 1942
Red-faced cormorant	0	3?	3?	1	1	20-30?	
Red-necked phalarope	1	0	0	0	0	cm's	
Red phalarope	1	0	0	0	0	cm's	
Glaucous-winged gull	1	3	0	0	0	1	
Mew gull	1	3?	0	0	0	1?	
Black-legged kittiwake	1	3	0	0	0	1-2	Burt 1974
Arctic tern	1	0	0	0	0	0.5?	
Aleutian tern	1	0	0	0	0	0.5?	
Common murre	0	2?	1	2?	3	180	Piatt and Nettleship 1985
Thick-billed murre	0	2?	1	2?	3	72	Tuck and Squires 1955
Pigeon guillemot	0	0?	2	1	1	23-40	Sanger and Jones 1982; Kuletz 1983
Marbled murrelet	0	2?	1	3	3	40?	cf. Bédard 1969b
Kittlitz's murrelet	0	2?	1	3	3	40?	cf. Bédard 1969b
Ancient murrelet	0	2?	1	0	0	40?	cf. Bédard 1969b
Cassin's auklet	3 ^b	2?	1	0	0	40?	cf. Bédard 1969b
Parakeet auklet	0	3?	2?	2	2	40	Bédard 1969b
Crested auklet	0	3?	1	2	2	40	Bédard 1969b
Rhinoceros auklet	0	1	2	3?	0	60	cf. Piatt and Nettleship 1985
Tufted puffin	0	2	2	3?	0		cf. Piatt and Nettleship 1985
Horned puffin	0	1	2	3?	0		cf. Piatt and Nettleship 1985

^a 1 = major, 2 = moderate, 3 = minor, 0 = none.

^b Sanger, personal observation.

The diets of seabirds found in the Gulf of Alaska (Sanger 1983, in press) were examined in terms of the percent volume (%V), the percent numbers (%N), and the percent frequency of occurrence (%FO) of the prey found in bird-stomach samples. These three values are combined into an Index of Relative Importance (IRI) (Pinkas, Oliphant, and Iverson 1971), and the percent of total IRI for all prey eaten by a bird species was used to further evaluate and compare the importance of various prey species. By combining these three parameters (*i.e.*, $IRI = [\%V + \%N]/\%FO$), the IRI attempts to overcome the shortcomings of using any of them alone to represent a predator's diet. Briefly, these are the shortcomings:

- The differential in digestion rates for hard- or soft-bodied prey may distort their original relative volumes.
- Percent numbers can make abundant small prey in the diet seem more important than sparse larger prey.
- Percent frequency-of-occurrence ignores volume and numbers.

We emphasize that the IRI is an index and not a measure of prey importance. Until a method for measuring prey ingestion rates (biomass eaten/time) is devised, however, the IRI is useful for estimating the relative importance of various prey and for comparing diets among predators. Details on %V, %N, and %FO of prey in the diets of the various seabird species can be found in Sanger (1983).

Surface Feeders. Diet data are available for seven species of surface feeders (Table 16-13):

- 1) northern fulmar
- 2) fork-tailed storm-petrel
- 3) glaucous-winged gull
- 4) mew gull
- 5) black-legged kittiwake
- 6) arctic tern
- 7) Aleutian tern.

Of these species, both the fulmar and the fork-tailed storm-petrel forage almost exclusively in oceanic and shelf-break

Table 16–13.
Diets (% of total Index of Relative Importance for prey taxa) of surface-feeding seabirds in the Gulf of Alaska. (Adapted from Sanger 1983.)

Bird Species ^a Main Habitats ^b Sample Size, n	NOFU O	FTSP O, S	MEGU C	GWGU C, S	BLKI C, S	ARTE		ALTE	
						ADULTS	IMMATURES C	ADULTS	IMMATURES C
	46	14	68	13	328	36	32	14	48
PREY TAXON									
Cephalopods	96.3	60.7			0.1				
Miscellaneous crustaceans ^c	0.7		6.7	0.2	0.6	0.1		2.2	
Gammarid amphipods			84.8						
<i>Thysanoessa inermis</i>	0.2			0.3	8.2	94.8		76.4	
Euphausiids ^d		22.3		0.1	2.2	0.8	2.2		0.1
Decapods ^e		3.0	7.4	0.3	0.2	0.1			
<i>Mallotus villosus</i>	0.1			2.6	61.3	1.4	64.7	3.2	44.3
<i>Theragra chalcogramma</i>	0.6	1.7			1.2				
Hexagrammids				0.2					0.6
<i>Ammodytes hexapterus</i>			1.7	1.6	8.6	1.3	25.9	12.0	6.5
Miscellaneous fishes ^f	2.1	4.2	3.5	92.0	10.0	0.2	2.1	4.6	37.7
Birds ^g	0.1			0.6					
Other ^h	0.2	1.3	2.6	1.6	2.2	0.1		1.5	0.1
Index of Stomach Fullness, Max. (n) ⁱ	3.5(40)	1.2(11)	25.1(119)	3.9(13)	12.3(325)	14.9(31)	11.4(12)	8.5(15)	8.4(5)

^a NOFU = northern fulmar, FTSP = fork-tailed storm-petrel, GWGU = glaucous-winged gull, MEGU = mew gull, BLKI = black-legged kittiwake, ARTE = Arctic tern, ALTE = Aleutian Tern;

^b C = coastal, S = shelf, O = oceanic.

^c Includes barnacles, copepods, isopods, hyperiid amphipods, and *Paracallisoma alberti*.

^d Includes unidentified euphausiids, *Thysanoessa raschii*, and *T. spinifera*.

^e Includes unidentified decapods, pandalid shrimp, and unidentified shrimp.

^f Includes *Clupea harengus*, *Hypomesus pretiosus*, *Gadus macrocephalus*, *Trichodon trichodon*, *Blepius cirrhosus*, *Zaprora silenus*, unidentified osmerids, unidentified gadids, and unidentified cottids.

^g Fork-tailed storm-petrel in northern fulmar; ancient murrelet chicks in glaucous-winged gull.

^h Includes nereid polychaetes, gastropods, chitons, bivalves, sea urchins, and insects.

ⁱ Weight of stomach contents / (field body weight - weight of stomach contents) × 100; n represents sample size.

habitats, while mew gulls and both species of terns are primarily coastal foragers. Glaucous-winged gulls and kittiwakes forage almost equally in coastal and shelf areas.

Cephalopods dominated the diet of both the oceanic fulmars and the storm petrels, while capelin (*Mallotus villosus*) and Pacific sand lance were the mainstay prey of most of the coastal-foraging surface-feeders. Other studies have shown that jellyfishes and their symbiotic hyperiid amphipods may be locally common in the diet of fulmars (Harrison 1983) and that larval capelin and the gammarid amphipod *Paracallisoma alberti* are common prey brought by parent fork-tailed storm-petrels to their nestlings at the Barren Islands (P.D. Boersma, University of Washington, pers. comm., 1984).

The euphausiid *Thysanoessa inermis* was especially important to adults of both Arctic and Aleutian terns. In contrast, chicks of both species fed exclusively on fish brought by their parents (Table 16–13). The diets of nestling black-legged kittiwakes (Sanger 1983) were made up of quantities of fish and euphausiids, while *T. inermis* was important to adult birds in early summer (Table 16–13) (see also Krasnow and Sanger 1982). Glaucous-winged gulls had one of the most varied diets of all seabirds in the Gulf, although fish still constituted over 90% of the total IRI (Table 16–13).

Maximum values for the Indices of Stomach Fullness (ISF) (the percent of body weight accounted for by the weight of the stomach contents), are shown at the bottom of Table 16–13. These values are assumed to represent the

amount of food in the most recent meal. Values for each species ranged as high as 12% for kittiwakes, 15% for Arctic terns, and 25% for glaucous-winged gulls. The meaning of these data is speculative, but a value as high as 25% may indicate gorging instead of frequent consumption of smaller meals.

Shallow Divers. The diets of two species of shallow divers—the sooty and the short-tailed shearwaters—are shown in Table 16–14. The shearwaters forage mainly over the shelf where *Mallotus villosus* (capelin) stood out as important prey for both species. Cephalopods were eaten by both of these species, although they were of moderate importance in the diet of only sooty shearwaters—the more oceanic species of the two (Table 16–14). The low volume of cephalopods found in sooty shearwaters (2%) was mainly accounted for by beaks. Euphausiids were particularly important in the diet of short-tailed shearwaters.

As in the case of the surface feeders, maximum ISF values for the shearwaters tended to be high (Table 16–14), indicating gorging instead of smaller meals eaten more often.

Coastal Divers. This group includes (Table 16–15):

- the pelagic cormorant
- the pigeon guillemot
- marbled and Kittlitz's murrelets
- parakeet and crested auklets.

Table 16-14.
Diets (% of total Index of Relative Importance for prey taxa) of shallow-diving seabirds in the Gulf of Alaska. (Adapted from Sanger 1983.)

Bird Species Main Habitats Sample Size, n	SOOTY SHEARWATER SHELF, OCEANIC 187	SHORT-TAILED SHEARWATER SHELF 228
PREY TAXON		
Cephalopods ^a	26.6	2.0
Miscellaneous crustaceans ^b	0.2	0.1
Euphausiids ^c	1.5	72.4
<i>Mallotus villosus</i>	68.5	21.8
<i>Theragra chalcogramma</i>		0.1
<i>Ammodytes hexapterus</i>	1.3	0.2
Miscellaneous fishes ^d	1.9	1.6
Other ^e	0.1	1.8
Index of Stomach Fullness, Max.(n) ^f	16.6(181)	20.0(215)

^a Includes gonatid squids, *Onychoteuthis borealijaponicus*.

^b Includes calanoid copepods, *Paracallinoma alberti*, gammarid amphipods, hyperiid amphipods, and *Telmessus chieragonus*.

^c Mostly *Thysanoessa* sp., but includes *T. inermis*, *T. raschii*, and *T. spinifera*.

^d Includes *Stenobrachius nanochir*, *Microgadus proximus*, and *Trichodon trichodon*.

^e Includes nereid polychaetes and gastropods.

^f Weight of stomach contents / (field body weight - weight of stomach contents) × 100; n represents sample size.

The presence of demersal and benthic prey such as gastropods, mollusks, gammarid amphipods, mysids, and a variety of decapods (depending on bird species) attests to varying degrees of benthic foraging by all species in this group. However, it seems likely that murrelets and auklets forage primarily within the water column (Table 16-12; see below).

The pigeon guillemot had the most generalized diet of the group (or of any of the seabird species considered in this chapter), eating mostly benthic prey. Prey included at least 12 invertebrate species and seven fish species (Table 16-15). Kuletz (1983) showed that breeding guillemots in Prince William Sound ate mostly fish, with some birds specializing on sand lance (*Ammodytes hexapterus*), while others specialized on benthic species even when sand lance were abundant closer to nest sites.

Among the four smaller alcid in this group, marbled and Kittlitz's murrelets both ate a variety of invertebrates and fishes, although capelin and sand lance were the main prey (Table 16-15). Both species included mysids and euphausiids in their diets, with the latter eaten more by Kittlitz's than by marbled murrelets. In general, Kittlitz's murrelets appear to eat more crustaceans and forage closer to shore, while marbled murrelets forage across a broader range of habitats and eat mostly fish (Sanger, in press).

Both the parakeet and the crested auklets ate pelagic and demersal prey. The parakeet auklet's diet was almost equally divided between crustaceans and fish, while crested auklets ate crustaceans exclusively, particularly *Acanthomysis* mysids

Table 16-15.
Diets (% of total Index of Relative Importance for prey taxa) of coastal diving seabirds in the Gulf of Alaska. (Adapted from Sanger 1983.)

Bird Species ^a Sample Size (n)	PECO 16	PIGU 64	MAMU 158	KIMU 16	PAAU 13	CRAU 25
PREY TAXON						
Miscellaneous crustaceans ^b	0.2	1.3	1.4			24.1
Hyperiid amphipods						5.0
<i>Acanthomysis</i> spp.			9.4			42.6
<i>Thysanoessa inermis</i>			3.8	15.2		28.2
Unidentified euphausiids ^c			1.5	9.1	46.5	
Hippolytid shrimps		2.1				
Pandalid shrimps		3.0	0.1			
Decapods	0.4	32.7			12.1	
<i>Mallotus villosus</i>	1.8	13.0	47.9	1.8		
<i>Theragra chalcogramma</i>	0.6		0.1			
<i>Trichodon trichodon</i>		4.8	0.3	1.7		
Cottidae	0.9	0.4				
Stichaeidae		1.5				
<i>Ammodytes hexapterus</i>	85.8		21.3	3.6		
Miscellaneous fishes ^d	10.1	39.9	14.0	67.7	41.4	
Other ^e	0.2	1.3	0.2			
Index of Stomach Fullness, Max.(n) ^f	4.7(12)	5.1(68)	8.6(156)	1.8(14)	1.1(14)	3.2(22)

^a PECO = pelagic cormorant, PIGU = pigeon guillemot, MAMU = marbled murrelet, KIMU = Kittlitz's murrelet, PAAU = parakeet auklet, CRAU = crested auklet.

^b Includes unidentified gammarids, unidentified mysids, *Neomysis rayii*, *Spirontocaris* spp., *Lebbeus* spp., and eualid shrimps.

^c Mostly *Thysanoessa* sp., *T. raschii*, and *T. spinifera*.

^d Includes *Clupea harengus*, unidentified osmerids, unidentified gadids, *Pholis* sp., and unidentified pleuronectids.

^e Includes polychaetes, echinoids, gastropods, bivalves, and cephalopods.

^f Weight of stomach contents / (field body weight - weight of stomach contents) × 100; n represents sample size.

and the euphausiid *Thysanoessa inermis*. Mysids may occur within the water column at night, but they are generally demersal in daylight (Mauchline 1980) when the auklets were collected. This observation—and the similar presence of demersal crustaceans in the diets of these auklets in the northern Bering Sea (Bedard 1969b)—suggests that both species regularly forage near the bottom when water depth is shallow enough. However, it is unknown how important this mode of feeding is when compared with foraging within the water column.

Maximum ISF values were generally low for all coastal foragers. Values ranged from 1% for parakeet auklets to 9% for marbled murrelets indicating the frequent consumption of small meals as opposed to sporadic gorging.

Pelagic Midwater- and Deep-divers. Seven species of alcids may be placed in this category:

- 1) common murre
- 2) thick-billed murre
- 3) ancient murrelet
- 4) Cassin's auklet
- 5) rhinoceros auklet
- 6) horned puffin
- 7) tufted puffin.

Common murres are abundant in coastal areas in winter (Forsell and Gould 1981), but in summer this species forages mainly over the shelf, whereas thick-billed murres forage over both the shelf and in oceanic waters (Table 16–16). The ability of murres to descend to depths of 180 m (and probably deeper), and to forage extensively on the bottom (Piatt and Nettleship 1985), allows them to capture prey from a wide variety of mid-water and benthic habitats (Table 16–12). Although 70% of the 12,243 common murres studied by Piatt and Nettleship (1985) were observed in gill nets within 30 m of the surface, 4% (450) were found at 70- and 80-m depths, suggesting a greater amount of deep foraging by these species than was previously suspected.

Ancient murrelets and Cassin's auklets forage both in shelf and in coastal habitats, but are apparently restricted to shallower foraging depths. There are no definite diving-depth records for these species, although it seems likely that they should be able to forage to at least 40 m as do other small alcids (Bedard 1969b). Sealy (1975b) observed that ancient murrelets in British Columbia foraged in water depths of at least 50 m, although their deepest foraging depths are unknown. In the present study, mysids made up a small portion of the ancient murrelet's diet (Table 16–16), suggesting occasional benthic foraging (Mauchline 1980; see above).

Table 16–16.

Diets (% of total Index of Relative Importance for prey taxa) of pelagic midwater- and deep-diving seabirds in the Gulf of Alaska. (Adapted from Sanger 1983.)

Bird Species ^a	COMU	TBMU	ANMU	CAAU	RHAU, AD	RHAU, IMM	HOPU	TUPU, AD	TUPU, IMM
Main Habitats ^b	S, C	S, O	S, C	S	C, S	C, S	C	C, S	C, S
Sample Size (n)	251	64	18	8	21	25	54	440	80
PREY TAXON									
Cephalopods ^c	0.1	73.8	0.2	1.1	1.2		1.2	7.8	0.1
Miscellaneous crustaceans						0.4	0.2		
Calanoid copepods				76.7					
<i>Neomysis rayii</i>		6.4	0.2						
Hyperiid amphipods		8.7							
<i>Thysanoessa inermis</i>	1.6		75.1						
Unidentified euphausiids ^d	1.6	0.2	2.3	3.5			0.5	11.2	
Decapods ^e	1.0	1.1		14.0					
<i>Clupea harengus</i>						32.8			
<i>Mallotus villosus</i>	35.9	3.1	0.4		27.9	0.4	61.5	74.3	64.9
<i>Theragra chalcogramma</i>	11.7	2.3	1.2			0.1	0.1	0.6	1.5
<i>Cololabis saira</i>					1.5	1.1			
<i>Sebastes</i> spp.					4.0	1.7			
<i>Hexagrammus</i> spp.						1.0			
<i>Ammodytes hexapterus</i>	23.9	1.4			9.8	61.6	16.2	5.4	33.2
Miscellaneous fishes ^f	14.6	9.5	20.1	4.6	56.8	1.2	19.8	0.7	0.4
Others ^g	0.2	0.1		0.1		0.5	0.1	0.2	
Index of Stomach									
Fullness, Max.(n) ^h	8.1(254)	8.9(42)	4.8(16)	–	14.5(21)	10.7(65)	16.1(423)	8.5(35)	

^a COMU = common murre, TBMU = thick-billed murre, ANMU = ancient murrelet, CAAU = Cassin's auklet, RHAU = rhinoceros auklet, HOPU = horned puffin, TUPU = tufted puffin, AD = adult, IMM = immature.

^b C = coastal, S = shelf, O = oceanic.

^c Includes gonatid squid and unidentified.

^d Mostly *Thysanoessa* spp., plus *T. inermis*, *T. raschii*, and *T. spinifera*.

^e Mostly pandalid shrimp and crangonid shrimp.

^f Includes *Clupea harengus*, unidentified osmerids, unidentified gadids, *Microgadus proximus*, *Trichodon trichodon*, and *Lumpenus* sp.

^g Includes nereid polychaetes, gammarid amphipods, or insects.

^h Weight of stomach contents / (field body weight – weight of stomach contents) × 100; n represents sample size.

The foraging depths of the three puffins are largely a matter of speculation, although puffins appear to feed mainly within the water column (Table 16–12). Presumably, they can descend to at least the 60-m depths common to the Atlantic puffin (*Fratrercula arctica*) (Piatt and Nettleship 1985). The nearly exclusive presence of epipelagic fish in the diet of rhinoceros auklets (Vermeer and Westrheim 1984; Sanger 1983) suggests that they may forage largely in the upper layers. In contrast, the occasional presence of epibenthic prey such as gammarid amphipods, mysids, and pandalid shrimp found in the stomachs of horned and tufted puffins that were collected in daylight (Table 16–16), indicates that they occasionally forage near the bottom.

The breadth of the foraging habitats that are available to the murre is reflected in the variety of both invertebrates and fish in their diet (Table 16–16). Common murre ate at least 15 species of prey, including eight invertebrates and seven fish, and the thick-billed murre ate nine species of prey (Table 16–16). Capelin and sand lance were predominant in the diet of common murre, although pandalid shrimps and mysids were their main food during one winter in Kachemak Bay (G.A. Sanger, U.S. Fish and Wildlife Service, unpubl. data). Cephalopods were the main prey of thick-billed murre.

Both of the small alcids in this group rely heavily on crustaceans (Table 16–14). In general, ancient murrelets and Cassin's auklets appear to specialize on planktonic crustaceans, with ancient murrelets eating mainly euphausiids (77% of total IRI) and Cassin's auklets eating mainly copepods (77% of total IRI) (see also Sanger, in press; Vermeer 1981). Maximum ISF values for these divers (Tables 16–13 through 16–16) were generally intermediate compared with the other species, ranging from 5% for the ancient murrelet to 16% for the tufted puffin.

Both rhinoceros auklets and horned puffins forage mainly in coastal waters, while tufted puffins forage almost equally over the shelf and in neritic waters. The diet of nestling rhinoceros auklets (Table 16–16) observed at Forrester Island in southeastern Alaska (Fig. 16–1) included mainly Pacific herring (*Clupea harengus*) and Pacific sand lance, although at least six other fish species were also in the diet. Sand lance were also an important food of nestling rhinoceros auklets on Middleton Island in the northern Gulf (Hatch 1984). In a recent study in British Columbia, rhinoceros auklets were shown to eat a wide variety of fish (Vermeer and Westrheim 1984).

In general, surface feeders and shallow divers tended to have relatively high ISF's (average of ~14%, with maxima of 16–25%), while ISF's in the demersal/benthic feeders were much lower (average ~4%, with maximum of 9%). These values may indicate a relatively patchy occurrence of prey for near-surface foragers, and their need to gorge when prey is available. The low values for benthic feeders may imply a steadier food supply and suggest that these birds eat smaller, more frequent meals than the surface feeders.

Trophic Levels for Seabirds and Their Prey

Trophic levels (TL's) for prey found in the diets of 19 Gulf of Alaska seabird species were estimated and then used to

graph the TL spectra of their diets (Sanger, in press). The average TL's of the pooled diet of each species was calculated by weighting the TL of each prey with a relative importance in the diet (percent of total IRI for all prey). This method is nearly identical to one used by Mearns, Young, Olson, and Schafer (1981) to examine trophic levels of prey in a fish community off California. Details of this concept as applied to seabirds in the Gulf of Alaska are given elsewhere (Sanger, in press).

Although this approach relies heavily on untested assumptions, it allows insights into how different bird species relate trophically and into how the bird community could relate to lower trophic levels in the ecosystem. The average prey trophic levels ranged from 2.2 in the case of Cassin's auklets—making them nearly primary carnivores, to 4.0 in the case of northern fulmars—making them third-order carnivores (Table 16–17). Other small alcids not included in the discussion (least, whiskered, and crested auklets) have diets consisting largely of calanoid copepods, making them the closest to primary carnivores of all seabirds in the Gulf. The albatrosses, with their diets mostly of large squid, probably have the highest trophic levels.

Biomass of Seabirds and Their Prey

First-order approximations of average summer biomass for seabirds in the Gulf are ~33,000 mt over the shelf, in bays, and in fjords; and ~12,000 mt in oceanic regions.

Table 16–17.

Summary of trophic levels for 19 species of seabirds in the Gulf of Alaska, ranked from highest to lowest. Means are calculated from the estimated trophic levels of each prey taxon in the diet, weighted by % volume of the taxon in the diet (from Sanger 1986b).

SPECIES	SAMPLE SIZE (n)	TROPHIC LEVELS FOR BIRDS' PREY			MEAN FOR BIRD SPECIES
		WEIGHTED MEAN	MIN.	MAX.	
Northern fulmar	43	4.0	2.0	4.0	5.0
Thick-billed murre	38	3.8	2.5	4.0	4.8
Sooty shearwater	178	3.3	2.5	4.0	4.3
Rhinoceros auklet	16	3.1	3.0	4.0	4.1
Tufted puffin	364	3.1	2.5	4.0	4.1
Common murre	166	3.1	2.5	3.2	4.1
Pigeon guillemot	58	3.1	2.0	3.5	4.1
Black-legged kittiwake	373	3.0	2.0	3.5 ^a	4.0
Glaucous-winged gull	66	3.0	2.0	3.1	4.0
Horned puffin	40	3.0	2.5	4.0	4.0
Pelagic cormorant	16	2.9	2.0	3.5	3.9
Marbled murrelet	129	2.8	2.5	3.1	3.8
Fork-tailed storm-petrel	8	2.8	2.0	3.0	3.8
Kittlitz's murrelet	15	2.8	2.5	3.0	3.8
Ancient murrelet	15	2.7	2.5	3.5	3.7
Short-tailed shearwater	201	2.6	2.5	4.0	3.6
Aleutian tern	13	2.6	2.0	3.5	3.6
Arctic tern	34	2.5	2.5	3.1	3.5
Cassin's auklet	8	2.2	2.0	3.0	3.2

^a TL 4.0, prey in diet in trace amount.

These figures are based on population estimates given in Table 16–18.

Since the metabolic rate of a bird is inversely proportional to its body weight, smaller species such as storm-petrels and auklets eat proportionally more than larger species such as shearwaters. We know that short-tailed shearwaters, (which average ~634 g in the Gulf) can eat at least 20% of their body weight per day (Table 16–14).

To estimate the biomass of prey consumed by Gulf seabirds we followed the same procedure as for waterfowl; that is, we assumed that birds of less than 200 g eat the equivalent of 40% of their body weight per day; birds weighing between 200 and 600 g eat 30% of their weight per day; and birds weighing over 600 g eat 20% of their weight per day. Our results (Table 16–19) indicate that the Gulf's pelagic bird community eats an average of ~7,000 mt/d over the continental shelf, and 2,500 mt/d in oceanic waters. These values convert to ~18 kg/km²/d over the shelf and 2.4 kg/km²/d in oceanic waters. Shearwaters account for 61% of the prey consumed over the shelf while murrees and tufted puffins account for another 25 percent. In oceanic waters, shearwaters eat an estimated 65% of the prey biomass, and murrees and puffins eat another 19 percent.

Seabird/Fisheries Interactions

Although Hunt, Burgeson, and Sanger (1981) documented the heavy use of walleye pollock (*Theragra chalcogramma*) by seabirds in the Bering Sea, our feeding studies

suggest that birds are far less dependent on currently harvested species of fish and shellfish in the Gulf of Alaska. Although those commercial species eaten by the birds we studied included Pacific herring, pollock, Pacific cod (*Gadus macrocephalus*), salmon (*Oncorhynchus* spp.), sablefish (*Anoplopoma fimbria*), razor clams, and pandalid shrimps, their cumulative IRI's were generally low (Sanger 1983). However, we made no attempt to sample birds at those times and in those areas where there were concentrations of commercial species of the sizes eaten by birds. The scarcity of both juvenile herring and salmon in the birds' diets is perplexing.

The relatively new, but rapidly expanding pollock fishery in the Gulf may possibly affect bird populations. However, a greater immediate consequence to seabirds in the Gulf would be the development of fisheries for Pacific sand lance and capelin. A capelin fishery may already be imminent. The Icelandic Ministry of Fisheries has expressed an interest in cooperative research with the United States on capelin stocks in Alaskan waters and small experimental fisheries have recently occurred in Bristol Bay (J.M. Nelson, U.S. Fish and Wildlife Service, pers. comm., 1985).

Discussion

Primary production by phytoplankton forms the basis of most marine food chains (Steele 1974). While seabirds are two or more trophic levels removed from primary pro-

Table 16–18.

Estimated populations of seabirds in the Gulf of Alaska in summer (June to August). (Adapted from Gould *et al.* 1982.)

SPECIES	SHELF, SHELF BREAK, AND BAYS (382 × 10 ³ km ²)			OCEANIC (1,025 × 10 ³ km ²)		TOTAL	
	CORRECTION FACTOR ^a	BIRDS (× 10 ³)	%	BIRDS (× 10 ³)	%	BIRDS (× 10 ³)	%
Black-footed albatross	1.0	11	0.1	184	1.0	195	0.3
Northern fulmar	1.3	1,239	2.6	2,276	12.0	3,515	5.2
Mottled petrel	1.0	17	0.1	543	2.8	560	0.8
Sooty shearwater	1.0	12,696	26.5	7,920	41.7	20,616	30.8
Short-tailed shearwater	1.0	13,775	28.8	102	0.5	13,877	20.8
Storm-petrels	1.5	1,519	3.2	4,134	21.8	5,653	8.4
Cormorants	2.0	122	0.2	0	0	122	0.2
Phalaropes	1.0	464	1.0	41	0.2	505	0.8
Jaegers	2.0	182	0.4	369	1.9	551	0.8
Glaucous-winged gull	2.0	992	1.9	61	0.3	983	1.5
Black-legged kittiwake	2.0	2,768	5.8	758	4.0	3,526	5.3
Terns	2.0	385	0.8	328	1.7	713	1.1
Murrees	2.5	3,815	8.0	1,050	5.5	4,865	7.3
Pigeon guillemot	1.5	140	0.3	0	0	140	0.2
<i>Brachyramphus</i> murrelets	1.5	486	1.0	0	0	486	0.7
Ancient murrelet	1.5	252	0.5	15	0.1	267	0.4
Cassin's auklet	1.5	1,397	2.9	184	1.0	1,581	2.4
Rhinoceros auklet ^b	–	139	0.3	61	0.3	200	0.3
Tufted puffin	1.5	5,651	11.8	953	5.0	6,604	9.9
Horned puffin	1.5	1,876	3.9	15	0.1	1,891	2.8
Total		47,857		18,994		66,851	

^a Multiplied by the population estimate to account for birds on colonies.

^b Population estimate adapted from SOWLS *et al.* (1978) for coastal birds and from Gould *et al.* (1982) for oceanic birds.

Table 16-19.

Estimates of biomass of seabirds and prey ingestion by seabirds in the Gulf of Alaska in summer (June to August).

SPECIES	SHELF, SLOPE, AND BAYS						OCEANIC			
	BIRDS			PREY BIOMASS EATEN			BIRDS		PREY BIOMASS EATEN	
	MEAN WEIGHT (g)	ESTIMATED BIOMASS (mt)	INGESTION RATES ^a	mt/d	kg/km ² d	%	ESTIMATED BIOMASS (mt)	mt/d	kg/km ² d	%
BFAL ^b	3,090	34	20	7	< 0.1	0.1	569	114	0.1	4.6
NOFU	610	756	20	151	0.4	2.2	1,388	278	0.3	11.3
MOPE	350	6	30	2	< 0.1	< 0.1	190	57	0.1	2.3
SOSH	842	10,690	20	2,138	5.6	30.8	6,669	1,334	1.3	54.3
STSH	634	8,773	20	1,747	4.6	25.2	65	13	0.1	0.5
STPE	50	76	40	30	0.1	0.4	207	83	0.1	3.4
CORM	1,850	226	20	45	0.1	0.6	0	0	0	0
PHAL	45	21	40	8	0.1	0.1	2	1	< 0.1	< 0.1
JAEG	500	91	30	27	0.1	0.4	184	55	< 0.1	2.2
GWGU	1,290	1,189	20	238	0.6	3.4	79	16	< 0.1	0.6
BLKI	396	1,096	30	329	0.9	4.7	300	90	0.1	3.7
TERN	125	48	40	19	< 0.1	0.3	41	16	< 0.1	0.6
MURR	1,060	4,094	20	809	2.1	11.7	1,113	223	0.2	9.1
PIGU	530	74	30	22	0.1	0.3	0	0	0	0
BRMU	235	114	30	34	0.1	0.5	0	0	0	0
ANMU	226	57	30	17	< 0.1	0.3	3	1	< 0.1	< 0.1
CAAU	203	283	30	85	0.2	1.2	37	11	< 0.1	0.4
RHAU	525	73	30	22	0.1	0.3	32	10	< 0.1	0.4
TUPU	796	4,498	20	900	2.4	13.0	759	152	0.2	6.2
HOPU	547	1,026	20	308	0.8	4.4	8	2		
Total		33,136		6,938	18.2		11,646	2,455	2.4	

^a Assumed ingestion rates as a % of body weight per day; for birds 0 to 200 g, estimate was 40%; for birds 200 to 600 g, 30%; for birds greater than 600 g, 20%.

^b BFAL = black-footed albatross, NOFU = northern fulmar, STPE = storm-petrels, MOPE = mottled petrel, CORM = cormorants, PHAL = phalaropes, JAEG = jaegers, GWGU = glaucous-winged gull, BLKI = black-legged kittiwake, TERN = terns, MURR = murrelets, PIGU = pigeon guillemot, BRMU = *Brachyramphus* murrelets, ANMU = ancient murrelet, CAAU = Cassin's auklet, RHAU = rhinoceros auklet, TUPU = tufted puffin, HOPU = horned puffin.

ducers (Sanger, in press), knowledge of both the environmental mechanisms by which primary production is enhanced and the spatial distribution of such enhancement is of great importance in understanding seabird distribution.

In the coastal Gulf of Alaska, primary production typically increases in spring and decreases through the summer as nutrients in the upper water column are depleted (Sambrotto and Lorenzen, Ch. 9, this volume). Mechanisms that enhance the nutrient supply to the euphotic zone will prolong the phytoplankton bloom through the summer. Five such mechanisms operate in the Gulf of Alaska:

- 1) tidally mixed frontal systems
- 2) advection of oceanic water of the Alaska Current onto the continental shelf
- 3) upwelling promoted by wind stress on the continental shelf
- 4) upwelling in lower Cook Inlet as the result of the intrusion of the Alaska Coastal Current
- 5) vertical shear caused by the Alaska Coastal Current.

It is unclear how these mechanisms, particularly the Alaska Coastal Current, affect seabird distribution. The high seabird densities and the increased primary production as a result of advection of nutrient-rich water onto the shelf are probably related because of the close coupling between primary and secondary production in the Gulf of

Alaska (Cooney, Ch. 10, this volume). Evidence of this coupling may be found in the high densities of shearwaters and albatrosses along the shelf break (Gould *et al.* 1982). The shelf break in the Gulf roughly corresponds to the edge of the Alaska Current, where nutrient enhancement occurs as oceanic waters are pushed onto the shelf (Sambrotto and Lorenzen, Ch. 9, this volume).

The distribution of large seabird colonies in the Gulf may be related to areas of high primary productivity. The continental shelf in much of the Gulf of Alaska is narrow, especially in comparison to the Bering Sea. Most large colonies in the Gulf, such as Forrester and St. Lázaria Islands in southeastern Alaska, Middleton Island in the northern Gulf, and the Semidi and Shumagin Islands in the western Gulf, are relatively close to the shelf break and within the foraging range of many species. Birds nesting on these colonies can exploit food resources in the more productive waters shoreward of the Alaska Current.

Although the Barren Islands in lower Cook Inlet lie far away from the shelf break, large numbers of seabirds nest there. This concentration of nesting birds may be related to upwelling that occurs in lower Cook Inlet as water intrudes from the Alaska Coastal Current (Sambrotto and Lorenzen, Ch. 9, this volume). In addition, we have observed concentrations of shearwaters feeding in lower Cook Inlet near a region of tidal mixing. These mixed fronts may be important to feeding seabirds.

Hunt, Eppley, and Drury (1981) divided the seabird colonies in the Bering Sea into three geographic regions: 1) eastern colonies, 2) outer continental shelf colonies, and 3) northern colonies. The divisions are based on the species composition of nesting seabirds as well as on their feeding habits. The outer continental shelf colonies were the most diverse, supporting large colonies of planktivorous and piscivorous species. We were unable to develop a similar scheme for the Gulf of Alaska, although we found that the breeding seabird avifauna of the western Gulf is more diverse than that of the eastern Gulf. The major differences between the regions are that several planktivores (least, crested, and parakeet auklets), one surface feeder (northern fulmar), and one diving piscivore (red-faced cormorant) found in the western Gulf are absent from the eastern Gulf.

The three parameters that most likely define a species' breeding distribution are: 1) oceanographic conditions, 2) food availability, and 3) the presence of suitable nesting habitat. Relatively few least and crested auklets nest in the Gulf of Alaska. This is especially interesting since their primary food (large calanoid copepods and euphausiids) is abundant (Cooney, Ch. 10, this volume). We suggest that a lack of suitable nesting habitat is the critical factor limiting their eastward penetration into the Gulf. Both species are gregarious inhabitants of talus slopes, which are either rare or totally absent east of the Shumagin Islands. The crested auklet winters in abundance near Kodiak Island (Forsell and Gould 1981), indicating that suitable food is present at least that far east in winter.

Of the three Beringian planktivores in the Gulf of Alaska (least, crested, and parakeet auklets), it is not surprising that parakeet auklets are the most widespread. There is an abundance of their preferred nesting habitat (rock crevices), they have less gregarious nesting habits, and they have a more diverse diet (Sanger 1983; Bedard 1969b). Nevertheless, we cannot explain the lack of parakeet auklets east of Cape St. Elias. Similarly, we are unable to explain the eastward range limits of red-faced cormorants at Cape St. Elias and black-legged kittiwakes in northern southeastern Alaska. Perhaps the red-faced cormorants, the least, crested, and parakeet auklets, and the horned puffins are still expanding their ranges outward from the Bering Sea.

Seabirds migrate into the Gulf of Alaska, arrive at their colonies, and begin reproductive activities coincident with periods when food is available in the spring. Shearwaters fly thousands of miles to reach feeding grounds in the Northern Hemisphere during their non-breeding season. Most shearwaters depart the Northern Hemisphere in late summer and early fall, about the same time that North Pacific nesting species are dispersing from their breeding colonies. The departure of shearwaters from the Northern Hemisphere is probably prompted by an urge to return to their breeding grounds and possibly by a diminished food supply.

Numerous authors have presumed that birds time their reproductive cycles to coincide with food abundance (Belopolskii 1957; Bedard 1969a; and Harrison, Hida, and Seki 1983). Seabirds in the Gulf of Alaska appear to follow this same pattern, although there are no specific studies that relate breeding phenology to food availability. Zooplankton

growth in the Gulf is tightly coupled to the spring phytoplankton bloom (Cooney, Ch. 10, this volume). This means that energy is transferred rapidly to higher trophic levels and presumably is available to plankton-feeding birds early in the season. It follows, then, that the earliest-breeding seabirds in the Gulf of Alaska—fork-tailed storm-petrels, ancient murrelets, and Cassin's auklet—are largely planktivorous (Fig. 16-4). Bedard (1969b) theorized that crested auklets in the Bering Sea delayed their egg laying until the adult calanoid copepods that had overwintered at depth ascended into the birds' foraging range. Most fish-eating seabirds breed later than plankton feeders in the Gulf, reflecting the time lag as energy moves into higher trophic levels.

The productivity of marine birds in the Gulf of Alaska is highly variable, both among colonies and, for some species, among years at the same colonies. Several factors act either individually or in concert to influence seabird productivity. These factors include:

- weather
- age and experience (Ryder 1980)
- type of nest site (Gaston and Nettleship 1981)
- predation
- food supply.

Storms may limit the ability of surface feeders such as kittiwakes to feed in the southern Bering Sea (Hunt, Burgeson, and Sanger 1981b). Storms are also known to affect diving birds (Vermeer, Cullen, and Porter 1979) and may directly affect the nesting success of some species by washing away nests and increasing the exposure of the nestlings (Baird and Gould 1985).

Probably the most important factor influencing the reproductive success of seabirds in the Gulf of Alaska is the food supply. Decreases in the availability of food may hamper egg formation in females, and once eggs are laid, the decreased food supply may increase the amount of time that seabirds must spend foraging. Consequently, this increases the length of each incubation shift, and if the situation became acute enough, it would decrease nest attentiveness by adults. For surface- and cliff-nesting seabirds, decreased nest attentiveness frequently results in an increase in both chick and egg predation by gulls, common ravens, and bald eagles. For example, the reproductive success of northern fulmars on the Semidi Islands has been relatively uniform, except in 1976 and 1985, when longer incubation shifts and decreased nest attentiveness (presumably related to low food availability) resulted in low productivity and increased predation (Hatch 1985).

Avian predation contributes significantly to both chick and egg mortality for several species, including pelagic cormorants, glaucous-winged gulls, black-legged kittiwakes, terns, and murrelets. A lack of food may also decrease reproductive success of kittiwakes by increasing the rate of siblicide (Braun and Hunt 1983). In addition, limited food supplies may increase the mortality rate for gull chicks, since unfed chicks wander farther from their parents than well-fed chicks and are attacked more frequently by neighboring adults (Hunt and Hunt 1976).

Some seabirds maintain high levels of reproductive success when food is in short supply by switching to alternate prey. For example, Baird and Gould (1985) found that tufted puffins at Kodiak Island in 1978 maintained production levels similar to the previous year by supplementing chicks' diets with sand lance when capelin were less available. In order to maintain high levels of reproductive output when switching prey, the alternate prey must be of suitable quality. The reproductive success of glaucous-winged gulls in the northern Gulf decreased when this species was forced to switch from fish to blue mussels (Murphy, Day, Oakley, and Hoover 1984), suggesting that blue mussels were not adequate to sustain reproduction.

Of all the species in the Gulf, the black-legged kittiwakes seem the most susceptible to low food availability, and their reproductive success shows more variability than any other species. Some variation in the reproductive success of black-legged kittiwakes has been successfully explained as a function of both age and experience (Coulson and White 1958). Although age and experience are undoubtedly important for Gulf of Alaska seabirds, it neither explains all the variability in kittiwake productivity, nor explains the low reproductive output for kittiwakes in the Gulf.

There is evidence that productivity in the Gulf for surface-feeding seabirds such as the black-legged kittiwake is more variable than productivity for diving birds from the same colonies. At Kodiak Island in 1978, surface schools of capelin failed to appear during the nestling period, and productivity of kittiwakes fell dramatically from the previous year's level. In contrast, tufted puffins maintained similar levels of production between years by using sand lance to supplement the diets of their young (Baird and Gould 1985). Similarly, in 1983, black-legged kittiwakes throughout the Gulf of Alaska experienced a widespread reproductive failure. In fact, food supplies appeared so limiting to surface feeders and shallow divers that adult kittiwakes and shearwaters were starving (D.W. Nysewander and J.L. Trapp, U.S. Fish and Wildlife Service, pers. comm., 1984). The reproductive success of tufted puffins at Kodiak Island and horned puffins at the Semidi Islands, however, appeared normal (S.A. Hatch, U.S. Fish and Wildlife Service, pers. comm., 1984).

These examples suggest that diving seabirds that are able to exploit the water column are less vulnerable to unfavorable surface water conditions than are surface-feeding birds. A similar phenomenon was observed in the Bering Sea (Hunt, Burgeson, and Sanger 1981). Recent work in the North Atlantic (Piatt and Nettleship 1985) shows that the larger alcids regularly forage far deeper than was previously suspected—to at least 180 m for common murre. It is evident that murre and puffins in the Gulf of Alaska are far less susceptible to the factors that limit the availability of prey for surface feeders.

At present, however, very little is known about Gulf seabird prey or about those factors that influence both the spatial and the temporal variability in the abundance of that prey. It is tempting to speculate that abnormally high surface-water temperatures, presumably related to the 1983 El Niño event in the Pacific Ocean, caused a decrease in the abundance of capelin and sand lance normally found near

the surface. Capelin in Newfoundland will spawn in deeper water if temperatures near the beach are too high (Carscadden 1984), so a strong relationship seems to exist between the natural history of capelin and water temperature.

Two mechanisms have evolved in North Pacific seabirds that enhance productivity in environments with unpredictable food resources: 1) multi-egg clutches and 2) egg and chick neglect. Black-legged kittiwakes lay one to four eggs (Belopolskii 1957) and in good years, they can raise more than one young, offsetting poor reproduction in other years. In years when there is poor reproductive success, brood reduction has usually occurred as a result of increased aggressiveness by the older and larger sibling (Braun and Hunt 1983). Despite their potential for high productivity, kittiwakes in the Gulf of Alaska rarely raise more than one chick (Baird and Gould 1985), contrary to the pattern for kittiwakes in the North Atlantic (Maunder and Threlfall 1972; Wooller and Coulson 1977).

Some seabirds that nest in protected locations are able to periodically neglect their eggs and young. Such a mechanism is particularly important to storm-petrels, which forage far from their colonies and feed on a widely dispersed or patchy prey (Boersma and Wheelwright 1979). Egg neglect has recently been observed in several small alcids as well (Murray, Winnett-Murray, and Hunt 1979; Sealy 1984).

It is clear from Gulf of Alaska feeding studies that two fish species, sand lance and capelin, are very important to seabirds, yet little information is available on their abundance. Winter trawl surveys in Kodiak (Alaska Department of Fish and Game, unpubl. data) indicate considerable annual variability in capelin numbers in some bays, but whether such variability reflects age-class strengths and weaknesses for the fish is unknown.

Our estimates of overall prey biomass consumed per day in the Gulf of Alaska suggest that seabirds are important apex consumers. For a summer period of 120 days, total prey consumption is estimated at 830,000 mt in nearshore, shelf, and shelf-break habitats, and 290,000 mt in oceanic regions. In terms of individual prey species, seabirds in the Gulf consume ~370,000 mt of capelin and 37,000 mt of sand lance during the summer according to diet data from 1977 and 1978 (Sanger 1983). In some areas of the world, fish stock exploitation has had a deleterious effect on seabird populations (Nettleship, Sanger, and Springer 1984). With new interest in developing capelin fisheries in Alaska (J.M. Nelson, U.S. Fish and Wildlife Service, pers. comm., 1985), and the unknown effects that the rapidly growing pollock fishery in the northern Gulf will have on seabirds and other apex predators, it is imperative that we learn more about the interactions between fisheries and seabirds so that we can make scientifically sound recommendations to resource managers regarding the health of the ecosystem.

Conclusions

Adequate descriptive data on bird use of marine habitats in the Gulf of Alaska now exist that can provide a basis for planning future work. Migration times for most shorebirds

and waterfowl are generally well known, as are the migratory pathways for several species. The importance of the Copper River Delta for migrating shorebirds and waterfowl cannot be overemphasized. However, other regions are of equal importance for some species (e.g., the Stikine River Delta and upper Cook Inlet are important for migrating snow geese). The importance of the western Gulf of Alaska to migratory birds remains unclear.

Additional information is needed on the distribution, abundance, and ecology of marine birds wintering in the Gulf of Alaska. Studies to date indicate that thousands of shorebirds and millions of seabirds and waterfowl winter in the Gulf of Alaska. Little is known of their biology, with the exception of a few studies that focused on their distribution and their food habits.

Most seabird research in the Gulf has been descriptive in nature. We are encouraged by recent efforts to continue long-term monitoring programs for seabirds at select colonies. Ideally such studies should include several species that feed at different trophic levels and in different habitats. Future work on colonies should also emphasize collecting both nestling and adult foods over a multi-year period in order to examine the long-term importance of various prey. Offshore seabird distribution studies using dedicated ship time would be very useful, especially for locating and studying important foraging zones. It would be highly beneficial to integrate the study of marine birds into future Gulf of Alaska interdisciplinary scientific investigations.

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ABSTRACT

Seven species of large cetaceans, 12 species of medium and small cetaceans, six species of pinnipeds, and one species of marine mustelid use the Gulf of Alaska. Marine mammals are important components of the marine ecosystem. Human harvesting of these mammals prior to colonization was primarily for use as a source of food and clothing. However, Russian exploration brought a quest for furs which decimated sea otters and fur seal populations.

The protection provided for marine mammals in the Gulf has taken many forms. Federal legal protection was extended to both sea otters and fur seals by the Fur Seal Treaty Act of 1911. The International Whaling Commission regulates the legal harvest of whales. The Marine Mammal Protection Act places a moratorium on the taking of all marine mammals in the United States (except fur seals), while the Endangered Species Act extends special protection to those species in danger of becoming extinct. The State of Alaska also managed and protected several species of marine mammals between the time of statehood (1959) and the passage of the Marine Mammal Protection Act (1972).

This chapter presents a detailed review of the 14 most common species including their:

- habitat requirements
- movements
- distribution and numbers
- vital statistics
- food habits
- food requirements.

Marine mammals in the Gulf are top trophic-level feeders, annually consuming 7.55×10^6 mt of euphausiids, copepods, fishes, cephalopods, and crustaceans. The fin and the sei whales have the highest annual consumption rates followed by Dall's porpoises and Steller sea lions.

The chapter also reviews the interactions between marine mammals and humans, looking at:

- the incidental catch of sea lions during pollock fishing in Shelikof Strait
- the entanglement of marine mammals in marine debris
- how sea otters use commercially important invertebrates
- whale viewing and suspected disturbance
- public awareness of marine mammals.

For the Gulf, there is a lack of information on all aspects of the biology of both beaked whales and most small cetaceans. Belukha whale food habits, taxonomic status, movements, and numbers need more study, as do the food habits of the sea otters. Current declines of pinniped populations warrant immediate attention.

Introduction

The Gulf of Alaska is rich in terms of both the abundance and the diversity of its marine mammals (Table 17-1). There are seven species of large cetaceans, 12 species of medium and small cetaceans, six pinniped species, and one marine mustelid (Morris, Alton, and Braham 1983; Consiglieri and Braham 1982; and Calkins, Pitcher, and Schneider 1975). Marine mammals use the Gulf of Alaska for a number of activities, such as migration, intensive summer feeding, or as a year-round range. Most of the Pribilof fur seals and most of the California gray whales travel through the Gulf of Alaska on their seasonal migration to their summering grounds in the Bering Sea. Several species of Cetacea take advantage of the rich summer food resources of the Gulf, then move south to avoid harsh winter conditions.

Some of the Cetacea, two species of pinnipeds, and the sea otter all inhabit the Gulf for their entire life. The Gulf also makes up a major part of the range of harbor seals, Steller sea lions, and sea otters. The Gulf of Alaska, for the

purposes of this chapter, will be considered as the North Pacific waters north of 52°N and between 130°W and 165°W, or along the coast from Dixon Entrance to Unimak Pass.

There has been a long and close association between Gulf marine mammals and the people who have lived on its shores. Prior to Alaska's colonization, marine mammals were heavily relied upon for food, clothing, and shelter by the indigenous population. Marine mammals were of paramount importance to coastal dwellers who depended upon them for much of their survival. Natives of the Gulf of Alaska used sea lions in much the same way that walrus were used by people of the Bering Sea region. The flesh was eaten, the hides were used both for clothing and for boat coverings, and the intestines were used to make water-repellent clothing. The fur from sea otters, harbor seals, and fur seals was used for garments, and the flesh was an important food source. Belukha whales were also taken for food in Cook Inlet and other cetaceans may have been used on an opportunistic basis throughout the Gulf.

Table 17-1.
Marine mammals of the Gulf of Alaska and their seasonal abundance.

COMMON NAME	SCIENTIFIC NAME	SEASONAL ABUNDANCE*			
		SPRING	SUMMER	FALL	WINTER
Large Cetaceans					
Blue whale	<i>Balaenoptera musculus</i>	R	R	R	-
Fin whale	<i>Balaenoptera physalus</i>	C	A	R	R
Sei whale	<i>Balaenoptera borealis</i>	A	C	R	R
Humpback whale	<i>Megaptera novaeangliae</i>	C	A	C	R
Gray whale	<i>Eschrichtius robustus</i>	C	R	C	A
Pacific right whale	<i>Balaena glacialis</i>	R	R	R	-
Sperm whale	<i>Physeter macrocephalus</i>	C	C	C	-
Medium and Small Cetaceans					
Mink whale	<i>Balaenoptera acutorostrata</i>	A	A	?	?
Killer whale	<i>Orcinus orca</i>	C	C	C	C
Belukha whale	<i>Delphinapterus leucas</i>	C	C	C	C
Short finned pilot whale	<i>Globicephala macrorhynchus</i>	-	R	-	-
Risso's dolphin	<i>Grampus griseus</i>	R	R	-	R
Bering sea beaked whale	<i>Mesoplodon stejnegeri</i>	?	?	?	?
Cuvier's beaked whale	<i>Ziphius cavirostris</i>	R	R	R	R
Northern right whale dolphin	<i>Lissodelphis borealis</i>	-	R	-	-
Baird's beaked whale	<i>Berardius bairdi</i>	R	R	?	?
Pacific white-sided dolphin	<i>Lagenorhynchus obliquidens</i>	C	A	R	R
Dall's porpoise	<i>Phocoenoides dalli</i>	C	C	C	C
Harbor porpoise	<i>Phocoena phocoena</i>	C	C	C	C
Pinnipeds					
Pacific walrus	<i>Odobenus rosmarus</i>	R	R	R	-
Steller sea lion	<i>Eumetopias jubatus</i>	C	C	C	C
Northern fur seal	<i>Callorhinus ursinus</i>	C	C	A	A
Harbor seal	<i>Phoca vitulina richardsi</i>	C	C	C	C
Northern elephant seal	<i>Mirounga angustirostris</i>	-	C	-	-
California sea lion	<i>Zalophus californianus</i>	R	R	-	-
Mustelid					
Sea otter	<i>Enhydra lutris</i>	C	C	C	C

* Modified from Morris, Alton, and Braham (1983).

- C = Regularly present
- A = Greatest abundance
- R = Rare visitor
- = Not known or expected to occur
- ? = No recent data

The rich fur resources of Alaska were probably the driving force that brought most of the early Russian explorers. Bering's second voyage of 1741 created an awareness of these valuable fur resources (Chavigny 1965). The two most highly prized furbearing mammals were the sea otter and the fur seal. The Russian settlements at Kodiak and Sitka were established primarily to serve as bases of operation for fur collection. Operating out of these two bases (occasionally imposing involuntary servitude on local Natives), the Russians harvested sea otters until the sea otter stocks were decimated. During the later period of Russian occupation, some degree of protection was afforded both the fur seal and the sea otter. This protection continued until the Russians sold Alaska to the United States in 1867.

After the U. S. purchased Alaska, unrestricted harvesting was resumed until 1911, when the first International Fur Seal Treaty was signed by the United States, Great Britain, Japan, and Russia. This treaty gave full protection to both fur seals and sea otters. The Pribilof Islands are the breeding grounds for most northern fur seals found in the Gulf of Alaska (Fiscus 1978). This population was reduced to such low levels that commercial harvest ceased until 1917 and then was resumed only for those males considered surplus to reproduction (Baker, Wilke, and Baltzo 1970). In 1956, harvesting of females was resumed on the Pribilof Islands under strictly controlled conditions and continued through 1968 (Chapman 1973).

The Fur Seal Treaty of 1911 gave full protection to sea otters in U. S. waters (Kenyon 1969). By this time, the sea otter had been totally eliminated from much of its former range in the Gulf, although remnant populations remained in Prince William Sound, in the Kodiak Island area, and along the Alaska Peninsula. Once they were given protection, the survivors expanded their population until they repopulated much of their former range. In many areas, the sea otter population has reached the habitat's carrying capacity. In other parts of their range, where otters historically occurred at low density, their numbers have increased markedly and the range they occupy has greatly expanded (Calkins and Schneider 1985).

In addition to the Fur Seal Convention of 1911 and the Fur Seal Treaty Act and its various amendments, there have been numerous state, national, and international laws, conventions, and treaties designed to manage and protect marine mammal stocks. Among the most notable of these are the Marine Mammal Protection Act of 1972, the Endangered Species Act of 1973, and the International Whaling Convention.

Prior to passage of the Marine Mammal Protection Act, responsibility for management and conservation of marine mammals was delegated to the individual states. The state of Alaska pursued a vigorous management and conservation program for harbor seals, sea lions, sea otters, and belukha whales in the Gulf. All other species commonly found in the Gulf were governed by federal authorities. Passage of the Marine Mammal Protection Act curtailed all state management of marine mammals, although provisions were made to return management to the state when certain conditions were met.

The primary objective of the Marine Mammal Protection Act was to maintain the health and stability of the marine ecosystem and—whenever consistent with this primary objective—to obtain and maintain optimum sustainable populations. The act as amended defines an optimum sustainable population as the population level that maximizes species productivity, keeping in mind both the carrying capacity of the habitat and the health of the ecosystem.

Classification of a species as 'endangered' under the Endangered Species Act of 1973 extends special protection to those species that are considered in danger of extinction throughout all or a significant portion of their range (Breiwick and Braham 1984). A species is considered 'threatened' if it is likely to become 'endangered' in the foreseeable future. All seven species of large cetaceans listed in Table 17-1 are presently listed as 'endangered' under the Endangered Species Act of 1973.

The present form of whale management was preceded by the International Whaling Agreement, signed in 1937. It required the signatories to observe a three-month season, limited the number of vessels that could take part, and placed a ban on harvesting gray and right whales (Chapman 1973; Gaskin 1982). Although there was some reference to conservation, according to Gaskin (1982), the participants were far more interested in regulating whale-oil prices. The International Convention for the Regulation of Whaling (drawn up in 1946 and ratified in 1948) gave treaty status to previous agreements and formed the basis for modern whale management (Chapman 1973; Gaskin 1982). This treaty established the International Whaling Commission, which had the power to amend the regulatory provisions from previous agreements and to "organize studies and investigations relating to whaling."

Setting quotas became immediately controversial. Lasting quota allocations were not agreed upon until 1961 (Chapman 1973). The commission was severely limited in its effectiveness because of the provision that allowed any nation to enter an objection to any amendment within 90 days following the annual meeting (Gaskin 1982). Any nation that filed a formal objection was not bound by that amendment.

In 1975, the commission introduced a management policy based on three categories of whale stocks. The first category is the 'protection stock'. Species in this category have populations which have fallen more than 10% below the maximum-sustainable-yield level. No hunting is allowed on these species. The second category is the sustainable management stock. The population of these species is between 10% below and 20% above the level that gives a maximum sustainable yield. A sliding scale for harvesting these species ranges from 0 to 90% of the maximum sustainable yield. The third category is the initial management stock, which includes species whose population level is estimated to be more than 20% above the maximum sustainable yield level. The permitted catch for these species can be as high as 90% of the maximum sustainable yield.

The most effective (if inadvertent) conservation measure for large whales appears to be the overall economics of whaling. When species become depleted and difficult to find, it becomes more costly to operate long distances from home

ports, raising prices and thus reducing demand for whale products. In addition, more individual species of great whales have been protected legally. Worldwide, most species appear to be on the brink of total protection from commercial whaling (Gaskin 1982; Chapman 1973).

All of the great whales except the sperm whale are baleen whales, which feed primarily on euphausiids and copepods. The blue whale is considered to be the largest animal to have ever lived, exceeding 30 m in length and weighing in excess of 100 tons (Rice 1978a). Of the seven species of these great whales which inhabit or transit the Gulf, all have been subjected to heavy commercial exploitation. Pacific right whales were reduced to such low levels that they may be considered severely depleted and their chance of recovery remains uncertain. Gray whales were protected in time for the population to recover to what appears to be near its pre-exploitation level (Reilly 1981).

Our knowledge of the food habits, reproductive biology, size, growth, and internal structure of large whales was derived from animals taken in commercial harvests and from reports of the International Whaling Commission. As commercial whaling decreases, information of this type becomes less available.

The other 12 species of Cetacea are medium and small whales and include beaked whales and porpoises. All except the minke are toothed whales, which feed primarily on fish and squid. Belukhas, or white whales, reside year-round in the northern portions of the Gulf, while many of the other whales probably migrate southward out of the Gulf in the autumn and winter, returning in spring (Mitchell 1978; Wolman 1978; and Braham 1984). Very little information is available about beaked whales. These animals are generally considered deep diving, pelagic species which have not been commercially harvested in the Gulf in recent years (Rice 1978b). Most of our information on beaked whales was derived from examining a few stranded individuals, which were in varying states of decay.

Of the six pinniped species found in the Gulf, only two—the Steller sea lion and the harbor seal—are lifelong residents. Most northern fur seals pass through the Gulf on their annual migration, although some individuals are found in the Gulf during all seasons. The northern elephant seal is a regular summer visitor, found primarily in southeastern Alaska waters. Pacific walrus and California sea lions are also occasional visitors to the Gulf.

The sea otter is the only truly marine mustelid that inhabits the North Pacific. The mustelids also include weasels, mink, skunks, river otters, and wolverines. Unlike all other marine mammals, which rely on blubber or on a combination of fur, hair, and blubber for insulation, the sea otter depends on thick, heavy fur (and guard hairs) and an elevated metabolic rate in order to survive in Arctic waters (Kenyon 1969). The tips of the guard hairs stick together and form a barrier which water (due to its surface tension) does not penetrate. Thus, the otter's skin remains dry even though the otter spends much of its life in the water (Kenyon 1969).

Common Marine Mammals

The following is a brief summary of selected ecological aspects of the species that are commonly found in the Gulf of Alaska (Table 17-1). This summary is not intended to report all that is known about each species, but instead describes some of the more important points of our scientific knowledge of these species.

Fin Whale

The fin whale (*Balaenoptera physalus*) is among the largest of the great whales, second in size only to the blue whale. They are members of the family Balaenopteridae—the groove-throated mysticetes, or rorquals. This family can be divided into two genera: the humpback (genus *Megaptera*) and the finner (genus *Balaenoptera*), which includes blue, fin, sei, Bryde's, and minke whales (Mitchell 1978). Fin whales can attain lengths of up to 24 m, although 22 m is considered large (Leatherwood, Reeves, Perrin, and Evans 1982).

The head of a fin whale is V-shaped; the dorsal fin is prominent and falcate and can be 2 to 3 m tall. The fin whale has between 56 and 100 ventral grooves, which extend at least to the navel. Its color is a uniform dark gray on the back and sides with white underneath and occasionally a grayish-white chevron on the back (Leatherwood *et al.* 1982). Probably the most distinctive characteristic of the fin whale's external morphology is the white coloration on the right lower lip, on the right side of the mouth, and on the right side of the baleen (Leatherwood *et al.* 1982).

Most fin whales found in the Gulf spend the winter in subtropical and temperate waters off coastal California and Baja California, Mexico, where they breed and calve (Leatherwood *et al.* 1982). Most sightings in the Gulf have been in waters either along or inshore of the continental shelf; that is, in waters shallower than 200 m (Nemoto and Kasuya 1965; Consiglieri and Braham 1982). Fin whales begin their northward migration in spring, reaching the western Gulf of Alaska and the eastern Aleutians by April and May. Two main areas used by fin whales in the Gulf during the summer (Fig. 17-1) are the waters around Kodiak Island and those south of Prince William Sound (Hall and Tillman 1977). Use of Prince William Sound is limited to April, May, and June, when fin whales are migrating through the Gulf of Alaska to the Bering Sea (Hall 1979).

Winter sightings of fin whales in the Gulf of Alaska are rare (Consiglieri and Braham 1982), but this may be due to a lack of surveys or to poor sighting conditions. Although fin whales start their southward migration in August, most of them move south in September (Consiglieri and Braham 1982; Nasua 1974; and Slepstov 1961). Fin whales exploit a wide variety of food species whose distributions are highly variable. Accordingly, the fin whale distribution in the Gulf also varies. They are frequently found in coastal waters and can be found offshore to the edge of the continental shelf (Nemoto and Kasuya 1965; Consiglieri and Braham 1982).

Two tagging studies (Nemoto 1959; Fugino 1960) indicated little east/west movement across the North Pacific and supported the hypothesis of Tomilin (1957) and Nishiwaki

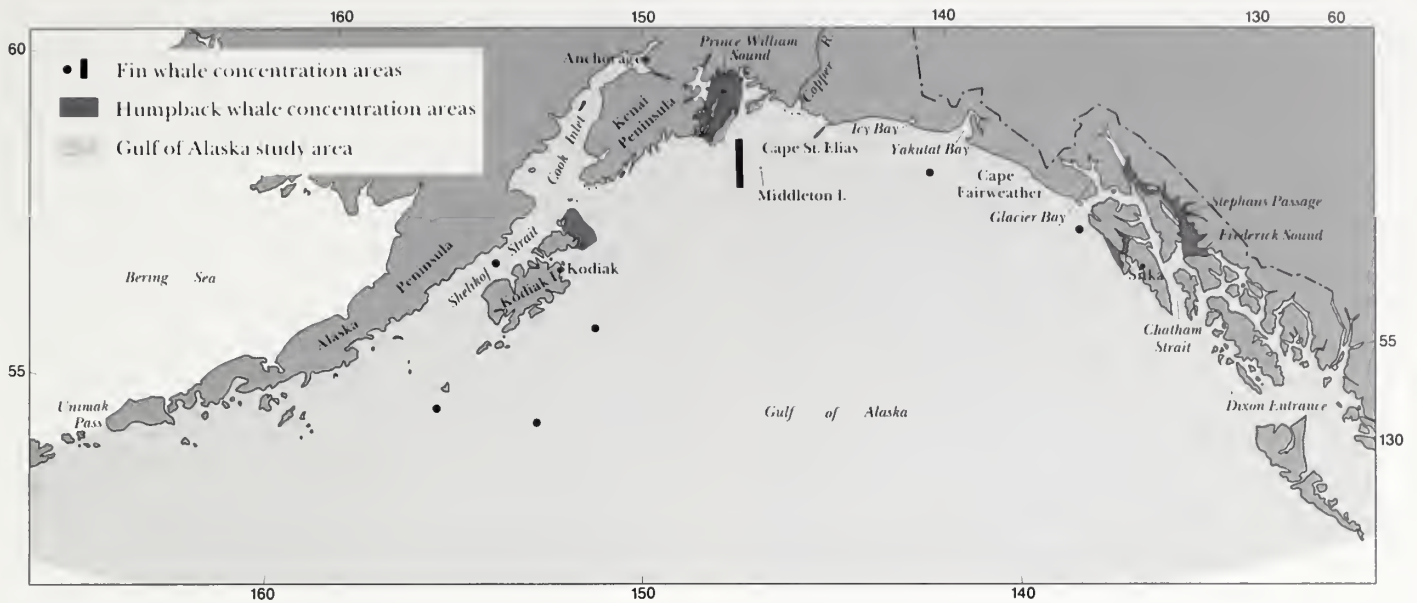


Figure 17-1. Summer sightings of fin and humpback whales in the Gulf of Alaska. (Modified from Consiglieri and Braham 1982.)

(1966) that fin whales are divided into eastern and western stocks. Both stocks migrate north and south, although the Gulf of Alaska stock stays closer to the North American coastline (Mitchell 1978).

The historical population of North Pacific fin whales was estimated at between 42,000 and 45,000 animals (Tillman 1975). The North Pacific stock is presently estimated at 17,000 whales (Ohsumi and Wada 1974). Consiglieri and Braham (1982) estimated that the population of fin whales from the Gulf of Alaska to the Bering Sea probably does not exceed 10,000 whales. Rice and Wolman (1981) estimated that 159 fin whales were present in an area of 76,117 mi² in the north central Gulf of Alaska. Although the International Whaling Commission granted protected-stock status to North Pacific fin whales in 1976, Allen (1974) suggested that it may take as long as 25 years for the population to recover to 90% of its original size.

Calves are born about 6.5 m in length, and lactation lasts until they double in size—which usually takes about 6 months (Ohsumi, Nishiwaki, and Hibiya 1958). Females are generally larger than males and take longer to reach sexual maturity. Sexual maturity occurs at about 18.6 m in females and at 17.5 m in males (Rice 1963). Physical maturity is reached at about 20 m for females and 19 m for males (Rice 1963; Ohsumi *et al.* 1958). The largest female recorded in the North Pacific was 24.4 m, and the largest male was 23.8 m (Tomilin 1957).

Fin whales have a breeding cycle that varies from biennial to triennial (Mitchell 1978). Gestation lasts between 11 and 12 months (Ohsumi *et al.* 1958). The breeding season extends from September through June, peaking in mid-winter (from November through January). Births occur over a similarly protracted period.

Both the abundance and the location of prey for the fin whales are related to seasonal planktonic blooms in the Gulf. Kawamura (1982) reported that fin whales may switch prey species from euphausiids (abundant in late spring and early

summer) to copepods (most abundant in summer and fall). Other less-used prey include fish and cephalopods, which are consumed more during the summer than during the spring (Kawamura 1982).

Calanoid copepods and several species of euphausiids are among the most important prey for the fin whales (Kawamura 1980; Nemoto 1957; Nemoto 1959; and Nemoto and Kasuya 1965). Important species include *Calanus cristatus*, *C. plumchrus*, *C. finmarchicus*, and *Metridia lucens*. These species dwell in warmer surface waters, as does the euphausiid *Thysanoessa spinifera*, which is also heavily used by fin whales (Kawamura 1980).

T. spinifera is a dominant neritic species of euphausiid found in the Gulf (Kawamura 1980). It is restricted to depths of 100 m or less in the shallower, nearshore waters. Other euphausiids preyed upon by fin whales include *Euphausia pacifica*, *Thysanoessa longipes*, and *T. inermis*, which migrate vertically in the water column, generally rising at night (Barnes 1974; Nemoto and Kasuya 1965).

Lockyer (1976a) estimated that fin whales feed twice daily for an average daily consumption rate of 1,000 to 1,500 kilograms. Nemoto (1959) reported that one 17.5-m male fin whale had 759 kg of fish in its stomach.

Sei Whale

Sei whales (*Balaenoptera borealis*) are large balaenopterids which grow to 16 m in length (rarely longer) in the North Pacific (Leatherwood *et al.* 1982). Lengths of physically mature females captured off California averaged 15.6 m; males averaged 13.7 meters. At birth, sei whales are between 4.3 and 5.3 m long (Leatherwood *et al.* 1982; Tomilin 1957; and Masaki 1976). Sei whales are dark gray or bluish gray on the back and sides and on the posterior portion of the ventral surface. On the abdomen, there is a region of grayish white that is almost always confined to the area of the ventral grooves. The right lower lip and mouth cavity are uniformly

gray, unlike on the fin whale. The body often has a 'galvanized' appearance due to scars inflicted either by lampreys (*Lampetra* sp.) or by parasitic copepods (Leatherwood *et al.* 1982).

Sei whales are seasonal residents of the Gulf. They are generally most abundant in the spring (Consiglieri and Braham 1982), although they apparently form local concentrations in summer in certain areas. Masaki (1976) stated that in spring sei whales migrate from the southern breeding and calving areas (20° to 30°N) to the northern feeding grounds. From May through August, the areas of greatest sei whale densities are in the northwestern and the northeastern parts of the Gulf (Masaki 1976).

Sei whales are found throughout the Gulf, although there may be local seasonal concentrations which can change from year to year as the abundance of copepods and euphausiids fluctuates (Nemoto 1959). Sei whales apparently leave the Gulf in late summer and by September, most have departed for southern waters (Masaki 1976). Apparently few sei whales remain in the Gulf during winter, although Consiglieri and Braham (1982) reported one sighting of five animals near the Fairweather grounds during winter months. Rice (1974) conjectured that sei whales winter offshore. Masaki (1976) indicated that sei whales are distributed between 20° and 30°N during January and February.

Heavy commercial exploitation of sei whales did not take place in the North Pacific until 1963, when other, more desirable species became depleted. Tillman (1977) estimated that prior to 1963, the number of sei whales in the North Pacific was on the order of 42,000 animals. By 1966, the sei whale population in the North Pacific had been designated a protected stock by the International Whaling Commission. Tillman (1977) estimated the North Pacific population at 8,600 sei whales.

Breeding and calving occur between October and March when sei whales are in warmer, southern waters. Calving peaks in November and breeding peaks in December (Masaki 1976). Both sexes are thought to attain sexual maturity by seven years; gestation lasts about 10.5 months, with calves born every other year (Masaki 1976).

The diet of sei whales in the North Pacific has been studied by examination of stomach contents of whales taken in the commercial fishery. Kawamura (1980) summarized the examination results for 12,000 whales and found that the most important food was copepods (primarily *Calanus plumchrus*), which accounted for 83% of the diet. Euphausiids made up 13% of the diet, fishes made up 3%, and squids accounted for 1 percent. Tomlin (1957) and Klumov (1963) found that fishes eaten by sei whales include:

- smelt (*Osmeridae*)
- sand lance (*Ammodytes hexapterus*)
- arctic cod (*Boreogadus saida*)
- rockfishes (*Sebastes* sp.)
- greenlings (*Hexagrammos* sp.)
- pollock (*Theragra chalcogramma*)
- capelin (*Mallotus villosus*)
- sardines (*Sardinops sajax*).

Little information is available on the food requirements of sei whales. Lockyer (1976a) estimated the average stomach-content weight for sei whales at 180 to 230 kg for those whales 13 to 17 m in length. Sei whales consume 1.5×10^3 kg of food per day, according to Lockyer (1976a).

Humpback Whale

The humpback whale (*Megaptera novaengliae*) is the only living representative of the genus *Megaptera* and a member of the family Balaenopteridae (rorqual). Newborn calves are between 4.5 and 5.0 m long and females (which are larger than males) reach lengths of 16 m as adults; sexual maturity is reached by both at about 11 to 12 m (Leatherwood *et al.* 1982). Body color is generally gray or black with some white on the ventral surface. The flippers are unusually long (one-fourth to one-third the total body length) and are usually white underneath. Humpbacks have between 14 and 22 throat or ventral grooves which extend to the navel. The baleen is short (seldom more than 80 cm) and numbers between 270 and 400 plates (Leatherwood *et al.* 1982).

Humpbacks are generally found in coastal areas or near oceanic islands (Berzin and Rovnin 1966; Leatherwood *et al.* 1982). They appear to have a strong affinity for nearshore waters, particularly for highly productive fjord-like areas such as southeastern Alaska and Prince William Sound. Those few sightings from the central Gulf of Alaska were probably of animals in transit (Consiglieri and Braham 1982). Humpbacks move seasonally from the warm, southern waters where they winter to the rich, productive waters of the north where they summer.

Humpbacks from the North Pacific winter in three locations: 1) off the Hawaiian Islands, 2) off the Mexican coast, and 3) near the Ryuko, Bonin, and Marianas Islands and Taiwan in the Western Pacific (Berzin and Rovnin 1966; Wolman 1978). Their northward migration begins in March and April, and they arrive in southeastern Alaska in April and May. They remain in the Gulf through the summer and fall and begin their southward migration in November. Some humpbacks apparently spend the winter in southeastern Alaska. There have been a few sightings in the Gulf in February (Consiglieri and Braham 1982), but most whales move further south.

In summer, humpbacks can generally be found in three nearshore areas of the Gulf: 1) near Kodiak Island, 2) in Prince William Sound, and 3) in southeastern Alaska (see Fig. 17-1). Offshore, humpbacks are typically sighted off Kodiak Island, Cape St. Elias, Yakutat, and the Fairweather grounds (Consiglieri and Braham 1982).

In 1966, the International Whaling Commission protected humpbacks from commercial whaling, after more than 50 years of overexploitation of this species. Prior to 1905, the North Pacific population of hump backs was estimated at 15,000 (Wolman 1978). Over 28,000 humpbacks were killed between 1904 and 1965. A recent estimate places the North Pacific population at 1,200 whales (Johnson and Wolman 1984). According to Consiglieri and Braham (1982), this gives the humpback whale the unenviable status of being the second-most depleted whale in the North Pacific, after the North Pacific right whale.

Hall and Johnson (1978) estimated that there were 50 humpbacks in Prince William Sound, while Rice and Wolman (1981) extrapolated their counts in the Gulf to provide an estimate of 306 whales. Von Ziegesar and Matkin (1985) obtained photographs of 96 whales in Prince William Sound. Baker, Herman, Perry, Lawton, Straley, and Straley (1985) estimated that there are between 270 and 373 humpbacks in southeastern Alaska.

Breeding for the humpback takes place in their wintering areas during the period from October to April, with peak activity occurring in December. Gestation lasts 11 to 11.5 months, and lactation continues for an additional 11 months (Tomilin 1957; Rice 1963), resulting in a two-year reproductive cycle. Chittleborough (1960) estimated that a female humpback whale may live for 47 years and give birth to as many as 15 calves.

Wolman (1978) assumed that humpbacks, like other rorquals, feed heavily during summer while they are in high latitudes and then live off the energy stored in their body fat during the winter. However, this assumption has not been tested (Morris *et al.* 1983; Wolman 1978). Nemoto (1959) found that humpback foods consisted primarily of fish and euphausiids. Important fishes were herring (*Clupea harengus pallasii*), capelin, saury (*Cololabis saira*), pollock, and Pacific mackerel (*Scomber japonicus*). Their principal prey varied with location. Kreiger and Wing (1985) suggested that in Glacier Bay, humpbacks switched from their primary diet of euphausiids in the mid-1970s to a diet in the early 1980s that consisted primarily of fish. However, they also found that most of the whales they sighted in Stephens Passage, Frederick Sound, and Chatham Strait were feeding on euphausiids in 1984.

Humpbacks have been observed using several feeding methods. In southeastern Alaska, they use a technique called 'lunge feeding'. During lunge feeding, they plough through prey concentrations with their mouths open. During 'flick feeding', they move their flukes forward at the surface and then dive through the concentrated food. In a third feeding method, they produce a 'bubble net' by swimming in a circle below agitated prey (such as a school of herring) while releasing air bubbles from their blowhole. The bubbles rise to the surface, forming a curtain; this presumably frightens the prey and concentrates them in the center of the rising ring of bubbles. The humpback then rises swiftly through the prey with its mouth open, engulfing the food (Ingebrigtsen 1929; Jurasz and Jurasz 1979).

The only information available on the food amounts consumed by humpbacks is from Tomilin (1957) who reported on the prey he found in two stomachs that contained large volumes of food. He found 500 kg of *Thysanoessa longipes* in the stomach of a 14.3 m female and 600 kg of saffron cod in the stomach of a male of unspecified length.

Gray Whales

Gray whales (*Eschrichtius robustus*) are morphologically distinct from other baleen whales (Barnes and McLeod 1984). Apparently, the incomplete fossil record does not provide any basis for understanding the evolutionary his-

tory of gray whales. Their baleen is considered to be primitive because there are fewer plates and the plates are thicker than those of other balaenopterids (Barnes and McLeod 1984).

Gray whales grow to a maximum length of ~14 m and typically weigh ~33 t (Leatherwood *et al.* 1982). They are strongly tapered at both ends, have a narrow, triangular head, have a slightly arched mouthline, and exhibit a low hump on their back. The skin is mottled gray due to both natural pigmentation and extensive scarring from barnacles (Leatherwood *et al.* 1982). The short, coarse baleen plates number between 138 and 180 per side and are colored yellowish-white to white.

Gray whales migrate through the Gulf of Alaska on their way both to and from summer feeding grounds in the Bering and Chukchi Seas (Fig. 17-2). Generally, gray whales are found within 4 km of shore except when crossing the entrance to Prince William Sound or when going from Kodiak Island to the south side of the Alaska Peninsula (Rugh 1984). Rice and Wolman (1971) report that gray whales are seldom found in waters deeper than 180 meters. Pike (1962) suggested that gray whales use topographical clues for orientation. Their migratory routes may be most influenced by the availability and the composition of food (Braham 1984).

Gray whales winter along the west coast of Baja California, Mexico, and migrate the 9,000 to 14,000 km to the Bering and Chukchi Seas each spring. The migration route through the Gulf of Alaska is entirely coastal (Braham 1984). Animals segregate by sex and age during the migration, with single adults arriving first followed by pregnant females, subadults, postbreeding males, and finally by the cows with their calves (Rice and Wolman 1971). In 1977 and 1978, the migration past Cape St. Elias peaked during the third week of April (Cunningham and Stanford 1979). Generally, the migration through the Gulf of Alaska and into the Bering Sea is complete by the end of June or by early July (Braham 1984).

Some whales remain south of the Bering Sea in summer (Pike 1962; Pike and MacAskie 1969; Rice and Wolman 1971; and Darling 1984). Summer distribution of gray whales in the Gulf of Alaska is not well documented. Consiglieri and Braham (1982) recorded sightings of gray whales at a variety of sites: 1) the south side of Kodiak Island, 2) in the Hinchinbrook Entrance to Prince William Sound, and 3) between Cape St. Elias and southeastern Alaska. All their sightings were in waters very near shore. These sightings may have been local feeding groups or may have been cows with their slower calves.

The peak of the southbound migration in the Gulf lasted from late November to early December (Rugh 1984; Consiglieri and Braham 1982; and Rugh and Braham 1979). Most gray whales have left the Gulf by early January. The route of the southward migration is not as well understood as the route of northward migration; however, sightings have been made both nearshore and offshore in the fall and early winter. Braham (1984) suggested that the few sightings which have been made indicate that the whales follow a coastal route, although possibly farther offshore.

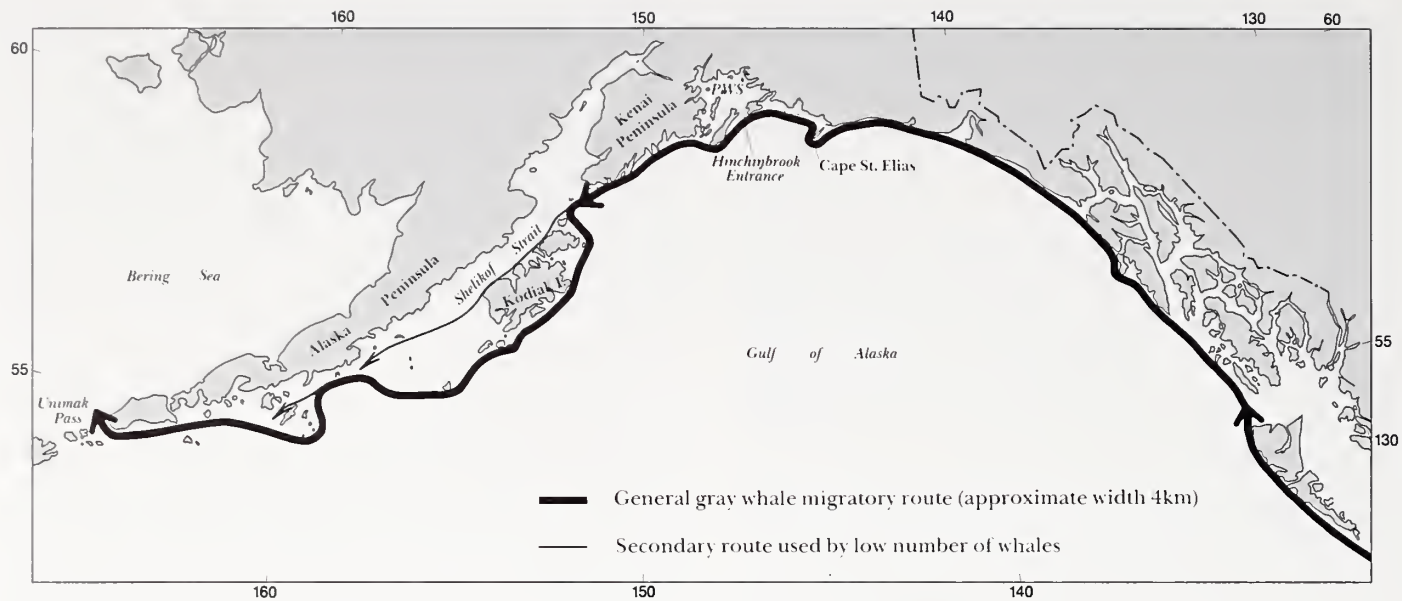


Figure 17-2. Generalized spring migratory route of gray whales through the Gulf of Alaska.

Nineteenth-century commercial exploitation of gray whales was devastating to the population because it took place in the wintering lagoons where cows and calves were easily taken (Henderson 1984). Reilly (1981) estimated the original gray whale population at between 15,000 and 24,000; Henderson (1984), however, suggested that the population did not exceed 15,000 when whaling began in the southern calving areas during 1845–1846. Approximately 4,000 whales still survived in 1874—when nineteenth-century gray whaling in the calving lagoons effectively ended (Henderson 1984).

Whaling on gray whales continued into the twentieth century. However, the emphasis was shifted to pelagic whaling. In 1966, commercial whaling on gray whales was terminated when they were designated a Protected Stock. In 1979, gray whales were redesignated a 'Sustained Management Stock', and currently a subsistence take is allocated to (or on the behalf of) the coastal Natives of the Soviet Union and the United States.

The eastern North Pacific gray whale population appears to have recovered to near pre-nineteenth century exploitation levels and probably is now nearing the carrying capacity of its range (Reilly 1981). The most recent population estimate is between 13,000 and 17,000 whales (Reilly 1981, 1984). The population apparently grew at a rate of 2.5% annually between 1968 and 1980 (Reilly 1981). This stock has been considered endangered by the United States; however, the National Marine Fisheries Service has initiated action to have the stock reclassified as threatened (S. Zimmerman, National Marine Fisheries Service, Juneau, AK., pers. comm., 1985).

Female gray whales become sexually mature at lengths of between 11.7 m and 12 m, while males reach sexual maturity between 11.0 m and 11.1 m (Blokhin 1984; Rice and Wolman 1971). Calving occurs off Baja California during January and February, although some calves may be born in the Gulf (Consiglieri and Braham 1982). Estrus and conception occur

in late November or in December (Rice and Wolman 1971) although sexual activity has been observed at other times of the year (Cunningham and Stanford 1979). Lactation continues until August (Rice and Wolman 1971). Gray whales take two years to complete a reproductive cycle; a female may reproduce for nearly 40 years and produce as many as 12 calves (Consiglieri and Braham 1982; Rice and Wolman 1971).

Generally, gray whales move to northern latitudes annually to take advantage of rich food resources. Some whales apparently linger along the coast to feed, rather than to complete the migration into the Bering Sea, while some feed at select locations along the route (Nerini 1984). Gray whales feed on several species of benthic amphipods in the Bering Sea and may also eat polychaetes, mysids, planktonic decapods, gastropods, and some bivalves. The extent to which these resources are used in the Gulf of Alaska has not been documented (Nerini 1984). Schooling fishes such as herring or capelin may be important during migration, since they are abundant near Kodiak Island and off southeastern Alaska (Consiglieri and Braham 1982; Morris *et al.* 1983).

Zimushko and Lenskaya (1970) estimated that a gray whale consumes ~ 300 kg of food per feeding. Lowry, Frost, Calkins, Swartzmann, and Hills (1982) assumed four feeding bouts per day, based both on their own observations of other baleen whales as well as on the field observations of Zimushko and Lenskaya (1970). They estimated a daily food consumption of 1,200 kg in the Bering and Chukchi Seas. We can only infer consumption amounts for the Gulf of Alaska because we have no feeding-rate estimates.

The Gulf of Alaska is important to gray whales primarily as a migratory corridor, although some feeding and reproductive activity probably occur there. The Gulf is used by nearly the entire eastern gray whale stock as it moves along its route between the breeding and calving lagoons of Baja California and the rich feeding areas of the north.

Sperm Whale

The sperm whale (*Physeter macrocephalus*) is the largest representative of the odontocetes or toothed whales and is classified as endangered by the United States under the Endangered Species Act of 1973. According to Leatherwood *et al.* (1982), sperm whales are among the easiest of the large whales to identify because of the disproportionately large head. Much of the bulk of the head consists of the spermaceti organ. The development of a spermaceti organ—which consists of an oil-filled structure that appears to have a role in controlling buoyancy—is a specialization peculiar to the physeterids (Gaskin 1982).

The sperm whale's huge head accounts for one-fourth to one-third its total length; the blowhole, an S-shaped structure, is located on the forward half of the head (Rice 1978c). The dorsal hump or fin is usually rounded at the peak, but is sometimes triangular shaped. It is located about two-thirds of the way back from the front of the head (Leatherwood *et al.* 1982). Sperm whales usually are dark brownish-gray with white areas on the belly, on the front of the head, and around the mouth.

The sperm whale's mandible has about 25 teeth per side and can be as much as 1.5 m shorter than the snout (Rice 1978c; Leatherwood *et al.* 1982). Maxillary teeth are usually rudimentary, seldom erupting through the gums. Adult males can reach lengths of 17 m and average 15 meters. Adult females are generally smaller, rarely exceeding 12 m (Leatherwood *et al.* 1982). At birth, calves are about 3.5 to 5 m long and weigh about 1.0×10^3 kilograms.

In the Gulf, sperm whales are found near the continental slope and in the deeper waters beyond (Smith 1980; Ohsumi 1980). According to Berzin (1970), sperm whales feed from mid-water depths to the ocean bottom.

Sperm whales spend the winter months in more temperate waters of the North Pacific from the equator to approximately 40°N (Berzin 1970). Pike and MacAskie (1969) reported the appearance of sperm whales off the coast of British Columbia in spring, and the young (subadult) males remain there throughout the summer. The northern limit of the females' range appears to be the 15C isotherm (or 50°N)—well south of the Gulf of Alaska. Consequently, adult females and immatures (maternity schools) would be rare visitors to the Gulf.

Apparently, the distribution of sperm whales shifts further offshore in summer, because Rice and Wolman (1981) sighted 36 individuals over deep water beyond the continental shelf. Very few sperm whale sightings have been made in the Gulf of Alaska in autumn. However, Consiglieri and Braham (1982) and Pike and MacAskie (1969) thought that the sightings were consistent with other records that indicated a southward movement. Consiglieri and Braham (1982) reported one winter sighting in the Gulf when a single sperm whale was observed on the Fairweather grounds in 1979.

Although sperm whales were continuously harvested for over three centuries, substantial numbers of animals were not taken prior to 1947 (Berzin 1970; Tillman 1976). Apparently, few sperm whales were taken from the Gulf of Alaska over the last several decades. Rice (1978c) estimated the

sperm whale population in the North Pacific at 7.4×10^5 individuals. The eastern North Pacific population is currently (1982) estimated at 1.74×10^5 whales (Gosho, Rice, and Brewick 1984). No estimate is available for the numbers of sperm whales that occur in the Gulf of Alaska.

Sperm whales mate in waters south of the Gulf of Alaska in spring or early summer (Rice 1978c). Females reach maturity at about nine years (Ohsumi 1965; Lockyer 1976b). According to Gosho *et al.* (1984), puberty is prolonged in the males, beginning at about nine years of age and reaching completion when the testes are fully spermatogenic at about 20 years.

Calves are born between June and October with peak calving activity occurring in August. The total gestation period is ~14 to 17 months (Best 1968; Ohsumi 1966), and lactation lasts from 12 to 24 months. With a reproductive cycle of between 3 and 6 years, sperm whales may have the lowest reproductive potential of any marine mammal (Gosho *et al.* 1984).

Throughout the North Pacific, sperm whales eat mainly cephalopod mollusks—particularly squid of the family Gonatidae—and bottom-dwelling fish (Gosho *et al.* 1984; Kawakami 1980; Okutani and Nemoto 1964; and Rice 1963). They are noted for their ability to make prolonged, deep dives (Rice 1978c). Sperm whales have been reported to feed on bottom-dwelling sharks in water depths over 3,049 m off South Africa (Rice 1978c). In the Gulf of Alaska, Okutani and Nemoto (1964) found fish to be the predominant prey, but gave no species identification. The most commonly eaten fish include rockfishes, cod (Gadidae), skates (Rajidae), lancet fish (*Alepisaurus ferox*), lumpfish (Cyclopteridae), and rattails (*Coryphaenoides* sp.) (Berzin 1959, 1970; Okutani and Nemoto 1964; and Kawakami 1980). Daily food consumption rates for sperm whales ranges from 2 to 4% of the total body weight (Lockyer 1976b; Kawakami 1980).

In the North Pacific, two stocks of sperm whales are currently recognized: the eastern and the western stocks (Best 1975; Harwood and Garrod 1980; Bannister and Mitchell 1980; and Gosho *et al.* 1984). The boundary between the two stocks runs through Amchitka Pass in the western Aleutians at 50°N, 180°W, then southeast to the Hawaiian Islands (20°N, 160°W).

Minke Whale

The minke whale (*Balaenoptera acutorostrata*) is the smallest baleen whale in the Gulf. Its nicknames—'little piked whale' or 'sharp-headed finner'—refer to its narrow head and pointed rostrum. The rostrum is divided sagittally by a distinctive ridge running forward from the blowhole (Leatherwood *et al.* 1982). Minke whales are usually black or dark gray, with white on the belly and undersides of the flippers. The most conspicuous marking is a white band across the top of the flippers (Leatherwood *et al.* 1982). The dorsal fin is tall and falcate and there are between 50 and 70 thin ventral grooves, the longest ending slightly forward of the navel. The size of minke whales at birth varies from 2.1 to 2.8 m and they double in size by six months (Omura and Sakiura 1956). Females, which are larger than males, reach physical matu-

rity at about 8 m, although they sometimes reach lengths of 10 m (Leatherwood *et al.* 1982).

With spring, sightings of minke whales become common over the continental shelf and in the nearshore waters of the Gulf. Over 95% of the sightings are shoreward of the 200-m contour (Consiglieri and Braham 1982). North Pacific minke whales are distributed from the equator north to the Chukchi Sea (Leatherwood *et al.* 1982), and are most abundant in Alaska waters during the summer. They are less common in British Columbia and southeastern Alaska than they are in the waters of the Gulf of Alaska and the eastern Aleutian Islands (Scattergood 1949).

In a 1980 survey of the Gulf, Rice and Wolman (1981) found minke whales in nearshore waters from southeastern Alaska to Kodiak Island; only three individuals were seen in oceanic waters of the Gulf. They are frequently observed in some bays of Kodiak Island in summer (T. Emerson, Alaska Department of Fish and Game, pers. comm. cited in Consiglieri and Braham 1982), as well as in Prince William Sound and Yakutat Bay. Their summer movements may be local and related to territoriality. In an area of 660 km² of Puget Sound, 16 whales used at least three adjoining, exclusive ranges (Dorsey 1983). At least part of this range was probably seasonal.

Minke whales move into the Gulf in April and summer there. By October, most have left coastal Gulf waters, and have moved south. Of the five recorded minke whale sightings in winter in the Gulf of Alaska, two were south of Icy Bay and three were near Sitka (Consiglieri and Braham 1982).

Minke whales are found near shore for the most part. In Japan, no minke whales were taken beyond the 185-m contour (Omura and Sakiura 1956). Sexual segregation was reported for minke whales off the coast of Japan, where the immature males remained in southern waters, while the mature animals—mostly adult females as well as some immature females—migrated to northern feeding grounds (Omura and Sakiura 1956).

There is no current population estimate for North Pacific minke whales, but they are considered abundant. There is no current minke whale harvest in the area nor has there been an historically heavy take (Consiglieri and Braham 1982; International Whaling Commission 1981). The worldwide population was estimated at 3.25×10^5 individuals (Scheffer 1976).

Based on samples taken from Antarctic minke whales, the mean age at sexual maturity has dropped from 14 years to 6 years for males and from 14 years to 7 years for females (Masaki 1979). Masaki (1979) suggested this might be a result of the intense exploitation of baleen whales, including the increased harvest of minke whales. There is no data available on age of sexual maturity of minke whales in the Gulf. Sexual maturity in minke whales off Japan was reached at 7.4 m for females and at 6.8 m for males (Omura and Sakiura 1956). Gestation takes from 10 to 11 months. Lactation, which lasts approximately 6 months, has been observed during ovulation in Antarctic minke whales, indicating an annual reproductive cycle (Lockyer 1981). The reported minimum pregnancy rate is 0.86 (International Whaling Commission 1981).

Very little information is available on the food of minke whales in the Gulf. In general, euphausiids and schooling fishes are their main foods (Ohmura and Sakiura 1956; Tomilin 1957; Nemoto 1959; and Klumov 1963). Fishes eaten include pollock, salmon (*Oncorhynchus* sp.), cod, sand lance, and herring. One whale found stranded on Unalaska Island had small pollock in its stomach (Frost and Lowry 1981). The main euphausiids taken are probably *Thysanoessa spinifera* and *Euphausia pacifica* (Nemoto and Kasuya 1965). Lockyer (1981) estimated daily food consumption by minke whales at 4% of the total body weight in summer.

Killer Whale

Killer whales (*Orcinus orca*) are among the most widely distributed of all marine mammals. They occur in all oceans, major seas, and all ocean zones of the world (Dalheim, Leatherwood, and Perrin 1982). There are certain areas where they concentrate, such as within a few hundred kilometers of the coast and in the higher latitudes (Perrin 1982). Killer whales have a conspicuous, prominent mid-dorsal fin which in adult males can be 1.8 m tall. Females and juveniles have a smaller, somewhat falcate dorsal fin, usually less than 1 m tall (Leatherwood *et al.* 1982). The large flippers, which are shaped like broad, rounded paddles, are also distinctive (Leatherwood *et al.* 1982). Coloration in killer whales is sharply contrasting white and black. There is a large oval white patch above and behind each eye, the chin and throat are white, and the ventral surface is white. The white on the ventral surface narrows between the flippers, then continues up on each side of the flanks. Most animals have a light gray saddle behind the dorsal fin. Male killer whales reach lengths of 9.5 m (average ~8 m) and weigh approximately 8 mt, while females reach lengths of 8.2 m (average ~7 m) and weigh approximately 4 mt (Dalheim 1981). Newborns are 2.1 m to 2.4 m in length and weigh about 180 kilograms.

Killer whales are ubiquitous and abundant in the Gulf of Alaska. According to Consiglieri and Braham (1982) and Leatherwood, Balcomb, Matkin, and Ellis (1984) they are especially common near Kodiak Island, in Prince William Sound, and in the coastal waters of southeastern Alaska. Some killer whales are probably year-round Gulf residents (Braham and Dalheim 1982). In spring, killer whales can be found throughout the Gulf, primarily in the shelf waters shallower than 200 meters. The summer concentration areas are south and east of Kodiak, over Portlock Bank, in Prince William Sound, and in the inland waters of southeastern Alaska (Consiglieri and Braham 1982).

No specific, well-defined seasonal migrations have been documented for killer whales in the Gulf, although sightings of whales in waters as far as 100 nautical miles offshore have been interpreted by Consiglieri and Braham (1982) to be migrating animals. A group estimated to contain 500 killer whales sighted near Middleton Island in April 1973 (Jim Branson, National Marine Fisheries Service, pers. comm. cited in Calkins, Pitcher, and Schneider 1975) could represent a northward spring migration. According to Dalheim (1981), both the movements and the distribution of killer

whales are related to fish movements in summer and autumn. They are known to prey on shoreward-migrating schooling fish such as salmon and herring both in southeastern Alaska and in Prince William Sound (Nishiwaki and Handa 1958; Fiscus 1980).

No reliable estimate of killer whale abundance is available. Leatherwood *et al.* (1984) counted a minimum of 286 killer whales in three study areas (173 in Prince William Sound, 96 in southeastern Alaska, and 17 in the Shelikof Strait area). These direct counts only represent a fraction of the total number of whales present in those areas and an even smaller fraction of the total number of killer whales in the Gulf of Alaska.

Age at sexual maturity is not known, but is inferred both from the size of collected specimens and from the known growth rates of captive animals. Based on commercial catches of killer whales by Norway (Jonsgård and Lyshoel 1970), few pregnancies occur in females that are less than 4.9 m (16 ft) long. There is a marked increase in pregnancies in females over 4.9 m (16 ft). Gestation ranges from 12 to 16 months (Nishiwaki and Handa 1958; Perrin 1982). No direct evidence is available on the length of lactation in killer whales, but the calf remains closely associated with the cow for a period of between one and two years (Perrin 1982; Dalheim 1981).

Killer whales prey on a variety of fish and marine mammals, but appear to prefer fish when they are abundant. Lowry *et al.* (1982), after extensively reviewing the literature, conclude that they have one of the most diverse diets of all marine mammals. The relative importance of individual food species in the diet has not been determined, but they are known to eat fur seals, walruses, sea lions, elephant seals, harbor porpoises, Dall's porpoises, minke whales, cods, flatfishes (Pleuronectidae), and salmon (Tomilin 1957; Nishiwaki and Handa 1958; Bychkov 1967; Rice 1968; Fiscus 1980; and Dahlheim 1981). The daily food intake for four captive killer whales was estimated by Sergeant (1969) to be between 3.6 and 4.4% of their total body weight.

Belukha Whale

The belukha (beluga, or white whale) (*Delphinapterus leucas*) is the only medium-sized odontocete, common in the Gulf, that lacks a dorsal fin. Adult male belukhas reach lengths of between 3.2 and 4.4 m and weigh 520 to 1,200 kilograms. Females can be between 3.1 and 3.6 m in length and weigh 480 to 700 kilograms. Most newborn calves are about 1.6 m long (Kleinenberger, Yablokov, Bel'kovich, and Terasovich 1964; Leatherwood *et al.* 1982). Most adults are completely white, while newborns and immature animals are gray-shaded with blue or brown. Males become white as they reach nine years of age or older, while the females may become white as early as age six—but may retain some gray coloration for as long as 21 years (Burns and Seaman 1985). Belukhas are closely related to narwhals (*Monodon monocerus*), and in the eastern Canadian Arctic, these two whales are sympatric.

Belukhas are generally found in the open waters of those arctic and subarctic regions that are seasonally covered with ice. The Cook Inlet stock in the northern Gulf of Alaska is

thought to be an isolated population. The nearest belukhas to the Cook Inlet stock are found in Bristol Bay on the north side of the Alaska Peninsula. No interchange between these stocks has been documented (Calkins 1984). Fay (University of Alaska, pers. comm., 1979) suggested the possibility of morphological differentiation between these stocks. He examined a limited series of skulls from Cook Inlet and compared them to skulls from other areas. The Cook Inlet sample was too small to conclude that the skull morphology differed from whales of the Bering Sea population (Calkins 1984).

Belukhas are sighted mostly in coastal or continental shelf waters. They frequent shallow waters, bays, and estuaries, and often enter rivers. Belukhas commonly concentrate in the mouths of rivers during calving, possibly because of a thermal advantage to newborns and other age classes (Sergeant 1973; Sergeant and Brodie 1975; and Fraker, Sergeant, and Hoek 1978). In Cook Inlet, belukha concentrations have been observed near the mouths of the Susitna, Lewis, and Beluga rivers in late May and June. They may be attracted to these areas by large numbers of anadromous fish, particularly eulachon (*Thaleichthys pacificus*), which are abundant there during the spring (Calkins 1984).

Belukhas move seasonally in relation to the ice that forms over much of their range. Virtually all of the belukhas from the Bering, Chukchi, and Beaufort Seas spend the winter along the Bering Sea ice fringes (Kleinenberger *et al.* 1964; Fay 1974; Seaman and Burns 1981). In the Gulf of Alaska, belukhas follow a seasonal pattern: they move into upper Cook Inlet in the spring, they concentrate near the mouths of rivers in the early summer (May and June), they can be found throughout Cook Inlet through late summer, and then probably move to the lower Inlet in winter (Fig. 17-3).

Some belukhas have been seen in Yakutat Bay (Calkins and Pitcher 1977) on an irregular basis. Consiglieri and Braham (1982) reported annual observations in Yakutat Bay by local fishermen. However, those reports are anecdotal and lack sufficient documentation to conclude that there is a small, resident population in Yakutat Bay. The belukhas that are seen in Yakutat Bay are probably members of the Cook Inlet stock and move across the north Gulf of Alaska. Other sightings reported outside Cook Inlet were at the Barren Islands, Marmot Bay north of Kodiak Island, Montague Island, and Shelikof Strait (Consiglieri and Braham 1982). In July 1983, approximately 200 belukhas were sighted in Prince William Sound just south of Bligh Island. These are assumed to have been part of the Cook Inlet stock.

No systematic, thorough surveys have been made of the Cook Inlet belukhas. Klinkhart (1966) estimated this stock at between 300 and 500 animals. Recent census work has not appreciably changed that estimate (Murray and Fay 1979; Calkins 1984). Estimates of between 300 and 500 individuals were based on direct counts and do not account for those animals that were underwater (and not seen) or for animals which were beyond the survey area. It is possible that there may be as many as 2 to 4 times more belukhas in the area than the current estimate.

Female belukhas are capable of breeding late in their third or fourth year. Males are sexually mature by the eighth year (Brodie 1971; Sergeant 1973; and Seaman and Burns

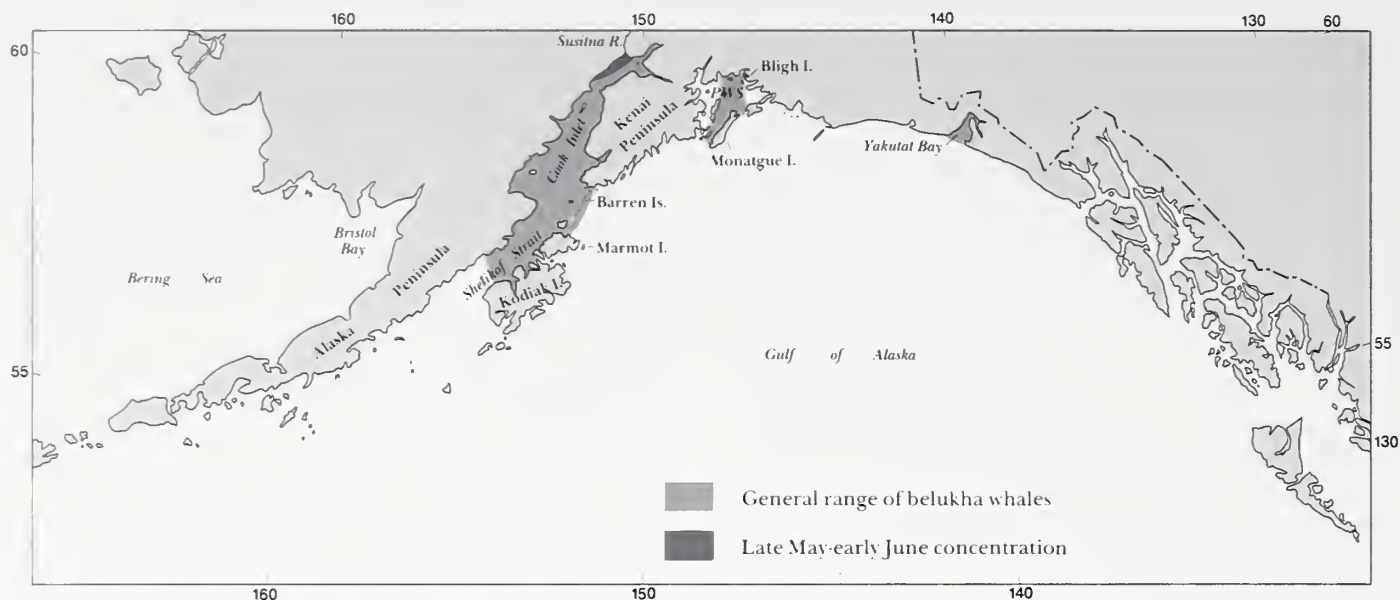


Figure 17-3. Distribution of belukha whales in the Gulf of Alaska.

1981). Breeding occurs in May and calving takes place in July or August after a gestation period of about 14 months (Lensink 1961; Fraker 1977; and Seaman and Burns 1981). Calving is followed by a two-year nursing period (Brodie 1971; Sergeant 1973) that completes a triennial breeding cycle.

Belukhas feed both on fish and on some invertebrates. Although they are capable of diving deeper, they feed primarily in the upper 10 m of water (Kleinenberger *et al.* 1964). Little information is available on the feeding habits of belukhas in Cook Inlet. However, Calkins (1984) observed whales (assumed to be feeding), in association with concentrations of anadromous fishes such as salmon or eulachon. In other parts of their range, belukhas eat over 100 species (Kleinenberger *et al.* 1964). Common in their diet are smelt, capelin, eulachon, herring, and saffron cod (*Eleginus gracilis*).

In offshore waters, Arctic cod and pollock may be important prey, along with shrimps, octopus, and sculpins (Lowry, Frost, and Seaman 1985). Sergeant (1969) presented data on the feeding rates of captive belukhas. He estimated that their consumption rate was between 4 and 7% of their body weight per day, with the highest percentage representing the feeding rate of a calf.

Pacific White-sided Dolphin

Pacific white-sided dolphins (*Lagenorhynchus ololiquidens*) are also commonly called lags, a term that is an abbreviation of the genus *Lagenorhynchus*. They are strong swimmers and leapers, sometimes turning complete aerial somersaults (Leatherwood *et al.* 1982). Lags reach a length of at least 2.3 m and may weigh as much as 150 kilograms. They have a moderately tall, strongly recurved dorsal fin that is situated in the mid-back. Their coloration is usually distinctive: a black back, light gray sides, and a white belly. A white or light-gray stripe starts at the forehead and face, then curves upward

over the top of the head, continues along the back to the area of the dorsal fin, and finally widens and curves toward the anus, forming a prominent, light gray patch on the flank. The dorsal fin is dark on the forward one-third and light gray on the rear two-thirds (Leatherwood *et al.* 1982).

Pacific white-sided dolphins frequent the continental shelf slope and the coastal heads of deep-sea canyons (Leatherwood and Reeves 1978). They range throughout the Gulf of Alaska. There is not enough information to characterize their seasonal movements as migrations, although they are seasonally abundant in some areas (Consiglieri and Braham 1982).

Pacific white-sided dolphins become increasingly abundant in the spring, particularly in the eastern Gulf. The period of highest abundance is during the summer, when they concentrate over the Fairweather Ground and Portlock Bank (Consiglieri and Braham 1982). Autumn sightings have been reported from both the northeast and the northwest Gulf. Winter sightings have been rare (Consiglieri and Braham 1982).

Lags are extremely gregarious and groups of over 1,000 individuals have been sighted in the Gulf. Groups consisting of over 100 lags are common (Morris *et al.* 1983). While no reliable estimate of the total number of Pacific white-sided dolphins in the Gulf was found, it is estimated that there are between 2,000 and 3,000 individuals.

Reproductive biology of Pacific white-sided dolphins is not well understood. Males are sexually mature at between 1.7 and 1.8 m and females mature at between 1.8 and 1.9 meters. Most calving apparently takes place in the summer (Leatherwood *et al.* 1982).

Almost no information is available about the feeding habits of Pacific white-sided dolphins in the Gulf. Near shore in California and Puget Sound, the usual prey consists of anchovies (*Engraulis mordax*), hake (*Merluccius productus*), and squids (Leatherwood and Reeves 1978). Lags are opportunistic feeders that consume a variety of small schooling

fishes and cephalopods similar to those taken by Dall's porpoise (Stroud, Fiscus, and Kajimura 1981). No information on their food requirements was found. It can be assumed, however, that similar to Dall's porpoise, they require approximately 10% of their body weight per day.

Dall's Porpoise

Dall's porpoises (*Phocoenoides dalli*) are the most common small cetacean of the northern North Pacific (Leatherwood *et al.* 1982). They are ubiquitous year-round residents throughout much of the Gulf of Alaska (Consiglieri and Braham 1982). They grow to a length of 2.2 m and weigh ~300 kg (Leatherwood *et al.* 1982). Dall's porpoises are stocky, with males exhibiting much thicker bodies than the females. Their striking black-and-white color pattern makes identification relatively easy. The body is shiny black, with large, oval, white patches on each side at about mid-body. The patches meet ventrally at the midriff and end below the dorsal fin. The upper half of the dorsal fin and the upper rear margin of the flukes are also white (Leatherwood *et al.* 1982).

Dall's porpoises can be found in the waters of the continental shelf and slope. They tend to prefer wide straits and areas of merging currents, or the channels between islands (Scheffer 1949; Cowan 1944). Hall (1979) rarely saw Dall's porpoises in less than 20 m of water in Prince William Sound. The only continental shelf or slope areas of the Gulf that are not frequented by Dall's porpoises are those shallow, turbid waters such as upper Cook Inlet and Icy Bay (Consiglieri and Braham 1982).

Dall's porpoises show evidence of seasonal movements, but no directed, consistent migrations have been documented. Kasuya (1976) described north/south, summer/winter movements in Japan, while Leatherwood and Fielding (1974) described seasonal on-shore and offshore movements in California. Hall (1979) documented clear seasonal population declines from summer to fall in Prince William Sound.

According to Bouchet (1981), the North Pacific population of Dall's porpoises is estimated at between 8.37×10^5 and 1.3×10^6 , excluding those animals found in the coastal waters of California, Oregon, and Washington. The Gulf of Alaska population estimates range from between 1.37- and 2.54×10^5 individuals. Density estimates in the Gulf range from 0.277 to 0.514 porpoises/nmi².

Parturition occurred between June and August for those Dall's porpoises that were taken in gillnets incidental to the North Pacific Japanese salmon fishery (Newby 1982). Morejohn (1979) reported that calving occurred year-round in northeastern Pacific waters from Alaska to California, while Kasuya (1976) found that parturition occurred from August to September in the western Pacific. Newby (1982) found that males became sexually mature at 183 cm or at 5.7 years, while females mature sexually at 171 cm or 3.3 years. At birth, calves are about 95 cm long and weigh 16.5 kilograms. Weaning occurs after one to two months.

Stomach content data from 457 Dall's porpoise taken during the high seas salmon gillnet fishery in 1978 and 1979 show that they eat squids (primarily of the family

Gonatidae), as well as 29 fish species (Jones, Newby, Crawford, and Treacy 1980). Of the fishes eaten, a major proportion were from the family Myctophidae. Other important fishes were bathylagids and sand lance (Scheffer 1953). Based on a review of the available literature, Lowry *et al.* (1982) concluded that a daily food intake of about 10% of the body weight is necessary in order to sustain a Dall's porpoise in the Bering Sea.

Harbor Porpoise

The harbor porpoise (*Phocoena phocoena*) is the smallest cetacean that inhabits the Gulf of Alaska. It grows to a maximum length of about 1.8 m and a maximum weight of about 90 kg (Leatherwood *et al.* 1982). The harbor porpoise is dark brown or gray above and gray or white below, with the white coloration extending onto the chin. The upper jaw and lower lip are both dark, and a dark stripe extends from the corners of the mouth to the flippers.

Harbor porpoises appear to prefer coastal areas—particularly harbors, bays, and the mouths of rivers (Tomilin 1957). They dive to at least 80 m in search of food (Scheffer and Slipp 1948). No specific migrations have been documented for harbor porpoises, although several investigators (Consiglieri and Braham 1982; Hall 1979; and Leatherwood and Reeves 1978) have noted changes in seasonal abundance. Hall (1979) estimated the winter population in Prince William Sound to be about half the summer population. The Prince William Sound concentration of harbor porpoises may be the largest in the eastern North Pacific (Leatherwood and Reeves 1978).

No population estimate is currently available for the Gulf of Alaska. Hall (1979) estimated 590 harbor porpoises in Prince William Sound in the winter and 946 in the summer. There is extensive suitable habitat in the Gulf of Alaska and sightings are numerous. This led Morris *et al.* (1983) to suggest that harbor porpoises are abundant, and to estimate that there may be between 2,000 and 3,000 in the Gulf.

Little is known about the reproductive biology of harbor porpoises in the eastern North Pacific. Tomilin (1957) thought that breeding periods were similar for the North Atlantic, North Pacific, and the Black Sea stocks. In the Black Sea, harbor porpoises mate from June to October, with peak activity occurring in August. Calving occurs in May and June after a gestation period of between 10 and 11 months (Tomilin 1957). In the Atlantic stock, sexual maturity is reportedly attained by males at age 4 to 5 years and by females at age 6 years (Prescott and Fiorelli 1980; Fisher and Harrison 1970).

Harbor porpoises in the North Atlantic feed on cod (*Gadus morhua*), herring, and Atlantic mackerel (*Scomber scombrus*) (Smith and Gaskin 1974). Frost and Lowry (1981) found the remains of small fish (primarily saffron cod) and crustaceans in the stomachs of three harbor porpoises from Norton Sound. The predominant food species in the North Atlantic were pelagic, schooling fishes that were often of some economic importance (Smith and Gaskin 1974).

In the Gulf of Alaska, harbor porpoise probably feed on fishes such as herring, capelin, pollock, and eulachon—although no data are available to verify that. Hall (1979)

reported harbor porpoises at the mouth of the Copper River and assumed they were foraging on those fish species that concentrate in the area where the Copper River water mixes with water from the Gulf. Little information on food requirements exists for harbor porpoises. Sergeant (1969) and Prescott and Fiorelli (1980) all suggested a daily feeding rate for harbor porpoises of between 8.3 and 10% of their body weight.

Harbor Seal

The harbor seal (*Phoca vitulina richardsi*) is found in all coastal areas of the Gulf of Alaska, where Pitcher (1985) considered it to be the most widely distributed of the Pinnipedia. Harbor seals are relatively small 'earless' seals, with stiff, bristle-like hair and short limbs. There is a considerable variety in their coloration and markings—ranging from spots of white-gray to dark brown or black along with rings, and splotches that occur on a background of similar colors (Bigg 1981). The average birth size of harbor seal pups in the Gulf of Alaska varied by area. Near Kodiak, for example, newborn pups weighed 12 kg and measured 78 cm in length while in the northeastern Gulf, they weighed 10 kg and were 73 cm in length (Pitcher and Calkins 1979). Adult males averaged 155 cm in length and weighed 85 kg, while females were 145 cm in length and 77 kg in weight throughout the Gulf.

Harbor seals use land areas known as terrestrial haulouts for resting and nurturing their young. Haulout substrate is highly variable, ranging from rocky intertidal reefs to broad, flat sandy beaches and calved glacial ice. According to Pitcher (1985), some important characteristics of seal haulouts are: ready access to water, isolation from disturbance, protection from wind and wave action, and access to food.

There are thousands of locations in the Gulf of Alaska where harbor seals haul out. However, Pitcher and Calkins (1979) list only 103 locations where more than 25 seals were sighted (see Fig. 17-4). During the early to mid-1970s, Tugidak Island off the south end of Kodiak Island had the largest concentration of harbor seals on the west coast of North America. However, the numbers have recently declined and Tugidak no longer holds this distinction (Alaska Department of Fish and Game, unpubl. data).

Harbor seals, although often considered to be sedentary and limited to coastal areas, are known to move relatively long distances and have been sighted as far as 100 km offshore (Pitcher and Calkins 1979; Wahl 1977; and Spalding 1964). The movements of 31 radio-tagged seals in the Gulf of Alaska were documented by Pitcher and McAllister (1981). The longest movement was 194 km along the shores of Kodiak Island. One of the tagged seals crossed 74 km of open ocean to occupy a different hauling area, then subsequently returned to the site where it was tagged. At least for adults, there appears to be considerable fidelity to haulout sites as demonstrated by the fact that 23 of the 31 harbor seals tagged by Pitcher and McAllister (1981) remained at the capture site. There is no evidence of true migration. Both the numbers and the distributions of seals in the Gulf of Alaska remain relatively constant throughout the year.

In the Gulf, most harbor seal pups are born between the 5th and the 25th of June (Pitcher and Calkins 1979). Pups nurse for a period of between three and six weeks—after which they completely separate from the female. Ovulation occurs between mid-June and mid- to late July, shortly after weaning in those females that have pupped, but implantation is delayed for approximately 11 weeks. Age of first ovulation is from 3 to 7 years, and the pregnancy rates for females 8 years old and older is 92 percent. Male seals in the Gulf become sexually mature by age 6 (Pitcher and Calkins 1979).

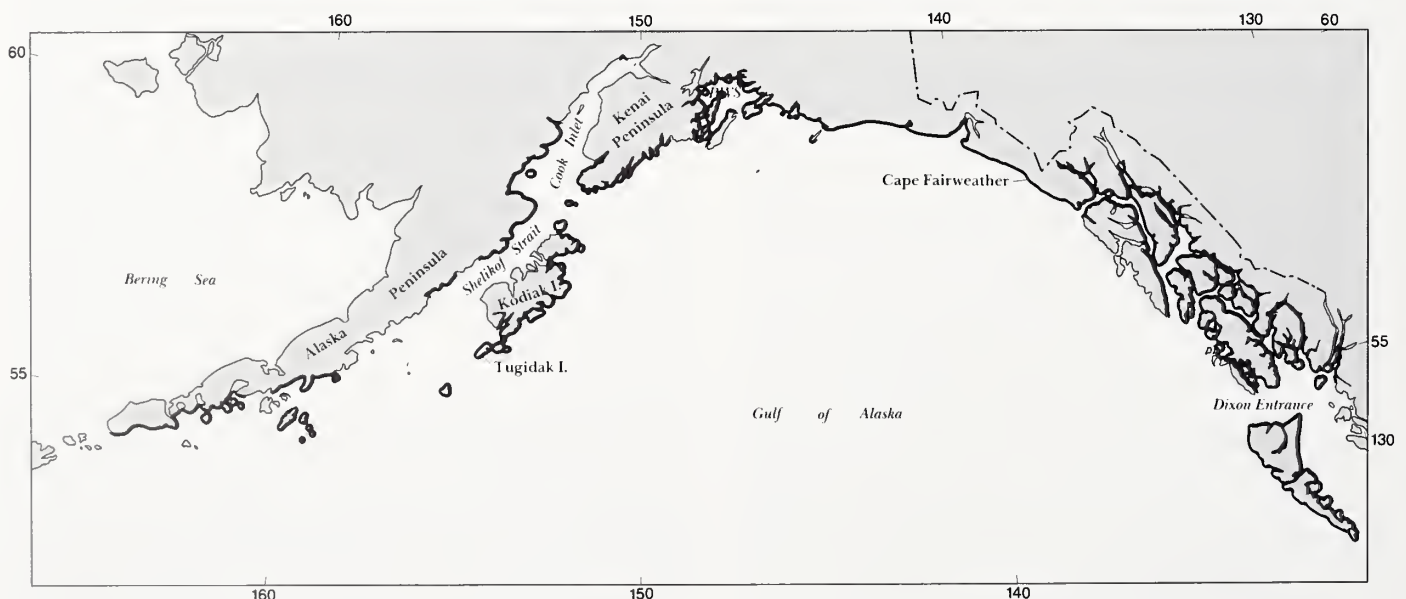


Figure 17-4. Areas of known concentrations of harbor seals in the Gulf of Alaska. (All sightings were made of hauled-out animals only.)

The prey of harbor seals (by frequency of occurrence) consisted of 73.8% fishes, 22.2% cephalopods—both octopus and squid—and 4.1% decapod crustaceans (primarily shrimps). Twenty-seven species of fishes belonging to 13 families were identified as harbor seal prey. The three most-important prey were pollock, octopus (*Octopus* sp.), and capelin (Pitcher and Calkins 1979). Most investigators agreed upon a daily consumption rate for harbor seals of 7.5% of the seal's body weight (Ashwell-Erickson and Elsner 1981).

Because harbor seals are distributed in small groups throughout coastal areas and because of their relatively shy nature, they are very difficult to count. Various methods have been used to estimate their numbers in a given area, including direct counts of those that are hauled out at a given time, as well as estimates based on harvest statistics. Those estimates that are based on harvest data are probably the most accurate because they take into account the entire population rather than the instantaneous number that are hauled out at a given time.

Based on harvest statistics, Pitcher (1985) estimated the abundance of harbor seals in the Gulf of Alaska as follows: Dixon Entrance to Cape Fairweather—30,000; Cape Fairweather to Kenai Peninsula, including Prince William Sound—70,000; Cook Inlet, Kodiak Archipelago, Shelikof Strait, and the south side of the Alaska Peninsula—55,000. The total estimate for the Gulf of Alaska was 155,000 harbor seals. These estimates were originally made for an environmental impact statement in 1973. No data are available to update these estimates, although Pitcher (K. Pitcher, Alaska Department of Fish and Game, pers. comm., 1985) considers them to be imprecise. Recent information gathered by ADF&G suggests that this stock may have declined substantially since 1973.

Steller Sea Lion

The Steller sea lion (*Eumetopias jubatus*) is the largest and one of the most conspicuous pinnipeds inhabiting the North Pacific Ocean—and its range is restricted to this area. The Steller sea lion is the largest of the eared seals, the Otariidae. The only other member of this family that is found commonly in the Gulf of Alaska is the northern fur seal (*Callorhinus ursinus*).

The pups are chocolate brown, but because they lack pigment in the tips of their hair, they have a frosty appearance. The pups appear to gradually grow lighter in color as the animals get older. Many adults are a yellowish cream color on the back, although some remain darker. Males generally remain darker on the front of the neck and chest and grow a short mane over the back of the shoulders and neck. The mane and the large front shoulders and neck resemble the terrestrial lion—thus the name sea lion. The common name 'Steller' is used to honor the German naturalist G. W. Steller, who first described this species in 1751.

Steller sea lions show a pronounced sexual dimorphism in size. Males average more than twice the weight of females and are about 20% longer. Calkins and Pitcher (1982) found that sea lion pups weigh approximately 23 kg at birth and

are 110 cm long (curvilinear length). Average weight and standard length for adults was 263 kg and 228 cm for females and 566 kg and 282 cm for males.

Steller sea lions are widely distributed over the continental shelf and throughout the coastal waters of the Gulf of Alaska. Offshore, they are normally found at depths shallower than 2,000 m and are frequently found in greatest numbers near the 200-m contour (Consiglieri and Braham 1982).

Sea lions use terrestrial haulouts for resting and they tend to gather on traditional, well-defined rookeries in order to pup and breed. Calkins and Pitcher (1982) listed 61 locations in the Gulf where sea lions haul out on a regular basis and 46 more locations which are used irregularly. The latter are referred to as stopover areas. The majority of pups are produced at 11 pupping rookeries (Fig. 17-5). Generally, stopover areas are used by small numbers of animals—usually less than 200. Haulouts can be used by as few as 50 or as many as 4,000 animals. Rookeries are usually used by several thousand animals during the breeding season. All rookeries become haulouts during non-breeding periods. Some rookery haulouts are used by only a few hundred individuals during winter months while other areas continue to be used by up to 3,000 animals in winter.

The haulout behavior of sea lions is complicated and not completely understood. At some haulouts during some periods, there appears to be specific sex and age segregation and usage. On rookeries, non-territorial males apparently stay on the fringes while parturient females and territorial males use the central part of the rookery. The intervening area is used by a mixture of all age classes and by both sexes.

Adult sea lions gather on the rookeries beginning about mid-May. Males defend territories on the rookeries and generally exclude other males. Territorial boundaries are often defined by the physical features of the rookery. Females enter and move about within the territories at will, although there appears to be some competition among females for particular locations on the rookery. It is not known whether they are competing for the most desirable location for parturition or for the most desirable males within the territories. Certainly, there is evolutionary advantage to mating with the fittest males, although Gentry and Withrow (1978) point out that some females may give birth in one territory, mate in another, and spend the majority of their time in still another.

The total range of Steller sea lions extends from the California Channel Islands along the North Pacific Rim to northern Japan. The center of abundance is the western Gulf and eastern Aleutian Islands. Loughlin, Rugh, and Fiscus (1984) estimated a total world population of 2.45- to 2.90×10^5 individuals. Calkins and Pitcher (1982) estimated that there were 1.4×10^5 sea lions in the Gulf of Alaska in 1979. However, recent surveys of all age classes suggest this population may be declining (Calkins 1985a).

Pups are born from about May 15 through July 15. The females breed again about 11 days after giving birth (Gentry 1970; Sandegren 1970). Early embryonic growth temporarily ceases at the blastocyst stage which does not implant on the uterine wall until late September or October (Pitcher and Calkins 1981).

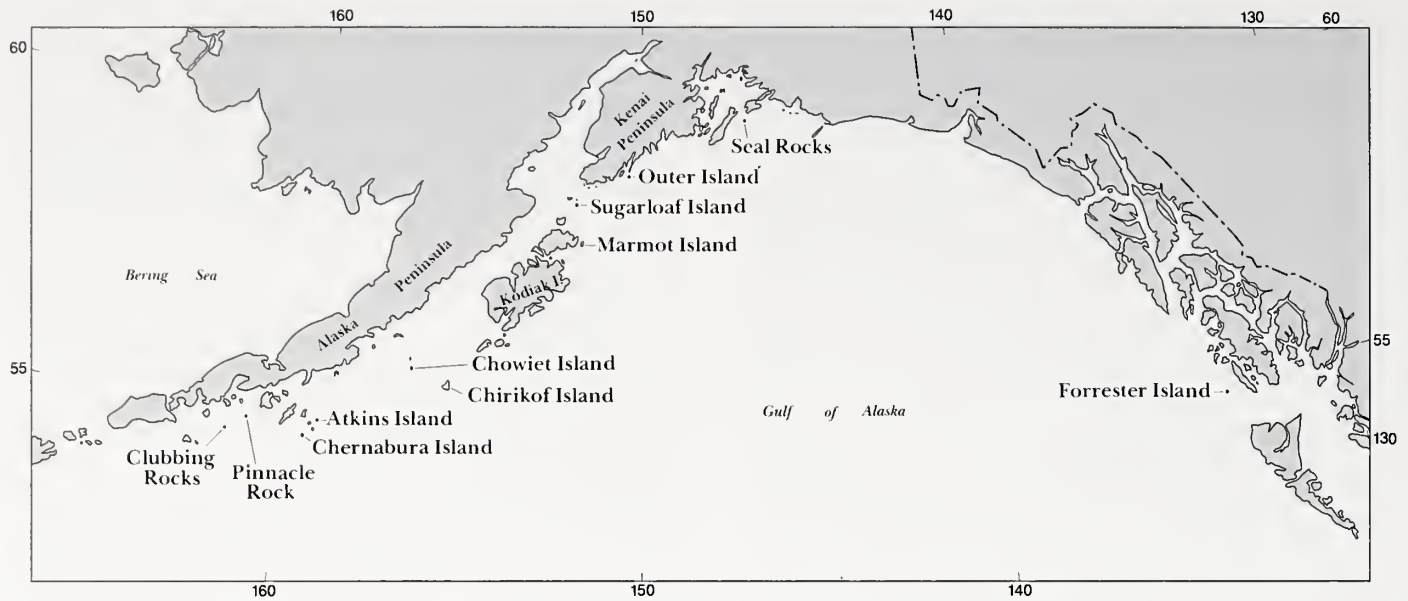


Figure 17-5. Locations of major Steller sea lion pupping rookeries in the Gulf of Alaska.

Some males are physiologically capable of breeding at three years of age and most are probably capable of breeding by age seven years. However, they are not large enough and strong enough to defend territories until about their tenth year. Some females breed for the first time in their third year and bear the first pup at age 4. Most females attain sexual maturity by age 6 and bear a pup each year (Pitcher and Calkins 1981).

Pollock is the most important prey species for sea lions in the Gulf of Alaska. Pitcher (1981) found the diet of Steller sea lions in the Gulf to consist of 67% pollock by frequency. Other important prey found were:

- squids (*Gonatidae*)—23%
- octopus—13%
- Pacific cod (*Gadus macrocephalus*)—19%
- Pacific herring (*Clupea harengus pallasii*)—16%
- capelin—16%
- salmon—6%
- sculpins (*Cottidae*)—6%
- flatfishes—7%
- rockfishes—4%.

Harbor seal remains have rarely been found in the stomachs of sea lions in the Gulf of Alaska (Pitcher and Fay 1982). Although information on the food requirements of sea lions is incomplete, Keyes (1968) concluded that sea lions consume from 6 to 10% of their body weight per day.

Northern Fur Seal

The northern fur seal (*Callorhinus ursinus*) has a thick, heavy, water-repellent coat of underfur, along with unusually large flippers. Adults appear yellowish brown on the rookeries, but at sea they appear black with a gray or light-colored throat. Adult females in prime condition usually weigh between 37 and 40 kg, while males average 127

kilograms. At birth, female pups weigh about 4.5 kg and males weigh about 5.5 kg (Fiscus 1978).

For much of their life, fur seals are pelagic and rarely come ashore except on their home islands during the breeding season. The northern fur seal is found in the Gulf of Alaska primarily on a seasonal basis, although Kajimura (1980) stated that they can be found in all parts of their range in any month of the year. They are most abundant in the Gulf in the spring, during their annual migration to the Pribilof Islands breeding grounds (Consigleiri and Braham 1982). The spring fur seal distribution in the Gulf of Alaska is shown in Figure 17-6.

Some young males and non-pregnant females remain in the Gulf during summer. Small numbers of fur seals regularly haul out in summer on Sugarloaf Island in the Barren Islands and at Forrester Island off Dixon Entrance in southeastern Alaska (Fiscus 1983). Most of the adult population moves to the Pribilof Islands for both pupping and breeding, which take place from mid-June through mid-August (Bartholomew and Hoel 1953; Kajimura 1980; and Fiscus 1983).

After the breeding season, fur seals remain at the Pribilof Islands until late October when some of the females begin the southward migration. As this southward migration escalates, the number of fur seals increases in the Gulf. Some breeding-age males remain in the southeastern Bering Sea, although most of the animals move into the Gulf of Alaska and southward towards their wintering areas (Kajimura, Lander, Perez, York, and Bigg 1980a). Some older males spend the winter in the Gulf (Alexander 1953), while most younger males and females move south to winter along the continental shelf off British Columbia, Washington, Oregon, and California (Kajimura *et al.* 1980a). Consigleiri and Braham (1982) stated that one large group of fur seals winters off Baranof Island. Fur seals have also been seen during the winter on the edge of Portlock Bank and in the deep waters of the central Gulf (Consigleiri and Braham 1982; Kajimura *et al.* 1980a).

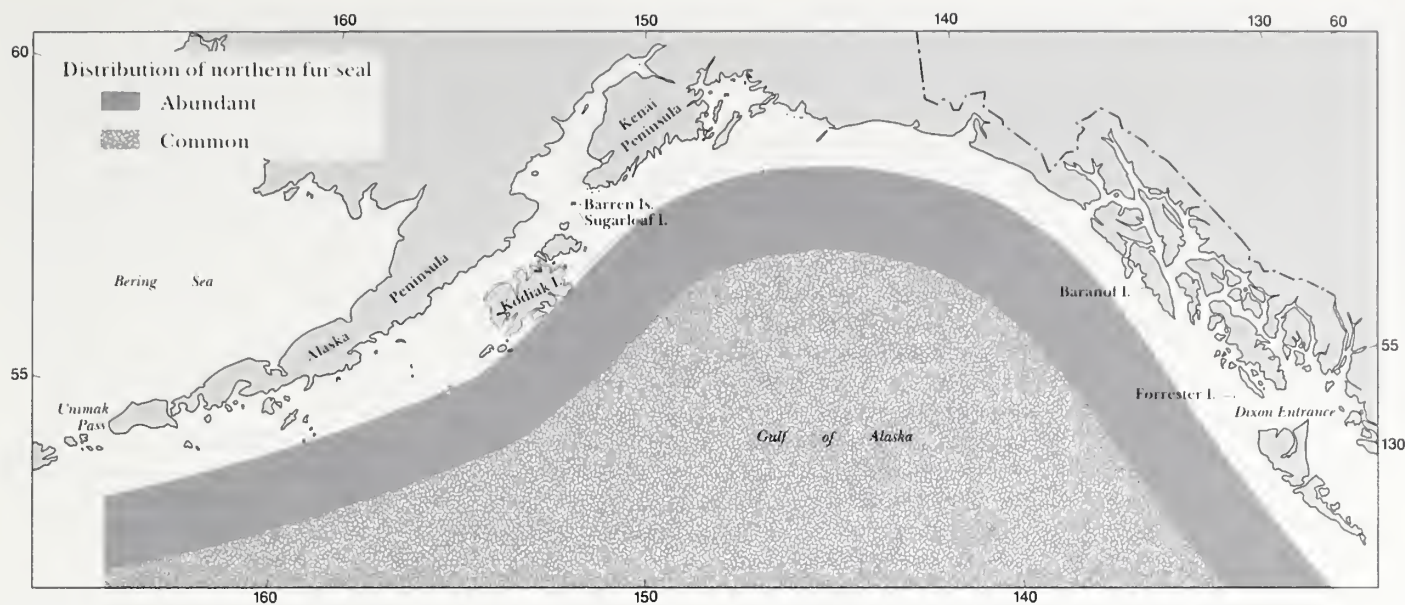


Figure 17-6. General distribution of northern fur seals in the Gulf of Alaska during spring. (Modified from Consiglieri and Braham 1982.)

When hunters began killing fur seals commercially for their skins in 1786, the Pribilof fur seal population was estimated at 2.5×10^6 animals. The herd steadily declined to a low point in 1835, when Russia provided some protection. The herd was allowed to grow to relatively high numbers (numbers unknown) until the United States purchased Alaska in 1867 (Gentry 1981). The herd again decreased until 1910 when fewer than 2.0×10^5 animals remained.

The Fur Seal Treaty in 1911 both protected the seals and regulated their harvest and the herd was again allowed to grow. By 1950, the herd was producing over 4.0×10^5 pups annually (Lander and Kajimura 1976). An attempt to stimulate reproduction by harvesting females between 1956 and 1968 resulted in another herd reduction (Fowler 1982; Gentry 1981; and Chapman 1973). The Pribilof fur seal herd was estimated at 2.1×10^6 in 1951 and most recently at 8.77×10^5 individuals (Briggs and Fowler 1984).

During the breeding season, male fur seals defend their territories and mate with the females shortly after the females give birth to pups (Fiscus 1978). The blastocyst does not implant on the uterine wall until October or November. Most females attain sexual maturity at four or five years of age (Kajimura *et al.* 1980a) and from that point on, over 80% of the females between the ages of 6 and 17 years become pregnant each year (Kajimura *et al.* 1980a).

Fur seals feed on a wide variety of fish and cephalopods (Kajimura *et al.* 1980b), and they are capable of diving to 200 m in search of prey—although most feeding dives have been reported to be in the range of 20 to 100 m (Kooyman, Gentry, and Urquhart 1976). Their principal prey in the Gulf of Alaska includes pollock, capelin, sand lance, herring, and several species of squid (Kajimura *et al.* 1980b). Scheffer (1950) calculated the daily food requirement of fur seals to be 6.7% of the total body weight, whereas Miller (1978) estimated a minimum feeding rate of 14% of body weight per day.

Sea Otter

The sea otter (*Enhydra lutris*) is the only marine representative of the mustelid family in North America. It inhabits the nearshore areas of the North Pacific from California to the Kuril Islands. The best paleontological evidence suggests that otters, including sea otters, descended from common Asiatic ancestors (Kenyon 1969). Three races of sea otters have been described, and those otters found in the Gulf belong to the race *Enhydra lutris lutris* (Kenyon 1981).

Sea otter pups appear yellowish because of the light coloration in their guard hairs, although their dense underfur is brown (Kenyon 1969). Adults typically tend to be dark-bodied with buffy to light gray heads. The head tends to become lighter with age, and a more grizzled coloration may appear on other parts of the body. Body color varies from light buff (rare) through shades of brown to nearly black. The coloration of their guard hair ranges from dark to silver white (Kenyon 1969). Sea otters may vary in size according to nutritional conditions, and therefore their overall average size may not be the same for different areas. Based on data from Kenyon (1969), mean body sizes for sea otters in the Aleutian Islands are:

- newborns—2 kg in weight and 57 cm in length
- adult female—21 kg in weight and 125 cm in length
- adult males—28 kg in weight and 135 cm in length.

Sea otters are found in nearshore habitats throughout the Gulf of Alaska. Although they are apparently capable of diving to depths in excess of 90 m, they prefer depths of less than 55 m (Kenyon 1981). Their preferred habitat appears to be those waters that are adjacent to rocky coasts that have extensive areas of submerged reefs. Although sea otters favor areas where kelp beds (*Alaria* sp., *Macrocystis* sp., and *Nereocystis* sp.) occur, this does not appear to be a requirement (Kenyon 1969).

Certain areas are occupied exclusively by the males, while other areas are used both by females with pups and by small numbers of territorial males. Those areas occupied solely by males tend to be in more exposed, newly colonized locations while areas occupied by females tend to be in better-protected locations (Garshelis, Johnson, and Garshelis 1984). This pattern indicates that different sexes and age classes may have different habitat requirements (Calkins and Schneider 1985). Sea otters make use of terrestrial haul-out sites, using some sites more frequently than others. Abundant food at accessible depths is probably the most rigid habitat requirement; other habitat characteristics may be desirable, but not necessarily required.

The seasonal movements of the otters between their male and female areas are apparently influenced by factors such as breeding, pup-rearing, boat traffic patterns, and protection from inclement weather (Garshelis and Garshelis 1984)—as well as by the availability of food. Although much of the Gulf coast is considered potential sea otter habitat, not all areas have been completely repopulated. At the time when the United States gave protection to sea otters (1911) under the Fur Seal Treaty, several isolated locations of the Alaskan coast had small, remnant populations of sea otters. Those groups that had survived were apparently located in Prince William Sound, at Kodiak Island, on the south side of the Alaska Peninsula, and near Sanak Island (Kenyon 1969).

These nucleus populations increased and expanded until they occupied much of Prince William Sound, including the area of Controller Bay and Kayak Island, the Kenai Peninsula, lower Cook Inlet, the Barren Islands, much of the south side of the Alaska Peninsula, and most of the Kodiak Island area (Fig. 17-7). There are still scattered areas that are not fully repopulated throughout the Gulf. The unoccupied areas west of Cape St. Elias are small and otter populations are increasing within those areas. The Gulf coast from Cape

Spencer to Cape St. Elias supports only scattered small groups and individual animals.

During the period from 1965 through 1969, the Alaska Department of Fish and Game (in cooperation with the Atomic Energy Commission) perfected techniques for large-scale sea otter translocations (Burris and McKnight 1973). A total of 413 sea otters were reintroduced into areas of former habitat both in the northeastern Gulf and in southeastern Alaska between Yakutat Bay and the Barrier Islands. Data from surveys in 1983 showed this population had grown to more than 1,500 animals (Johnson, Jameson, Schmidt, and Calkins, 1983) and probably exceeded 2,000 animals (Alaska Department of Fish and Game, unpubl. data).

Sea otter populations have been increasing throughout most areas of the Gulf of Alaska since 1911. The most recent population estimates by Calkins and Schneider (1985) are shown in Table 17-2.

Table 17-2.
Estimate of sea otter numbers in the Gulf of Alaska (from Calkins and Schneider 1985).

LOCATION	ESTIMATE
Southeast Alaska	2,000*
Yakutat to Cape St. Elias	100
Prince William Sound	4,000-6,000
Kenai Peninsula and Cook Inlet	2,500-3,500
Kodiak (including Barren Islands)	4,000-6,000
South side of Alaska Peninsula	22,000-25,000
Total	34,600-42,600

* From Johnson *et al.* (1983) and Alaska Department of Fish and Game (unpubl. data).

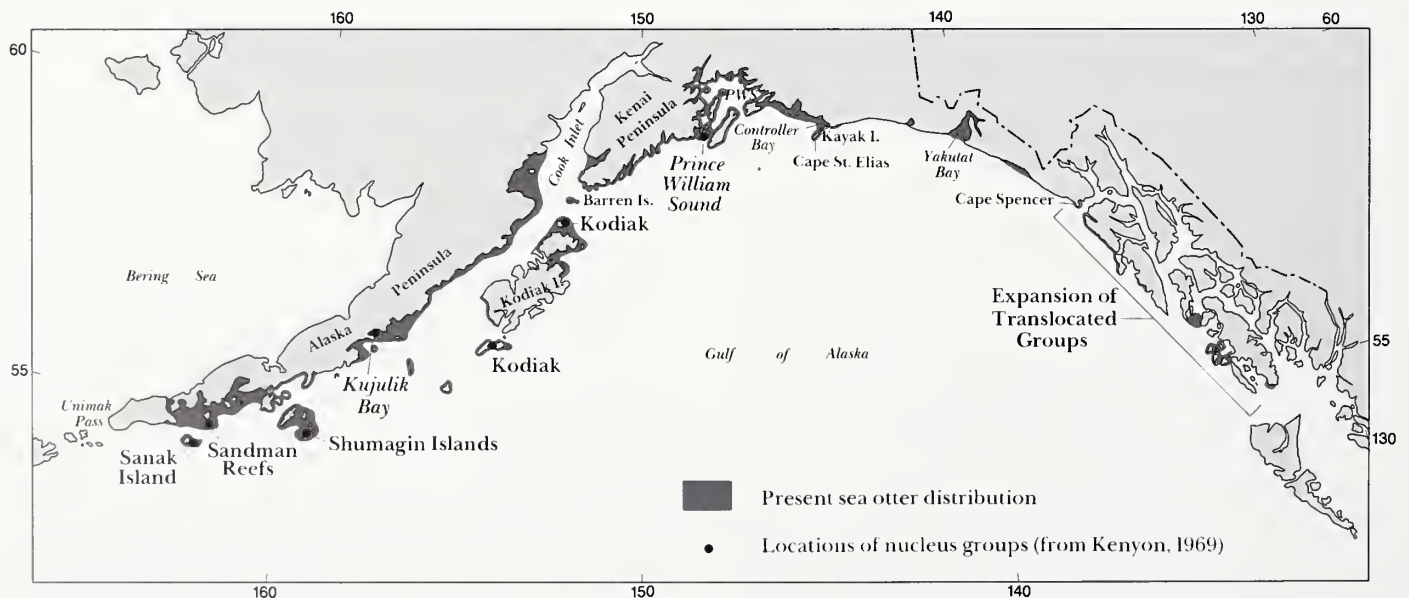


Figure 17-7. Present distribution of sea otters in the Gulf of Alaska with assumed locations of nucleus groups and expansion of translocated populations.

Productivity and reproduction in sea otters have not been completely studied. There appears to be variability in the timing of events between growing populations and those populations that have become well established and exist at a level that is near the habitat's carrying capacity. Sea otters apparently mate and give birth at any time of the year (Murie 1940; Fisher 1940; Barabash-Nikiforov 1947; Lensink 1962; and Kenyon 1969). Schneider (1972) found that in the Aleutian Islands, breeding activity peaked in September and October and parturition reached a peak in April, May, and early June. The average gestation period was estimated to be about 7.5 months. A delayed implantation lasted approximately half of the gestation period.

Schneider (1972) found that most females became sexually mature at age 3 and bore their first pup at age 4. The females nursed their pups for as long as a year and rarely became pregnant during this period. Thus, a two-year breeding cycle was postulated for sea otters in the Aleutians (Schneider 1972). However, recent studies in Prince William Sound indicated that pupping may occur annually in areas where the population is well below the habitat's carrying capacity (A. Johnson, U. S. Fish and Wildlife Service, Anchorage, AK., pers. comm., 1984).

Sea otters feed on a wide variety of bottom-dwelling invertebrates and fishes. Generally, they feed heavily on invertebrates until they deplete the supply, then the otters move to unoccupied habitat or consume fish. Kenyon (1969) found that at Amchitka Island sea otters ate a variety of species, including:

- chitons (*Cryptochiton stelleri*)
- snails (*Buccinum* sp.)
- mussels (*Musculus vermicosa*)
- octopus
- rock oysters (*Pododesmus macrochisma*)
- crabs (*Cancer* sp.)
- green sea urchins (*Strongylocentrotus droebachiensis*)
- globe fish (*Cyclopterichthys glaber*)
- red Irish lords (*Hemilepidotus hemilepidotus*).

In the Gulf of Alaska, Calkins (1978) found that otters ate clams, primarily *Saxidomus giganteus* (81%), but also took octopus, crabs, and sea stars (*Evasterias troscheli*). Daily consumption rates of from 20 to 30% of body weight were estimated for otters (Morrison, Roenmann, and Estes 1974; Kenyon 1969).

Other Marine Mammals

Two species of the large cetaceans listed in Table 17-1—the blue whale (*Balaenoptera musculus*) and the Pacific right whale (*Balaena glacialis*)—are considered endangered. They both exist in such low numbers that their recovery may be extremely slow, and has probably not yet even begun (Mizroch, Rice, and Breiwick 1984; Braham and Rice 1984).

For a variety of reasons, the Pacific right whale was highly sought after by commercial whalers and was consequently reduced to such low levels that the population was dangerously near extinction. Less than 200 right whales may remain in the entire North Pacific (Braham and Rice 1984).

Blue whales, although present in higher numbers than the right whales, are also rarely sighted; and very little is known about either their biology or their ecology in the Gulf. Blue whale sightings have been recorded in the western Gulf in the summer, and they apparently migrate south in the winter (Berzin and Rovnin 1966; Rice 1978a; and Consiglieri and Braham 1982).

The short-finned pilot whale (*Globicephala macrorhynchus*) and Risso's dolphin (*Grampus griseus*) are both rarely sighted in the Gulf. Their range lies mostly to the south and the few sightings that have been made have usually been in summer (Consiglieri and Braham 1982). The northern right whale dolphin is also a species that occurs in more southern, temperate waters. Consiglieri and Braham (1982) state that there are no reliable sightings of northern right whale dolphins north of 50°N, although they list three tentative sightings north of 54°N.

The Bering Sea beaked whale (*Mesoplodon stejnegeri*), Cuvier's beaked whale (*Ziphius cavirostris*), and Baird's beaked whale (*Berardius bairdi*) are found in the Gulf, but little is known about them. No population estimates are available for any beaked whales in the Gulf. Bering Sea beaked whales have not been commercially exploited, so little is known about their life history. The only specific information comes from a few sightings of stranded animals. Morris *et al.* (1983) speculated that Bering Sea beaked whales inhabit the deep waters of the continental slope. However, the recent strandings of three individuals in Cook Inlet, during the autumn of three successive years indicate that they may, at least occasionally, be attracted to nearshore waters.

Although Cuvier's beaked whale and Baird's beaked whale have both been commercially taken in small numbers by Japan, little information is available about either species in the Gulf. They are both thought to inhabit water deeper than 1,000 m (Nishiwaki and Oguro 1971, 1972). Squid and deep water fish appear to be important prey for both species (Nishiwaki 1972; Nishiwaki and Oguro 1971, 1972). Neither food-habit data nor population estimates are available for any of the beaked whales in the Gulf of Alaska.

Pacific walrus (*Odobenus rosmarus*) have occasionally been sighted in the Gulf (Murie 1959; Calkins *et al.* 1975; Bailey and Faust 1981; and Fay 1982). Fay (1982) reviewed several sightings of walrus which had apparently entered the Gulf through Unimak Pass in the winter of 1979, and then in the spring had moved north along the south side of the Alaska Peninsula as far as Cook Inlet. He considered these to be extralimital sightings. Walrus sightings continue to be reported from Cook Inlet.

California sea lions (*Zalophus californianus*) have been reported in the Gulf of Alaska on at least two occasions: once from Point Ellington, outside of Prince William Sound, in June of 1974 (K. Schneider, Alaska Department of Fish and Game, pers. comm., 1974) and once at Point Lull, on Baranof Island, southeastern Alaska, in April 1982.

Northern elephant seals (*Mirounga angustirostris*) are regular summer visitors to southeastern Alaska where each year small numbers are found in the inside waters. Southeastern Alaska can be considered the northern limit of their range. Several individuals have been found stranded at other locations in the Gulf. For example, a subadult male elephant seal

was found stranded on Middleton Island in April 1975, and a young female was found stranded on Unalaska Island (in the eastern Aleutian Islands) in October 1976 (R. Nelson, Alaska Department of Fish and Game, pers. comm., 1976). In addition, a badly decomposed elephant seal was found in February 1977 at Wide Bay on the Alaska Peninsula.

Discussion and Conclusions

Marine mammals in the Gulf of Alaska are ecologically situated as high trophic-level consumers. They feed on a variety of nektonic, benthic, and planktonic animals. The most common prey for marine mammals in the Gulf are:

- copepods
- euphausiids
- schooling fishes such as herring, cod, pollock, capelin, and salmon
- cephalopods—primarily squids
- other crustaceans.

I used the daily consumption rates presented for each species in this chapter as the basis for calculating an annual consumption rate of 7.55×10^6 metric tons of food consumed by the common marine mammals of the Gulf (Table 17-3). This total does not take into account the marine mammals discussed in the section 'Other Marine Mammals'.

The method I used to derive this total was to multiply the estimated average daily consumptions by the estimated number of days spent in the Gulf annually, and then multiply that total by the estimate for the total number of individuals in the Gulf. This is among the simplest methods for deriving annual consumption rates. It does not fully take into account factors such as differential feeding rates between age classes or between seasons, nor does it consider the different caloric values of the foods that were consumed. Where information was not available, I interpolated it from comparisons with other marine mammals of similar size and with similar prey selection. Therefore, the information presented in Table 17-3 is crude, and is probably a conservative approximation.

The most accurate and useful information from Table 17-3 is the comparison of the total amount of food that was consumed by the different species. Among cetaceans, the fin whales consumed the most, followed by the sei whales and Dall's porpoises. It seems apparent that the largest species, such as fin and sei whales, should rank high. However, the Dall's porpoise also ranks high, even though it is a small cetacean, primarily because of the relative abundance of this species in the Gulf.

Steller sea lions had the highest consumption among the pinnipeds. This was because their large size requires a relatively high consumption rate. The annual food consumption of 5.5×10^5 mt by the Gulf sea lions is over twice as high as the 2.6×10^5 mt of groundfish harvested by commercial fishermen in the Gulf during the 1981 season (Kajimura and Loughlin, in press; Morris *et al.* 1983).

Marine mammals depend, to a large extent, on food species that are also harvested commercially by man. This means that numerous conflicts have developed between the

marine mammals and fishermen. Interactions between man and marine mammals have resulted in actions ranging from inconsistent federal legislation to more direct conflicts between the marine mammals and the fishermen (Metlef and Rosenberg 1984). The complexity of the problem is often reflected in management policy. For example, the Marine Mammal Protection Act of 1972 requires that marine mammals be managed to maintain the health and stability of the ecosystem. In contrast, the (Magnuson) Fisheries Conservation and Management Act of 1976 mandates that fisheries be managed to provide maximum sustainable yield under current environmental conditions.

Numerous conflict situations have developed between commercial fishermen and marine mammals. An example is the Shelikof Strait pollock fishery. This fishery was developed in order to take advantage of the enormous spawning schools of pollock which aggregate in Shelikof Strait between January and March (Loughlin and DeLong 1983). One thousand ninety-three sea lions were caught and killed incidental to this fishery in 1982, and 222 were killed in 1983. Since 1983, the number of sea lions that were killed in this fishery has been lower than the 1983 level (T. R. Loughlin, National Marine Mammal Laboratory, pers. comm., 1985). It is assumed that the reason a large number of sea lions were killed in 1982 involved both the timing and the location of the fishery, coupled with the inexperience of the fishermen (Loughlin and DeLong 1983). Since then, the fishing has taken place earlier in the year and further south in Shelikof Strait—and the fishermen have gained experience in avoiding sea lions.

Another serious problem that arises from the marine mammal/fisheries interaction is the entanglement of marine mammals in marine debris. Over the last decade, there has been an alarming increase in the amount of debris that is deposited into the world's oceans (Shomura and Yoshida 1985). Much of this debris is discarded net fragments. Uchida (1985) estimated that 5,500 km of trawl nets are used in the North Pacific. Trawl-net fragments are commonly seen on both fur seals and sea lions and nets are the most common debris in which these species become entangled (Fowler 1982; Scordino 1985; and Calkins 1985b).

The closed, plastic packing bands which are commonly discarded into the ocean are the second most common type of debris that entangles fur seals and sea lions. Entanglement in marine debris can cause mortality in marine mammals and it has been implicated as being partly responsible for the continuing decline in the Pribilof fur seal herd (Fowler 1982). Although it probably does cause some mortality in sea lions, entanglement is probably not responsible for the decline in these populations.

Sea otters are involved in fisheries conflicts because they can substantially reduce benthic invertebrate populations—some of which are commercially valuable. In Prince William Sound, sea otters have been blamed for the decline of shellfish (Garshelis and Garshelis 1984). Substantial (>80%) reductions in the dunghen crab population (*Cancer magister*) were noted in Orca Inlet following an influx of large numbers of otters. (A. T. Kimker, Alaska Department of Fish and Game, unpubl. data, 1985; Garshelis and Garshelis 1984). Other crab stocks that are close outside

Table 17-3.
Estimates of annual consumption rates of food by marine mammals in the Gulf of Alaska.

SPECIES	TYPES OF FOOD CONSUMED	AVERAGE DAILY CONSUMPTION (kg)	EST. NO. OF DAYS IN GULF	EST. NO. OF INDIVID. USING GULF	EST. OF TOTAL ANNUAL CONSUMPTION (mt)
Fin whale	Copepods, euphausiids, fish	1,500	150	10,000	2.25 million
Sei whale	Copepods, euphausiids, fish	1,500	120	8,600	1.55 million
Humpback whale	Euphausiids, fish	1,100 ^a	210	1,200	277,000
Gray whale	Unknown in Gulf	600 ^b	45	13,000	351,000
Sperm whale	Cephalopods, fish	1,000	120	3,000 ^a	360,000
Minke whale	Euphausiids, fish	270 ^a	210 ^a	3,000 ^a	170,000
Killer whale	Fish, marine mammals	240 ^a	365 ^a	300	26,300
Belukha whale	Fish, cephalopods, shrimp	51	365	500	9,310
Pacific white-sided dolphin	Fish, cephalopods	15 ^a	300 ^a	3,000 ^a	13,500
Dall's porpoise	Fish, crustaceans	30	300 ^a	150,000 ^a	1.35 million
Harbor porpoise	Fish, crustaceans	6	365	3,000 ^a	11,000
Total food consumed by common cetaceans					6.59 million
Harbor seals	Fish, cephalopods, crustaceans	6	365	155,000	340,000
Sea lions	Fish, cephalopods	14.3	365	105,000	548,000
Fur seals	Fish, cephalopods	7	45	450,000	142,000
Sea otters	Benthic invertebrates, fish	10	365	41,000	150,000
Total food consumed by common pinnipeds and sea otters					1.18 million
Total food consumed by all common marine mammals					7.77 million

^a Actual numbers not available; numbers inferred from data available compared to other species.

^b Gray whale feeding in the Gulf not documented.

Prince William Sound may be in jeopardy if the otters follow their pattern of depleting abundant benthic invertebrates and moving to nearby unused habitat.

In other areas near Kodiak Island and in lower Cook Inlet commercial fishermen have complained that sea otters are heavily foraging on the already depleted king crab (*Paralithodes camtschatica*) and tanner crab (*Chionoecetes bairdi*) populations. Generally, reports of depleted clam populations are common from both sportsmen and subsistence users soon after the otters expand into areas of recently vacant habitat. If they are allowed to expand unchecked, little doubt remains that sea otters will deplete some commercially valuable or highly favored invertebrate populations. Although the present legal framework under which sea otters are managed (the Marine Mammal Protection Act of 1972) was supposedly designed to promote both the health and the stability of the marine ecosystem, no provisions were made that would give the managing agencies the latitude necessary to resolve conflicting situations—particularly situations where marine mammals are responsible for depleting other species.

Whale viewing has become a popular activity in recent years. In Glacier Bay National Park, the annual return of

humpback whales attracts numerous tour vessels and private operators intent on viewing these whales. The substantial reduction in the number of resident whales in Glacier Bay that began in 1978 and lasted through 1984 has prompted a concern for the whales (Krieger and Wing 1985). It was assumed that there were two reasons why numbers of resident whales decreased: 1) the increase in vessel traffic and/or 2) changes in the forage in Glacier Bay.

The National Park Service took steps to reduce vessel traffic in Glacier Bay during the months of June, July, and August, and also regulated vessel speeds in those areas where whales concentrated (Krieger and Wing 1985). Concurrently, studies were initiated in order to 1) determine the acoustic environment of humpback whales in Glacier Bay and in Frederick Sound; 2) determine the effect of vessel traffic on whale behavior; and 3) determine both the distribution and the abundance of whale prey. Krieger and Wing (1985) concluded that the main reason for the decline of resident whales in Glacier Bay was variation in whale forage. They predicted that changes in the availability of whale forage will continue and that the humpbacks will respond by varying their use of Glacier Bay.

Generally, disturbance from both vessels and aircraft has been noted to have some effect on several different marine mammal species that are commonly found in the Gulf. Fraker *et al.* (1978) described the disturbance of belukhas by both vessels and aircraft. Johnson (1977) estimated that 10% of the harbor seal pup mortality could be attributed to aircraft disturbance at Tugidak Island. Loughlin (1974) believed the absence of seals in two bays in California was due to extensive commercial and sport boat traffic. Calkins (1979) described disturbance of sea lions by aircraft in the Gulf.

Public awareness of and attention to marine mammals have been growing in recent years. A notable example of this is the attention given a proposal to take killer whales for public display from Prince William Sound and southeastern Alaska. Concurrent with their capture proposal, Hubbs Sea World Research Institute began a long-term study of killer whales in those areas (Leatherwood *et al.* 1984). Public outcry has jeopardized the capture proposal, even though only 10 whales were to be taken. Certainly, the removal of 10 whales could not have affected the current population of killer whales in these areas, even if all 10 were taken from one area.

A great deal of information is available on marine mammals in the Gulf of Alaska even though some of the biological parameters of all the species remain unknown. Commercial whaling—which resulted in the decimation of the populations of great whales—also provided most of the information on distribution, numbers, and general biology. Much is yet to be learned about these animals. However, information will be more difficult to obtain because in some cases, the species' numbers are so low that even sightings are rare occurrences. Almost no information is available on beaked whales in the Gulf of Alaska; much is yet to be learned about the breeding biology, food habits, distribution, and numbers of these species.

Studies of belukha whales in the Gulf of Alaska have been supported through the Outer Continental Shelf Environmental Assessment Program (OCSEAP) and through the state of Alaska's Environmental Assessment Program for hydroelectric projects on the Susitna River (Calkins 1984). Both of these efforts were relatively small and provided only distributional information. Little is known about the food habits, the movements, or the numbers of the belukhas that inhabit the Gulf.

Work on Dall's porpoise by the National Marine Fisheries Service (in response to incidental catches on the high seas) is the best and only extensive work which has been performed on a small cetacean in the Gulf.

Much of the recent information on pinnipeds in the Gulf was gained through the OCSEAP-sponsored research efforts; however, pinniped research under that program has been terminated in the Gulf. Some information has been provided through studies supported by the National Marine Fisheries Service. However, much work remains to be done on both the distribution and the numbers of pinnipeds in the Gulf. Recent information indicates a decline in both sea lion and harbor seal stocks. Immediate investigation of this

problem is critical. Very little is known about either the sea otter's food habits or its abundance over much of its range in the Gulf, and more work is needed to determine the significance of this species in the ecosystem.

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ABSTRACT

Ecological relationships in the Gulf of Alaska are discussed separately for four zones: the open ocean, the continental shelf, the fjord, and the estuary. Estimates of primary-to-apex production have been made for each area. The open ocean apex production was estimated to be the lowest at $0.036 \text{ g C/m}^2\text{y}$, while the continental slope waters (including the shelf break) was the highest at $2.4 \text{ g C/m}^2\text{y}$. Also considered in this chapter are other important regional properties that influence larval and juvenile fish survival, demersal production, and the physical processes governing production.

Introduction

This section formulates some general principles related to production mechanisms in the Gulf of Alaska. The purpose is twofold: 1) to integrate detailed descriptions of production mechanisms from previous chapters, and 2) to consider the physical environment as the forcing function for biological production, in order to show how production in different ecological zones may be qualitatively and quantitatively related. From the great abundance of marine mammals, including whales, seals, and sea lions, and from evidence of formerly abundant sea otters and Steller's sea cows, it is apparent that there is a rich flow of nutrient-laden Pacific waters moving onto the south Alaskan coast. The reasons why this highly productive zone exists are the subject of this discussion.

Physical Considerations

The general physical oceanography of the Gulf of Alaska is described by Reed and Schumacher (Ch. 3, this volume). The area is dominated by a large cyclonic gyre (the Alaskan Gyre) that is formed when part of the Subarctic Current moves east towards Vancouver Island, and then moves on around the Gulf in a northwesterly direction to form the Alaska Current (Favorite, Dodimead, and Nasu 1976). Mesoscale eddies occur as part of the Alaskan Gyre. These eddies, which have diameters of 200 to 300 km, are formed along the coast of Alaska and may be either cyclonic or anti-cyclonic (Tabata 1982; Royer, Hansen, and Pashinski 1979; and Feely, Baker, Schumacher, Massoth, and Landing 1979).

In addition to these current systems, both high wind stress and a large volume of freshwater runoff affect local coastal conditions. Wind-induced convergence (downwelling) dominates the Alaskan Shelf from October to March/April, and relatively weak coastal upwelling occurs from May to September (Ingraham, Bakun, and Favorite 1976; Royer *et al.* 1979). In coastal areas, the quantity of freshwater runoff determines the depth of the seasonal pycnocline. Coastal water transparency is affected by both the volume of the runoff and the amount of silt carried by the runoff. Further discussion of these aspects can be found in Sambrotto and Lorenzen (Ch. 9, this volume).

In oceanic areas, the depth of mixing depends largely on the establishment of a seasonal thermocline. Physical parameters that affect biological production at the primary level are changes in:

- 1) solar radiation
- 2) mixed layer depth
- 3) extinction coefficient
- 4) intensity of upwelling or downwelling
- 5) in coastal areas, bottom topography and tidal velocity.

Solar radiation in the Gulf of Alaska increases from less than $100 \text{ g cal/cm}^2\text{d}$ in winter to more than $600 \text{ g cal/cm}^2\text{d}$ in summer. Increased radiant energy affects productivity by establishing a seasonal thermocline and by increasing photosynthesis. With fluctuations in the thermocline, the mixed layer in the open ocean extends to $\sim 150 \text{ m}$ during the winter, but rises to less than 50 m during the summer. In coastal areas, the mixed-layer depth is governed by the

halocline, so that in some areas, a mixed layer of only a few meters may support some primary production throughout the year. The amount of production depends on the amount of suspended sediment in the water, because the suspended sediment effectively limits light levels for photosynthesis.

Combining radiation and mixed layer factors with Sverdrup's (1953) critical depth model, Parsons and LeBrasseur (1968) produced a general explanation for the timing of the spring bloom in the Gulf of Alaska. Their model indicates that the spring bloom could be initiated in coastal regions by a combination of physical factors during February/March, but that in the central oceanic portion of the Gulf, the spring bloom would not occur until at least May. Subsequent studies have tended to support the general form of this prediction (e.g., Anderson, Parsons, and Stephens 1969; Parsons and Anderson 1970). However, in coastal areas (particularly over the shelf break) physical factors such as local river discharge, tidal mixing, bottom topography, the extinction coefficient, and the intensity of wind-induced upwelling or downwelling alter the above prediction.

Many recent analyses of nearshore production processes have employed Simpson and Hunter's (1974) stratification parameter to indicate zones of persistently high primary production. In this model, bottom depths and average current velocities are employed to show areas where stability and turbulence interface. This is valuable because primary productivity reaches a peak in zones between the two processes. A local example of this diagnosis is given by Perry, Dilke, and Parsons (1983) for Hecate Strait. In general, studies using the stratification parameter model have shown that both the shelf-break region of the continental shelf and the shallow sill areas (e.g., in the mouth of fjords, Burrell, Ch. 7, this volume) are areas of persistently high production, especially during the summer months when many local waters are depleted of nutrients by the presence of the strong pycnocline.

The general effects of the physical properties discussed above are summarized in Figure 18-1. The figure covers four ecological zones characteristic of the marine ecology of the Gulf of Alaska. These zones are: 1) the estuarine habitat, including a relatively narrow margin in the intertidal zone, 2) the fjord, 3) the continental shelf and shelf break, and 4) the open ocean. Seasonal and geographical differences in both primary production and the food chain of these areas can be described using existing data. However, longer-term cyclical events may substantially alter these production processes. Examples of these events include: 1) intrusions of warm water along the coast (Tully and Barber 1960; Gardner 1982), 2) changes in the strength and position of the major current systems (Wickett 1966), or 3) occurrences of large-scale, low-frequency baroclinic waves (Mysak, Hsieh, and Parsons 1982).

The Definition of Ecological Zones

The four ecological zones illustrated in Figure 18-1 can be defined on the basis of their physical properties. Of these properties, water depth and the timing of the seasonal pyc-

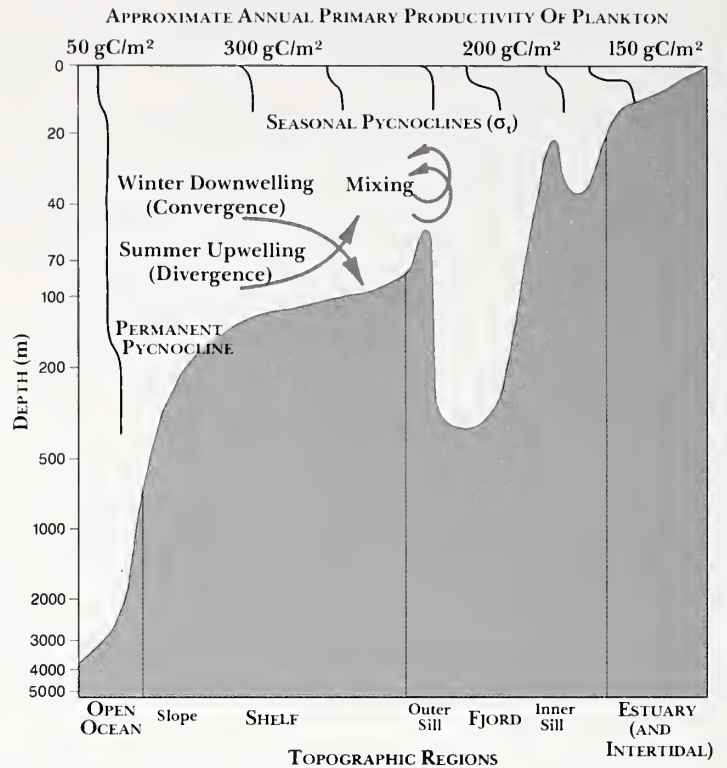


Figure 18-1. Production zones of the Gulf of Alaska showing relative pycnoclines, approximate annual primary productivities, and topographical sections for the four zones.

nocline are probably the two most decisive factors in determining primary production.

The estuarine pycnocline area is strongly developed throughout the year, but varies in its extent depending on river flow. This pycnocline allows primary productivity to occur very early in the spring or even throughout the year. However, large silt loads generally inhibit the *total* annual primary productivity by severely reducing light penetration. Seaward from the estuary, strong seasonal thermoclines form over deep fjord basins. The thermoclines limit vertical mixing and lead to nutrient depletion in the euphotic zone throughout the summer. They also cause the formation of a subsurface chlorophyll maximum at the nutricline.

Thermoclines may be eroded by turbulent tidal mixing in the vicinity of shallow sills, resulting in a biological front that gives rise to continued high production throughout the summer. The relatively shallow continental shelf is also subject both to large-scale tidal mixing near the shelf break and to wind-induced nearshore upwelling and downwelling. This mixing pattern on the edges of the shelf and thermal stabilization beyond the shelf lead to very high primary productivity over a large area between the shelf break and the coastline. In the open ocean, storm activity delays formation of the seasonal thermocline, and this suppresses primary productivity until late in the spring. Open-ocean nutrients are seldom limiting due to heavy grazing pressure on the phytoplankton throughout the summer (McAllister, Parsons, and Strickland 1960). Although the *total* annual primary productivity of the oceanic area is low, the pelagic

food-chain efficiency is probably very high relative to coastal regions, where much of the primary productivity sinks to the sea floor and may undergo bacterial decomposition to form part of a benthic food chain.

The basic difference in the cycle of phytoplankton and zooplankton in the coastal and oceanic regions of the Gulf can be seen in Figure 18-2 taken from Parsons and LeBrasseur (1968) and from Parsons, LeBrasseur, and Baraclough (1970). In the oceanic Pacific, increases in the dominant zooplankton species (*Neocalanus plumchrus*) parallel increases in primary productivity, and chlorophyll *a* seldom increases above $\sim 0.5 \text{ mg/m}^3$. In coastal regions however, primary production outstrips zooplankton growth and large blooms of phytoplankton result in sporadic chlorophyll *a* values of $\sim 20 \text{ mg/m}^3$.

The Estuarine/Intertidal Zone

The estuarine/intertidal zone is a narrow region along the shoreline of the Gulf of Alaska. If you include the estuarine marsh grasses and algal mat communities and the intertidal kelp and *Fucus* beds, the annual primary productivity of this zone is very high ($>1,000 \text{ g C/m}^2\text{y}$ in terms of macrophyte production alone) (Mann 1982). However, much of this production passes through a detrital food chain and consequently there is a considerable loss of energy in converting the autotrophic production into bacteria, fungi, and protozoa. The chief beneficiaries of this production are benthic invertebrates such as clams, amphipods, harpacticoid copepods, and nematodes. These invertebrates subsequently become food for crabs, shrimp, and flatfish as well as for the juvenile and larval stages of many commercial fish species such as salmon and herring.

The primary production of plankton in estuaries may be quite low because silt attenuates the available light. Larrance, Tennant, Chester, and Ruffio (1977) found, for example, that nearshore waters of Prince William Sound had a mean daily productivity of $163 \text{ mg C/m}^2\text{d}$ and a total suspended load of 1.12 mg/l , while offshore, productivity aver-

aged $538 \text{ mg C/m}^2\text{d}$ with a suspended load of 0.31 mg/l . Sampling in Howe Sound on the coast of British Columbia produced similar results. Stations under the direct influence of the Squamish River had a mean annual production of $\sim 140 \text{ g C/m}^2\text{y}$, while stations at the mouth of the same inlet had an annual primary production of $\sim 400 \text{ g C/m}^2\text{y}$ (Stockner, Cliff, and Buchanan 1977).

In addition to containing high silt levels, freshwater runoff from the Alaskan coastal range is generally devoid of nutrients other than silicate (Kinney, Groves, and Button 1970). However, some rivers carry higher loads of organic matter than seawater and this gives rise to high bacterioplankton production off the mouth of a river where the freshwater and nutrient-rich saltwater mix (Albright 1983; Atlas and Griffiths, Ch. 8, this volume).

Estuaries and intertidal waters serve several important functions in supporting higher trophic levels. Bird populations, particularly migrant shore birds, ducks, and geese, are ecologically tied to this zone. Anadromous fish such as salmon and lamprey are dependent on the estuary as a gateway to the rivers. The total fisheries production of this zone is low because the area is relatively small, although marsh grass, eelgrass, and seaweed beds all serve as important nursery areas for some species. The principal non-migratory fisheries of interest to man are the shellfish such as clams and crabs.

The Fjord

A recent review of fjord ecology has been given by Matthews and Heimdal (1980). Pickard and Stanton (1980) have described the general physical characteristics of fjords, and fjord dynamics are described by Burrell (Ch. 7, this volume). Alaskan fjords are characterized by Matthews and Heimdal (1980) as having well-developed pycnoclines at the head with less well-developed pycnoclines at the mouth where tidal exchange over a shallow sill may cause some mixing. Mixing at the mouth of a fjord forms a front of high biological activity due to the entrainment of nutrients from below the pycnocline during the summer months (e.g., Parsons, Perry, Nutbrown, Hsieh, and Lalli 1983). A third sub-zonal area of some fjords may exist if an inner sill isolates the head of the fjord from the main basin. This inner basin (sometimes called a *poll*) may be partially filled with riverine sediment. The *poll* community is generally dominated by nanoflagellates, small zooplankton, small fish, and medusae. In contrast, the main basin of the fjord is generally characterized by diatoms producing a summer chlorophyll maximum at depth, and by large calanoid copepods, euphausiids, and substantial fish stocks (e.g., lingcod and hake).

Thus the ecology of a typical Alaskan fjord may range from a highly productive region at the mouth and progress through the more stable waters of the main basin of the fjord to a region of low productivity at the head (Matthews and Heimdal 1980). As an example, the mouth of Cook Inlet, and particularly Kachemak Bay, appears to have the typical properties of a frontal zone with primary productivity values of $1 \text{ to } 7 \text{ g C/m}^2\text{d}$ from June through August when primary productivity in many other regions is much lower due to nutrient depletion (Larrance and Chester 1979).

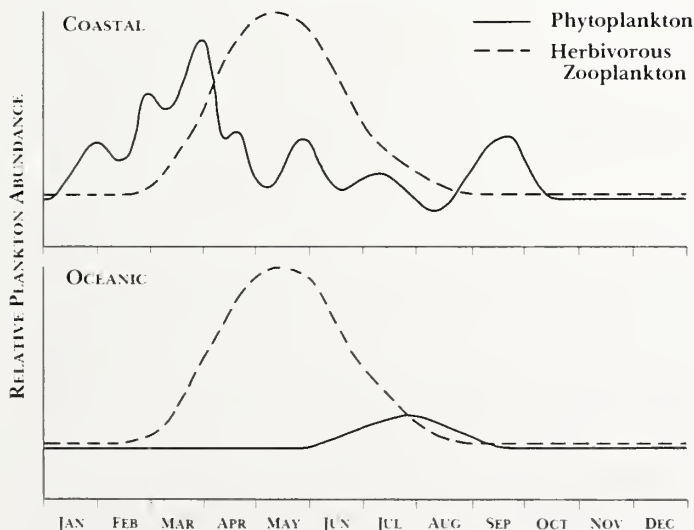


Figure 18-2. The general relationship between phytoplankton and herbivorous zooplankton in the coastal and oceanic regions of the Gulf of Alaska.

The Continental Shelf and Shelf Break

The continental shelf zone (that area out to 200-m depth) is the most productive zone in the Gulf of Alaska. This is due in part to topographical features of the shelf break and in part to its relatively extensive area. Other continental shelves throughout the world are similarly productive (Pingree 1978), although in comparison to the North Atlantic shelf, the Pacific Alaskan shelf is narrow. The higher productivity of the shelf break region is illustrated in Figure 18-3, taken from Larrance *et al.* (1977). The figure shows results of an autumn survey of daily productivity values. Values along the 183-m contour ran three to five times higher than values measured in the nearshore region. Similar observations have been made for British Columbian waters.

The reasons for this zone of high production have been discussed (Mackas 1984; Denman, Mackas, Freeland, Austin, and Hill 1981; and Freeland and Denman 1982). The mechanisms leading to high production involve physical processes that contribute to upwelling. These mechanisms include 1) the entrainment of nutrient-rich deep water into the surface layer due to the offshore movement of freshwater; 2) wind-induced upwelling; and 3) upwelling caused when a major offshore current interacts with topographic irregularities along the shelf break. The upwelling activity along the shelf break appears to be seasonally reversible. It

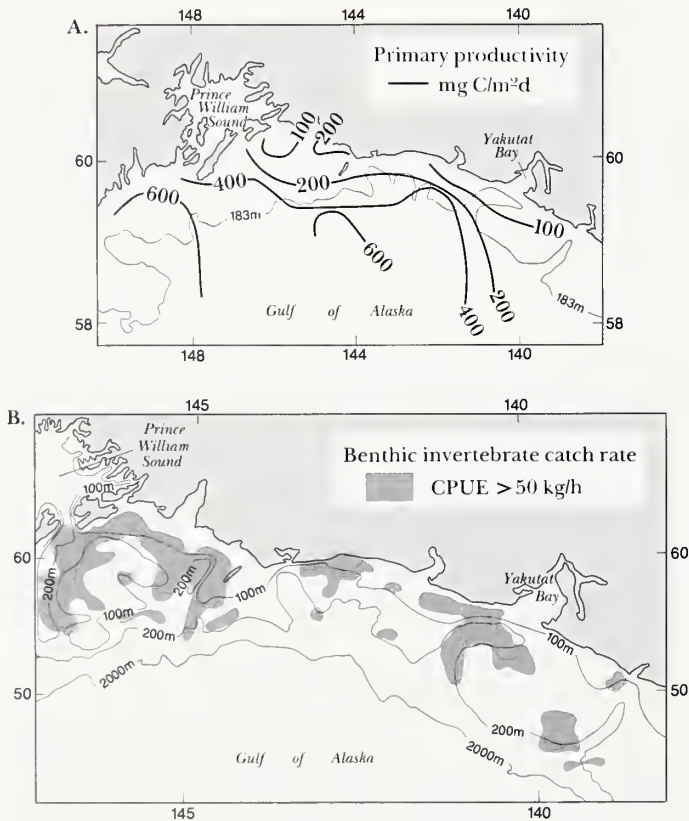


Figure 18-3. (A) Primary productivity on the Gulf of Alaska Shelf, October to November 1975. (Modified from Larrance *et al.* 1977.)

(B) Areas of benthic invertebrate concentrations on the Gulf of Alaska Shelf expressed as relative catch per unit effort (CPUE). (Modified from Ronholt, Shippen, and Brown 1978.)

becomes a downwelling (convergent) system for six to eight months during the winter. The reversal to the predominant downwelling system is due to a shift in wind direction (Ingraham *et al.* 1976; Royer 1981). Winds are primarily responsible for the summer upwelling on the Alaskan shelf break. However, some areas of the shelf may be subject to this seasonal upwelling for relatively brief periods (*i.e.*, one or two months, Reed and Schumacher, Ch. 3, this volume).

In these regions tidal mixing and the interaction of along-shore currents with subsurface topography may be the dominant force leading to the influx of nutrients into the euphotic zone during the summer. An example of tidal mixing as a force is shown in Reed and Schumacher's Figure 3-10, where the stability of the water column over Portlock Bank is dissipated by tidal flow. An example of a current interacting with subsurface topography appears in their Figure 3-8, where an intense, permanent eddy is produced in the lee of Kayak Island.

Microflagellate abundance increases from $\sim 10^4$ to 10^5 cells/l as one moves from the shelf area to the open ocean zone. Conversely, diatoms form the basis for nearshore plankton blooms (Larrance *et al.* 1977). From data presented by Larrance (1971) on daily productivities between 160 and 180°W, it is apparent that in nearshore oceanic areas primary productivities of more than 2,000 mg C/m²d could occur from June to August, while offshore the daily primary productivity is generally less than 300 mg C/m²d. If the annual primary productivity for the central oceanic zone is ~ 50 g C/m²y (McAllister 1969), then the near-shore shelf zone must have a minimum production of ~ 300 g C/m²y based on the six-fold daily differences observed by Larrance (1971). This value is similar to recent measurements of primary productivity on the continental shelf made in Hecate Strait and Queen Charlotte Sound, which ranged from 1 to 5 g C/m²d during July 1983 (J.R. Forbes, Institute of Ocean Sciences, Canada, pers. comm., 1983).

The general form of increased biological production over the shelf area is illustrated in Figures 18-3A and B, which show two data sets: 1) primary productivity (mg C/m²d), and 2) catch per unit effort (CPUE) of benthic organisms. Maximum primary productivity tends to occur along the shelf break near the 200-m contour while maximum benthic production is on the shelf. These patterns are consistent with the concept that water moves onto the shelf during summer, increasing the primary production available to the benthos in shallow areas (Feder and Jewett, Ch. 12, this volume). A similar frontal zone is shown in Figure 18-4 from Perry *et al.* (1983). The cross-sectional data, collected during June from the shelf break on the inside passage of Hecate Strait at approximately 54°N and 130 to 132°W, illustrate that chlorophyll *a*, nutrients, and zooplankton generally increase in the vicinity of the shelf break where water depth increases from ~ 50 to 300 meters.

The Open Ocean

The open ocean ecosystem of the Gulf of Alaska is characterized by a permanent halocline at depths near 150 m as well as by a seasonal thermocline which is established in April or May and persists until September or October (Tully

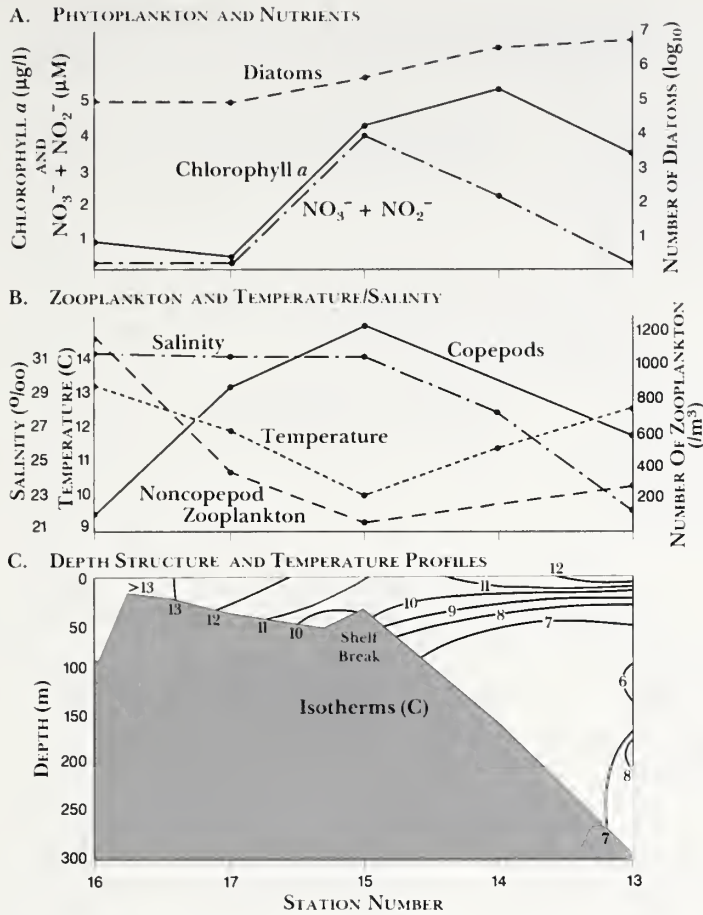


Figure 18-4. Cross-sectional data collected during June from the shelf break front in Hecate Strait at approximately 54°N and 130 to 132°W. (Modified from Perry *et al.* 1983.)

1965). Once the seasonal thermocline is established, net primary productivity increases from less than 50 mg C/m²d to more than 300 mg C/m²d between March and June/July (McAllister 1969). Intense grazing by zooplankton, which is in phase with the increase in primary production, keeps surface waters from becoming nutrient limited. Chlorophyll *a* levels are ~0.5 mg/m³ and the nitrate concentrations are above 5 µM, even during the most productive months (June and July) (McAllister *et al.* 1960; Parsons and LeBrasseur 1968; and Anderson, Parsons, and Stephens 1969). The major group of primary producers in the subarctic ocean waters of the Gulf of Alaska are 8 to 16 µm-sized flagellates (Parsons 1972) belonging to the Haptophyceae, Dinophyceae, and Cryptophyceae; the dominant diatom found in the area was *Denticulopsis seminae* (Booth 1975; Taylor and Waters 1982).

The standing stock of zooplankton is strongly linked to the seasonal timing of the phytoplankton bloom. The annual production of zooplankton at Ocean Station 'P' (50°N, 145°W) has been estimated to be between 4 and 13 g C/m² (McAllister 1969).

Knowledge of the critical depth and depth of mixing lets one predict the timing of the zooplankton bloom in the Gulf of Alaska (Parsons and LeBrasseur 1968) (Fig. 18-5). This model shows that net primary production becomes positive

from February to May. Due to the close coupling between increased primary productivity and zooplankton standing stocks, increases in zooplankton coincide with the general advance of the spring bloom from the coast (in March) to the center of the Gulf (in May).

The open ocean ecosystem is a major feeding ground for salmon, particularly the sockeye. The two principal species of zooplankton (*Neocalanus cristatus* and *N. plumchrus*) are not directly consumed by salmon to any large extent. Rather, copepods are principally consumed by euphausiids, squid, and myctophids, which in turn are the principal food of salmon. As much as 20% of the annual zooplankton production in the open-ocean environment of the Gulf of Alaska is indirectly required for salmon growth (LeBrasseur 1972). Large planktivorous predators that prey directly on the copepod biomass include baleen whales and some fish. Barraclough, LeBrasseur, and Kennedy (1969) documented the occurrence of dense swarms of copepods that would be attractive to planktivores and result in intensive seasonal grazing.

Annual Carbon Budget for the Ecological Zones

Estimates for the approximate carbon budget for the four ecological zones are shown in Figure 18-6. Primary productivity values have been taken from the previous discussion, and in the case of the estuarine food chain, the combined contribution of allochthonous organic carbon (from the land) and macrophyte detritus is estimated at 100 g C/m²y. This addition is based on a value derived by Stephens, Sheldon, and Parsons (1967) for a similar habitat

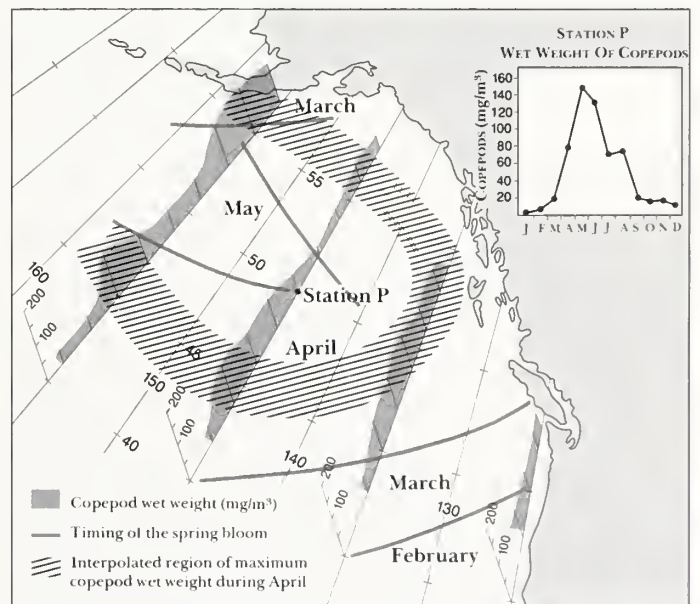


Figure 18-5. Timing of the spring bloom in the Gulf of Alaska. General progress of the spring bloom in oceanic waters is predicted from the Sverdrup model. Actual data on zooplankton standing stock are shown for the month of April. Zooplankton standing stock at Station P in the center of the Gulf (inset). (Modified from Parsons and LeBrasseur 1968.)

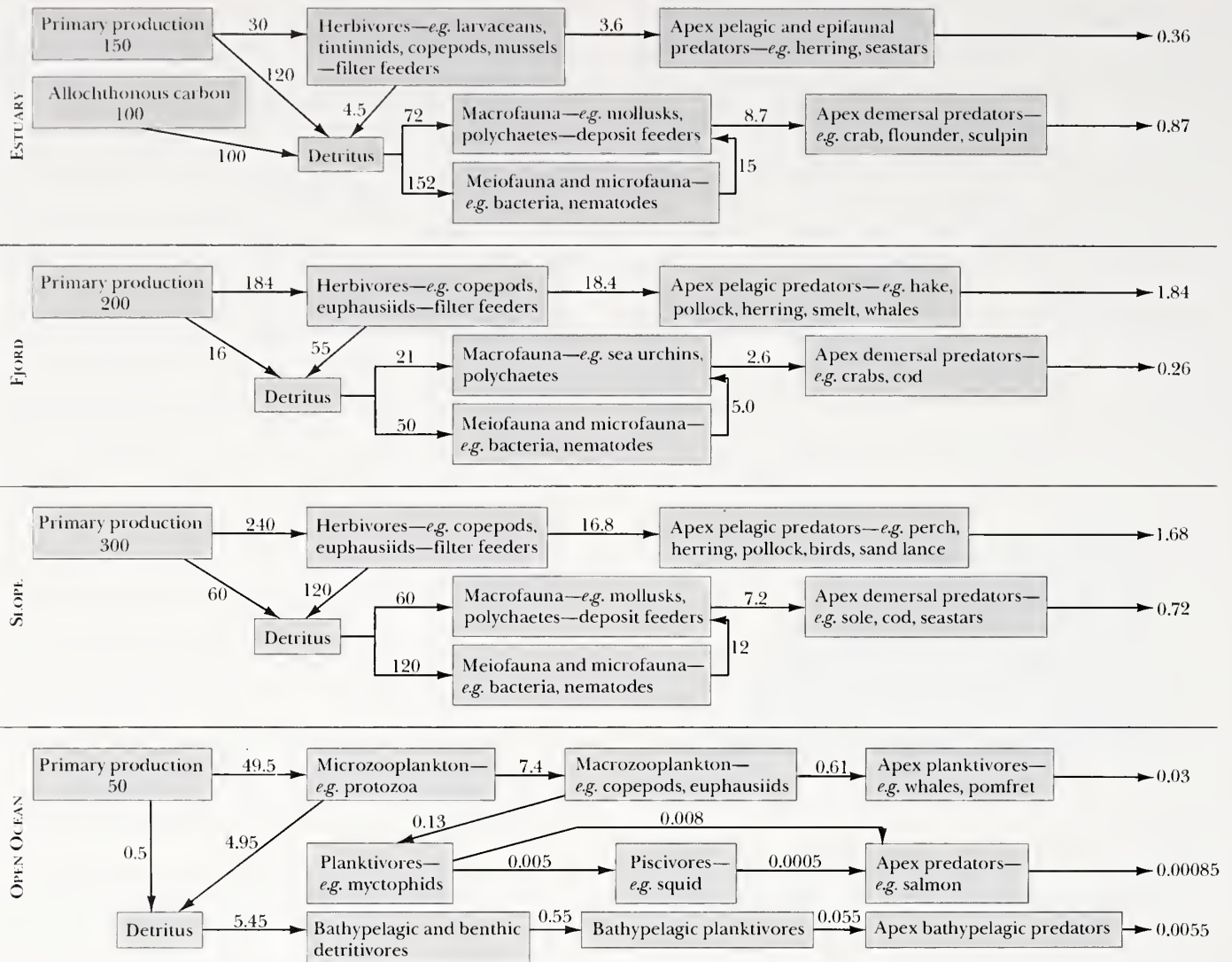


Figure 18-6. Estimated production of organic carbon ($\text{g C/m}^2\text{y}$) from primary to apex producers in the four ecological zones of the Gulf of Alaska.

in the Strait of Georgia. Larrance and Chester (1979) found 40 to 60 g C/m^2 sedimented at the mouth of Cook Inlet, of which nearly 90% originated on land.

The amount of primary productivity that is sedimented as phytodetritus has been estimated using Suess' (1980) relationship. This relationship gives the fraction of primary productivity that sinks through the water column as a function of water depth. Water depths of 10, 300, 100, and 3,000 m were assumed for the estuary, fjord, shelf, and open ocean, respectively. Sedimented phytodetritus, together with the allochthonous carbon in the estuary, has been labeled 'detritus' and has been assigned to the benthic community. The partitioning of the detritus into direct consumption by either macrofauna or meiofauna and microflora is based on Schwinghammer's (1981) observation that the total biomass of meiofauna and microflora (including bacteria) is about twice that of the macrofauna. However, while different-sized groups of benthic organisms compete for the same food resource (*i.e.*, sedimented organic matter), Reise (1979)

has shown that macrofauna in their role as nonspecific deposit feeders consume many of the microorganisms in sediments. For this reason, the detrital pool has been shared proportionally 2 to 1 between micro- and macrofauna, but the microorganisms have then been shunted through the macrofauna as an additional food supply to this trophic level. Demersal predators such as crabs, sole, cod, and seastars have been placed at the top of the benthic food chain (Feder and Jewett, Ch. 12, this volume). In general, the demersal predators represent the production of epifauna, while the infauna and flora are represented by the previous step in the benthic food chain.

All ecological efficiencies for the benthic food chain have been assumed to be 10 percent. However, this value may be too high for the initial conversion of detritus and too low for benthic carnivores. While the use of an average ecological efficiency compensates for this difference, the introduction of fewer or more steps in the food chain could alter the production of apex predators.

That portion of the primary production that is not sedimented is assumed to be consumed largely by planktonic herbivores, and, in the case of estuarine/coastal environments, by attached filter feeders such as mussels. The ecological efficiency for the conversion of primary productivity to secondary productivity has been based on the level of primary productivity. Cushing (1971) showed that as primary productivity increased, conversion efficiency decreased. Using this relationship, ecological efficiencies have been calculated by dividing the annual primary productivity by 200 days to give: 1) the approximate daily productivity, and 2) the transfer efficiencies interpolated from Cushing (1971) as 15% for the open ocean, 12% for the estuary, 10% for the fjord, and 7% for the shelf.

Since the assimilation ratio decreases exponentially with food intake (Gaudy 1974), it is expected that the low ecological efficiency of 7% on the shelf would lead to the production of fecal pellets that are rich in organic material. Using Gaudy's relationship, the assimilation efficiency of herbivores at the phytoplankton densities typically found on the shelf has been approximated at 50 percent. This means a large fraction of the primary productivity sedimented as fecal pellets is available to the benthos (Hargrave, Phillips, and Taguchi 1976). The input of fecal material from the zooplankton community has been graded against assumed ecological efficiencies for each ecological zone, to give 90% assimilation at an ecological efficiency of 15%, and 50% assimilation at an ecological efficiency of 7 percent. Corresponding assimilation efficiencies are approximately 70% for the fjords and 85% for the estuaries. Any unassimilated fecal material has been added to the detrital pool.

An ecological efficiency of 10% has been assumed for converting zooplankton to planktivorous fish. In the open ocean, it has been assumed that there are more steps in the food chain between phytoplankton and apex predator (Ryther 1969; Parsons and LeBrasseur 1970; and Sambrotto and Lorenzen, Ch. 9, this volume in reference to microzooplankton grazing). In addition, the divisions of herbivore production, apex planktivores (*e.g.*, whales), smaller piscivores (*e.g.*, squid), and apex carnivores (*e.g.*, salmon) have been based on LeBrasseur's (1972) suggestion that ~20% of the biomass of herbivore production served as food for salmon in the open ocean. The remainder of the herbivore production is consumed by a variety of species (OCSEAP Staff, Ch. 14, this volume), including baleen whales and pomfret. The ecological efficiency for the conversion of plankton to the latter group has been placed at 5% because of the high metabolic requirements of whales and because of the diversity of food items available to the oceanic apex predators such as pomfret.

A summary of apex production is shown in Table 18-1. Walsh and McRoy (1986) estimated the apex production of the Bering Shelf as 0.65 g C/m²y based on 162 g C/m²y primary productivity. Commercial fish production for the North Sea has been estimated as 0.66 g C/m²y based on a primary production of 82 g C/m²y, while for Georges Bank the commercial fish production was estimated as 0.8 g C/m²y based on a primary production of 374 g C/m²y (Cohen, Brosslein, Sissenswine, Steinle, and Wright 1982).

Table 18-1.
Approximate apex production in the four ecological zones of the Gulf of Alaska.

REGION	PRIMARY PRODUCTION (g C/m ² y)	APEX PRODUCTION (g C/m ² y)		TOTAL (g C/m ² y)
		DEMERSAL	PELAGIC	
Estuary	150	0.87 ^a	0.36	1.23
Fjord	200	0.26	1.84 ^a	2.10
Slope	300	0.72 ^a	1.68 ^a	2.40
Open Ocean	50	—	0.036	0.036

^aIndicates fisheries which may be partly or extensively used by man (*e.g.* crabs, mollusks, herring, cod, perch, sole, and salmon).

These values from the literature are generally lower than those calculated in Table 18-1 for the Alaskan continental shelf areas. There are probably several reasons for this. In the case of the Bering Sea estimates, the estimated primary productivity was nearly half that for the south Alaskan shelf. This estimate seems reasonable, since water turbulence, which affects the supply of nutrients, is greater along the narrow northern Gulf of Alaska shelf than it is on the wide Bering Sea shelf.

The estimates of apex production for the North Sea and Georges Bank (Cohen *et al.* 1982) apply only to fish. A more important consideration, however, is the assumed coupling between primary production and fish production. These authors suggest that much of the very high primary production (374 g C/m²y) on Georges Bank is actually exported off the bank, and this gives a relatively low transfer efficiency to fish on the bank. In the North Sea, the primary production is much lower (82 g C/m²y) than on the south coast of Alaska (300 g C/m²y), but it is used as efficiently as on the Alaskan coast. This gives apex productions that are similar in both areas if one allows for the difference in primary production between the two areas.

The annual estimated food required for marine birds (~5.5 × 10⁵ mt) on the shelf (DeGange and Sanger, Ch. 16, this volume) represents about 5% of the total apex production. This estimate assumes that birds prey on fish and they are therefore feeding at a high trophic level. Similarly, it is estimated that sea lions on the shelf require ~3.5 × 10⁵ mt of fish per year (Calkins, Ch. 17, this volume). This amount is about 3% of the apex shelf production.

Fisheries Potential

For apex predators (Fig. 18-6), production estimates are also estimates of the standing stock if one assumes an annual production-to-biomass (P/B) ratio (*cf.* Fig. 73 in Parsons, Takahashi, and Hargrave 1984). For some species, such as salmon, current harvest levels reach nearly 20% of the annual production. This harvest level may be sustainable for P/B ratios that are above 0.5. However, in general, the annual P/B ratio of subarctic apex species, including the wide variety of benthic predators, mammals and birds, is probably no more than 0.1. Furthermore, of this fraction,

which is required to replace the standing stock (B), a large part such as seastars, birds, and seals are not harvested by man. In addition, some commercial fish species may be underexploited due to the difficulties involved in harvesting in certain locations such as on rough bottoms.

The relatively high production of the fjord-sill environment is of limited commercial importance since it encompasses a relatively small area and is confined primarily to the frontal zones that occur at the mouth of certain inlets. However, certain inlets such as Frederick Sound and Glacier Bay are well known for their high productivity because they serve as feeding grounds for the humpback whale.

The most productive zone in the Gulf of Alaska is the shelf and slope area, both because of its high primary productivity and because of its relatively large area. If the total area of the Alaskan Shelf (from Dixon Entrance to 165°W, to a depth of 200 m) is approximately 3.15×10^{11} m², then according to Table 18-1, the annual production of apex predators in this area is $\sim 12 \times 10^6$ metric tons. Less than 2% of that tonnage is presently harvested. For slow-growing species, however, most of the production is required for replacement of adult stock (*i.e.*, P/B ratio ~ 0.1), and it is doubtful that more than 10% of the apex production should be harvested. Assuming that half of the production is unavailable because of harvesting difficulties as discussed above, it is apparent that the probable maximum yield of commercial fish from the shelf is only three times the current harvest level of 2.0×10^5 mt/yr. However, if some of the smaller, faster-growing fish such as the sand lance and the capelin are included as part of the harvest, then the total fishery resource might be increased considerably. This fishery tactic has already been employed in the North Atlantic.

At present, economically important demersal resources such as crabs and clams are found in the estuarine environment, while others, such as pollock and flatfish, are found on the shelf. Pelagic fisheries such as herring occur to a limited extent at the mouth of fjords and to a much greater extent over the shelf and slope waters. The open ocean apex production is largely unexploited except for the fraction that returns to the coast as salmon.

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Section 4

Issues and Perspectives

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ABSTRACT

Much of the research that has been done in the Gulf of Alaska was conducted in response to legislative needs and can properly be characterized as 'policy relevant'. Both the form and the substance of regional research are influenced by a variety of social factors, including: socioeconomic patterns, land ownership and use, and institutional, legislative, and technological change. The social fabric also gives rise to regional environmental issues, which in the Gulf are concerned primarily with fisheries, environmental degradation, multiple-use conflicts, and environmental hazards.

Fisheries issues have existed since Territorial days. They have become complex as more species are harvested, exploitation attains or exceeds sustainable yields, and socioeconomic considerations increase in relative importance. Concern over environmental degradation arose with the advent of large-scale timber and pulp production, the production and transportation of oil and gas, and a projected increase in mining activity. Marine pollution from municipal waste is not yet widespread because present discharge rates are small relative to the assimilative capacity of the waters that absorb the discharge. Localized pollution has occurred at coastal fish- and shellfish-processing centers. Foreign fishing activities have been identified as major contributors to litter both on beaches and the sea floor. Multiple-use conflicts are increasing as competition for finite resources increases. Sport/commercial/subsistence fishery conflicts and marine mammal-commercial fishery conflicts are included among several such conflicts. Seismic and other geophysical hazards are public policy issues that will gain importance as the region's population grows and the potential for a catastrophic event increases. The historic reliance of Alaska on natural resources as an economic base and projections for future development suggest that resource-extraction activities—and their associated perturbations—will continue to require directed research. Alaska's growing energy demands and the abundance of energy sources in the Cook Inlet area may cause coastal energy systems to become an environmental issue.

Introduction

"... the way in which we articulate environmental issues stems only partly from the forms of nature. Our perception of issues equally reflects the attitudes, wants and ways of living of society itself."

Robert B. Weeden, *Alaska Resource Development: Issues of the 1980s* (1984)

Research frequently results from issues of public importance. Such investigations can be categorized as 'policy relevant' and are often implemented by means of either legislative or regulatory mandates. Much of the environmental research undertaken in the Gulf of Alaska by state and federal entities has addressed pragmatic questions. In this chapter, we 1) identify factors that have influenced regional oceanographic research, 2) consider in more detail major

environmental issues, and 3) speculate on future issues. The intent is to provide a context for future discussions of both the status of current research and the implications for resource management that are presented in Chapter 20.

Underlying Factors

As Weeden noted, environmental issues are made up of a complex summation of society's wants, needs, and attitudes. Furthermore, they are dynamic and liable to wax and wane as the social fabric changes. At a national level, environmentalism and environmental issues probably reached a zenith in the late 1960s and early 1970s. In Alaska, they have been consistently visible because of the pervasive importance of natural resources to the state's well-being. Some underlying factors that have helped shape regional oceanographic research are described below.

Socioeconomic Factors

Population density in the Gulf is low in comparison with coastal regions in the Lower 48 states. According to the 1980 census, over one-half of the state's population of some 400,000 people was concentrated in the Cook Inlet area. Of these, about 175,000 were in Anchorage, the state's service hub—located at the head of the Inlet. Another 65,000 to 70,000 people lived in about 100 communities scattered along hundreds of kilometers of coastline between Dixon Entrance and the western Aleutian Islands—most of them in the cities of Juneau, Ketchikan, Sitka, and Kodiak. These smaller communities are economically dependent on renewable resources—predominantly fisheries and timber. Most communities in the coastal region are not served either by road or by rail and, therefore, they rely on marine and air transportation for both commerce and travel. In both absolute and relative terms, population growth in the region is dominated by Anchorage and adjoining communities that constitute the so-called 'Railbelt', which extends from Seward to Fairbanks.

Since its purchase from Russia in 1867, Alaska's abundant fish, game, timber, and minerals have been the basis for both jobs and income for its residents. Kresge, Morehouse, and Rogers (1977) likened Alaska during the years 1740 to 1940 to a colonial possession due to its highly specialized exploitation of raw materials for export to distant markets and populations. The analogy is still true today. Manufacturing plays a relatively small role in the state's economy. The oil industry has formed the dominant sector of the economy since the 1960s. Although oil development in the Arctic has received the most attention, considerable petroleum-related activity has occurred in the Gulf of Alaska region.

Land Ownership and Use

Both land ownership and use patterns are in transition. The Statehood Act of 1959 gave Alaska authority to selectively acquire over 400,000 km² of federal lands, and also gave the state title to the submerged offshore lands in the territorial sea extending 5 km offshore. Similarly, the Alaska

Native Claims Settlement Act (ANCSA) conveyed some 160,000 km² of federal lands and approximately \$1.0 billion to the state's Natives. Native-owned corporations created by ANCSA have initiated a variety of business ventures based on natural resource exploitation in the coastal region.

Both state and national public interest groups have influenced the withdrawal of a large amount of federal land for inclusion in national parks, preserves, monuments, and wildlife refuges. About 400,000 km² were so designated under Section 17d(2) of ANCSA and the Alaska National Interest Lands Conservation Act (ANILCA) of 1980. Such actions included the creation of the Admiralty Island and Misty Fjords National Monuments, the Wrangell–St. Elias National Park and Preserve, the Katmai National Park and Preserve, as well as additions to the Glacier Bay National Park and Preserve. As of 1984, the federal government owned and managed approximately 900,000 km² of Alaskan lands (Morehouse 1984).

Institutional Factors

A considerable marine research capability has evolved within Alaska's academic institutions and resource management agencies over the past 50 years. The University of Alaska was created by an act of the Territorial Legislature in 1935. The University's Geophysical Institute was established by an act of Congress in 1946. The Institute of Marine Science (IMS) was founded in 1960 by the state legislature; it is located in Fairbanks, but has research, teaching, and docking facilities at Seward. The University's research capabilities were increased by the establishment of the Alaska Sea Grant Program in 1970, the founding of the Arctic Environmental Information and Data Center (AEIDC) in 1972, and the founding of two affiliate campuses with marine studies programs in Juneau and Kodiak.

The conveyance of many natural resource management and regulatory functions from federal to state control following statehood resulted in the establishment of the Departments of Fish and Game (ADF&G), Natural Resources (DNR), Community and Regional Affairs (DCRA), and Environmental Conservation (DEC). All have substantial research, management, or regulatory roles involving the marine environment. The infusion of monies into the state treasury resulting from taxes and royalties on North Slope oil production has enabled the agencies to pursue a variety of marine resource management and enhancement projects.

The large federal presence in Alaska predates statehood and will continue because not only much of the state's uplands but also the submerged lands from 5 to 320 km (3 to 200 mi) offshore remain under federal control. Most of the coastal lands of the Gulf of Alaska region are under federal jurisdiction (Fig. 19-1). The U.S. Forest Service has stewardship of the huge Chugach and Tongass National Forests. The National Park Service administers Glacier Bay National Park and Preserve, the Wrangell–St. Elias National Park and Preserve, and other lands bordering the Gulf. The U.S. Fish and Wildlife Service manages the many islands composing the Alaska Maritime National Wildlife Refuge, as well as numerous mainland refuges.

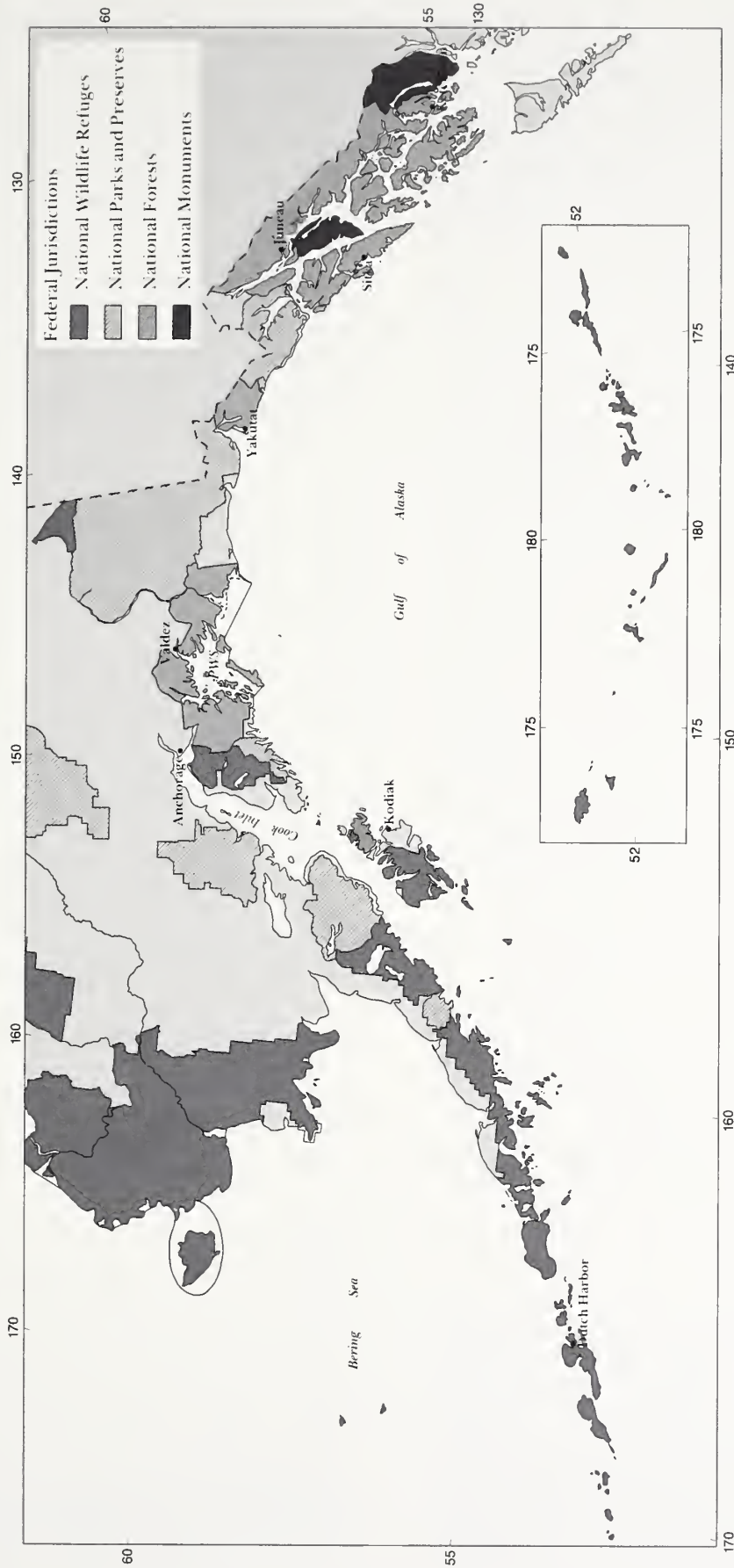


Figure 19-1. Alaska land areas under Federal jurisdiction.

The National Oceanic and Atmospheric Administration (NOAA) has responsibilities pertaining to the maintenance of environmental quality and to the conservation and exploitation of marine mammals, fish, and shellfish. NOAA's National Marine Fisheries Service (NMFS) and its predecessors, the United States Fish Commission and the Bureau of Commercial Fisheries, have conducted fisheries research in the Gulf of Alaska since the territorial period. Although the NMFS Northwest and Alaska Fishery Center is headquartered in Seattle, it maintains laboratories both at Auke Bay and at Kodiak, Alaska.

The advent of the large federal outer continental shelf (OCS) oil- and gas-leasing program, coupled with new legislative mandates concerning environmental quality in the 1960s, brought other federal agencies into marine research in the Gulf of Alaska. Oil, gas, and other mineral management on the OCS was initially the responsibility of the Department of Interior's Bureau of Land Management (BLM), but now resides with the Department's Minerals Management Service (MMS).^a The Environmental Protection Agency (EPA) was established in 1970; its activities include the maintenance of marine water quality.

Numerous international arrangements have furthered marine research in the Gulf of Alaska (Miles, Gibbs, Fluharty, Dawson, Teeter, Burke, Kaczynski, and Wooster 1983). Most are concerned with fisheries. The International Pacific Halibut Commission was created in 1925 to promote both stock maintenance and maximum sustained yields for halibut; its United States and Canadian members set fishing seasons and area catch quotas. The International Pacific Salmon Fisheries Commission promotes the conservation of both sockeye and pink salmon stocks; it was formed in 1930 by the United States and Canada. The International North Pacific Fisheries Commission (created in 1952 by Canada, Japan, and the United States) promotes and coordinates scientific studies of selected fish species, mainly halibut and salmon. The International Whaling Commission, of which the United States is a member, has regulated the taking of whales since 1948. The committee sets quotas by geographical areas, size limits, and closed seasons based on advice from its scientific committee. The North Pacific Fur Seal Commission, created in 1957 by the United States, Canada, Japan and the Union of Soviet Socialist Republics, formulates and coordinates fur seal research programs. There also have been several short-term bilateral research agreements between the United States and other nations that pertain to the Gulf of Alaska.

Legislative Influences

Legislative influences on marine research in Alaska are numerous and can vary in their scope from statewide to international issues. Upon attaining statehood, Alaska acquired responsibility for natural resources on both the state's uplands and on its submerged lands. Legislative action created the agencies which not only manage the resources, but also regulate activities in the coastal zone. In 1979, the Alaska Coastal Management Program was approved by the federal government. The plan gives the state certain powers to guide any development that takes

place in either coastal or offshore waters. It grants those powers through consistency provisions of the federal Coastal Zone Management Act.

Federal environmental legislation (see Dolgin and Guilbert 1974; Sive 1976) has provided the impetus for a large amount of marine research in the Gulf of Alaska. The Outer Continental Shelf Lands Act, enacted in 1953, was among the most influential. The Act and its amendments mandated the orderly development of energy resources on the OCS and provided for environmental protection. Another legislative landmark was the National Environmental Policy Act of 1969; it presented a national policy for environmental quality, required environmental impact statements for major actions initiated by federal agencies, and formally involved affected states and other parties in the decision-making process concerning such actions.

A variety of other environmental legislation was enacted in the 1970s. The Coastal Zone Management Act, the Marine Mammal Protection Act, the Federal Water Pollution Control Act (and its amendments), the Marine Protection, Research, and Sanctuaries Act, the Endangered Species Act, the Clean Water Act, and the National Ocean Pollution Research and Development and Monitoring Planning Act were passed during that decade. The legislation resulted in considerable research and coordination within and among local, state, and federal agencies in order to comply with requirements concerning waste discharges, ocean dumping, and protection of the environment. As noted by Like (1976): "The history of environmental legislation appears to reveal a transition from dealing with the effects of pollution to exercising controls over its sources."

Two federal legal actions relevant to the Gulf of Alaska region have international implications. The Fishery Conservation and Management Act (FCMA) of 1976 created a 320 km-wide (200 mile) fishery conservation and management zone surrounding the United States and its possessions. Under the FCMA, the North Pacific Fishery Management Council develops both regulations and catch quotas for the portion of the zone within the Gulf of Alaska. FCMA management includes the foreign fisheries. The Exclusive Economic Zone Proclamation of 1983 sets forth the United States' sovereign rights to explore, exploit, conserve, and manage natural resources of the seabed and overlying waters (excepting tunas) within the zone, thus extending the FCMA to include non-living resources (Pendley 1984).

Technological Factors

Technological advances have markedly improved marine research capabilities. This improvement is reflected in both the quality and quantity of the oceanographic data now being acquired in comparison with the data from the era of the Nansen bottle and reversing thermometer. Information storage and processing have been facilitated by

^a As part of the OCS leasing program, the BLM and NOAA initiated the Outer Continental Shelf Environmental Assessment Program (OCSEAP) in Alaska in 1974. The goal of OCSEAP is to provide decision-makers with the data and information they need to assess environmental risks of oil and gas development.

devices such as integrated circuits, transistors, and minicomputers. The coupling of electronic sensors with digital computers now allows shipboard data processing and survey refinement at sea. The superior facilities, the seaworthiness, and the endurance of modern oceanographic vessels are greatly improved over those qualities in their predecessors. Remote sensing from satellites and aircraft is now routinely used for applications requiring the synoptic coverage of large ocean areas.

All these technological advances, plus the availability of funds to address information needs, have yielded a quantum jump in both the quantity and quality of data collected during the past two decades. The powerful data manipulation and analytical capabilities of large computers enable researchers to address problems whose answers were, until recently, merely conjectural.

Issues

Most of the large variety of present and potential environmental issues pertaining to the Gulf of Alaska region fall into one of four general categories: fisheries, environmental degradation, multiple-use conflicts, and environmental hazards.

Fisheries

As used here, the term 'fisheries' encompasses the industrial use of fish, shellfish, and marine mammals. Fisheries issues normally arise when the goals of maintaining sustained yields, satisfying social needs, and satisfying economic needs conflict with either the condition of the resource, the demands by industry, or with regulatory policies. In Alaska, fisheries issues consist of a significant and continuing suite of high-visibility problems that are important to both the public and to government, since Alaska fisheries have played such a dominant economic role in the State's history.

Fish and Shellfish. The major domestic fish and shellfish fisheries in the Gulf of Alaska have traditionally been directed toward high-value species, and of these fisheries, the salmon industry is the most notable example. The perfection of salmon-canning techniques has allowed large-scale exploitation of this resource in Alaska (Berman 1984). The first cannery was established in southeastern Alaska in 1878 (Pennoyer 1979). The canneries spread rapidly throughout the region and persist to the present, although fresh and frozen products have eroded canned salmon's dominance of the market. Since its inception, the value of the statewide salmon harvest alone has exceeded \$3.5 billion (Browning 1980).

Exploitation of demersal fish and shellfish began shortly after the salmon fisheries. Many of these latter developments are reviewed in Ronholt, Shippen, and Brown (1977). Halibut were first harvested by United States and Canadian fishermen in the late 1800s and by the early 1900s, the stocks were heavily exploited. Shrimp fishing was relatively insignificant until the mechanical peeler was introduced in 1958 (Richardson and Orth 1979), after which the fishery grew

rapidly, then declined due to depressed stocks. By the 1960s king and Tanner crabs had become the basis for the most lucrative Alaskan fisheries. However, the decline in king crab stocks that occurred in the 1970s culminated in a precipitous drop in the mid-1980s. The common thread running through the histories of these and other fisheries is their 'boom or bust' character (Crutchfield and Pontecorvo 1969; Gusey 1978, 1979; and Francis 1985). The salmon industry has experienced several such cycles.

The Alaskan domestic fisheries have numerous regulatory controls intended to curb the fishing fleets' ability to exceed allowable harvests. Time-area closures, gear and area restrictions, vessel size limitations, and other measures are used. The roe-herring fisheries that in some instances last only a few hours (Rearden 1981; Wiley 1984) epitomize the tight control of some fisheries. The fishing industry's chronic overcapacity and the resulting economic inefficiency are now being addressed through management policies that include socioeconomic considerations. The State of Alaska introduced limited entry to certain fisheries in 1973, in an effort to increase fishermen's earnings (Adasiak 1978). The State also began addressing the financial problems being experienced by processors, the development of previously unused fisheries for selected species, and the marketing of Alaskan seafood products (Hall and Hickey 1983). Ventures to exploit the abundant groundfish resources of the Gulf—resources once monopolized by foreign fleets—are being used to bring more stability to the industry.

Foreign nations began harvesting significant quantities of fish and shellfish from the Gulf of Alaska in the 1960s. Russia and Japan have taken the greatest tonnages; however, several other nations also have participated. The extension of United States territorial waters to 19 km (12 mi) offshore in 1966, coupled with the passage of the FCMA in 1976, has progressively restricted foreign fishing until today; foreign fishermen concentrate heavily on groundfish and sablefish. Walleye pollock currently make up the bulk of the catch from the Gulf of Alaska.

American fishermen initially met with limited success in the groundfisheries, primarily due to high processing costs and a lack of viable markets. However, under provisions of the FCMA, the North Pacific Fisheries Management Council can decrease foreign catch quotas if such actions improve opportunities for the domestic industry (Hall and Hickey 1983). Because of these various circumstances, foreign companies have formed joint ventures with the American companies. The Americans capture the fish and then deliver them to foreign-owned, at-sea processors. American fishermen caught about one-half of the groundfish taken from the Gulf in 1984. It is possible that the Gulf of Alaska groundfishery will eventually become an exclusively American endeavor (Gorham 1979).

Recent annual fish and shellfish harvests from the Gulf have totaled some 3.0 – 4.0×10^5 mt and had ex-vessel values of \$200– to \$300 million (Alton 1981). Production from the existing fisheries may now be near the maximum allowable levels for sustained yields. Stocks of some species, such as Pacific ocean perch, pandalid shrimp, and king crabs, are currently at low levels. When the stocks recover,

management and catch quotas will be more conservative than they were previously, in order to avoid a recurrence of such conditions. Significantly increased production may be possible if certain species that are currently unfished or little fished are more aggressively exploited.

Capelin (*Mallotus villosus*), sand lance (*Ammodytes hexapterus*), mackerel (*Scomber japonicus*), pomfret (*Brama japonica*), grenadiers (Macrouridae) and squids are candidates for new fisheries. A comprehensive analysis of these and other unused fishery resources of the northeastern Pacific Ocean is presented by Trumble (1973). If a reliable and rapid screening method is developed for paralytic shellfish toxins, then the razor clam (*Siliqua patula*) and several species of hardshell clams may become commercially important. Given the finite size of the region's native stocks, aquaculture likely will assume a greater role in fisheries (see Kelly and Hood 1973; Rosenberg 1976, 1977).

The State has fostered private salmon-enhancement ventures through legislation that lets nonprofit corporations operate hatcheries (Kaill 1979). The success of both Norwegian and British salmon-pen ranching in the nearshore waters of those countries could serve as an impetus for similar ventures in the unpolluted, protected fjords of southeastern Alaska and Prince William Sound.

The intensive exploitation of both commercial fish and shellfish has increased the pressure on resource managers. They are simultaneously expected to conserve stocks, maximize yields, and satisfy all user groups. Pennoyer (1979) has provided a cogent description of the evolution of fisheries management in Alaska from the time of European entry into the region to the late 1970s. The complexity of present-day fishery management in the Gulf of Alaska region is best exemplified by the salmon fishery.

As indicated by Rogers (Ch. 15, this volume), salmon in the Gulf consist of five species and a mixture of age groups that range from smolts to mature fish up to seven years old. Salmon are highly migratory, with stock units that originate from lakes and streams as far north as the Bering Sea, as far south as California, and as far west as the Asian coast. Their life histories are diverse—both among and within species. Individual fish take up ocean residence for periods ranging from a few months to several years.

Salmon fisheries can occur anywhere within the fishes' range—from the Bering Sea south to California, as well as across the Pacific to Asia. Both immature and mature salmon are captured. A variety of both active and passive fishing methods are employed:

- trolling
- purse seining
- drift- and set gillnetting
- fish traps
- weirs
- rods and reels.

The methods vary widely in efficiency, which in turn varies according to stock density and the evolution of the equipment and the techniques. Because gear types and locales differ, some fisheries are relatively non-selective for species, age classes, or stock units, while others are very selective.

Inevitably, some of the salmon that form the mainstay of any given fishery are caught elsewhere—the so-called interception problem.

Commercial, sport, and subsistence fishermen make up the major user groups that compete for the resource, and their differing desires must be accommodated. Large hatchery and aquaculture programs inject additional salmon into the ocean, which then compete with the native fish for prey, alter their genetic makeup by interbreeding (Helle 1976), and endanger the survival of native stocks. This latter effect is hypothesized because returns of artificially propagated salmon can be manipulated to some degree in response to the needs of the harvester. An apparently healthy fishery based on mixed stocks can consist of large numbers of hatchery fish and very few native fish. As hatchery fish become more abundant, the prolonged exploitation of the native fish may drive them to commercial extinction. In addition, how well salmon survive in both freshwater and at sea is strongly affected by a number of factors, including:

- climatic conditions
- prey availability
- disease
- predation
- other physical and biological factors.

The result is a pronounced fluctuation in the interannual return rate.

The preceding descriptions of the Gulf of Alaska fisheries indicate some of the myriad factors that fishery managers consider in developing management schemes. Agreements must be reached at local, regional, interstate, and international levels concerning how allowable catches of the various species will be divided among the many user groups. Time, area, and gear restrictions must be developed to ensure that sufficient adults survive to spawn. A large suite of biological data must be available for the analyses that lead to the catch, allocation, and fishery restriction decisions.

As the issues have grown more complex, fisheries management has evolved from a primarily biological approach to one that formally includes socioeconomic concerns—and that evolution is continuing. Maximum sustained yield concepts have given way to others such as optimum yield and ecosystem management, the latter of which attempts a more holistic approach encompassing not only the target species, but also their predators and prey (*e.g.*, see Hammond 1980). Developments such as these will require not only more knowledge of the biology of individual species, but also information on structure and function of entire marine communities and ecosystems.

Marine Mammals. Marine mammals formed the basis for the first economic ventures in Alaska (Fay 1979). In the 1700s, Imperial Russia established stations from which to hunt sea otters and fur seals in the Gulf of Alaska. In the 20 years following the United States' purchase of Alaska in 1867, American sealers killed over two million fur seals, and foreign pelagic sealers also took a significant number (Chapman 1979). Nearly one million sea otters were harvested during the period of their exploitation. Pelagic harvests of these

species ended in the early 1900s, at which time both populations were severely depleted. Fur seal harvests continue to this day; however, they are allowed only at rookeries on the Pribilof Islands in the Bering Sea. As a result of these restrictions, both fur seals and sea otters have increased to their pre-exploitation abundances over much of their original ranges.

Commercial whaling in the Gulf of Alaska was begun by Yankee pelagic whalers in 1835 (Bockstoce 1978). Later, shore-based stations were established to exploit seasonal concentrations of the animals (Morgan 1978). Over 8,000 whales were processed at the Port Hobron and Akutan whaling stations between 1912 and 1939 (Reeves, Leatherwood, Karl, and Yohe 1985). Russian and Japanese whaling fleets operated in the region from the 1950s to the 1970s (Leatherwood, Bowles, and Reeves 1983). Commercial whaling has been controlled in recent years by three restrictions: 1) the International Whaling Commission's prohibitions on the taking of large baleen whales, 2) the moratorium imposed by the Marine Mammal Protection Act (MMPA) on the taking of any species of marine mammal, and 3) the Endangered Species Act.

The Territorial Government of Alaska allowed a regulated harvest of both harbor seals and sea lions for commercial use in the 1950s. This program continued under control of the Alaska Department of Fish & Game after statehood. Harbor seal harvests increased from between 6,000 and 10,000 animals annually before 1963 to over 50,000 in 1965 due to the demand for pelts in the European fur market (Fay 1979; Pitcher 1984). Harvests then declined to between 8,000 and 12,000 animals by 1972 when the MMPA was enacted. Subsequent seal harvests by Natives have been about 1,000 to 2,500 animals per year. Some harvests of sea lion pups for pelts also occurred between 1959 and 1972. Additional information on marine mammal exploitation is provided by Calkins (Ch. 17, this volume).

Since the enactment of the MMPA there has been little, if any, commercial exploitation of marine mammals in Alaska. While the act allows the taking of marine mammals by Natives and some use of their pelts for fur trim on salable handicraft articles, it seems unlikely that intensive exploitation will occur because of the limited demand for the handicraft products. However, if management of pinnipeds and sea otters is returned to the State of Alaska, regulated harvesting of the animals may resume.

Environmental Degradation

The issue of environmental degradation encompasses those agents that cause any alteration to the natural environment that is generally perceived as harmful or aesthetically displeasing. Such agents can be pollutants, activities that cause ecological disturbance, and activities that produce adverse visual impacts. Environmental degradation is an important issue in Alaska because of the State's predominantly pristine character and because its great natural beauty attracts both residents and numerous tourists. Equally important is the unsullied environment's intrinsic capacity to produce many living resources that can be of economic importance. Agents of environmental degrada-

tion found in the Gulf of Alaska include pollutants and litter stemming from:

- petroleum production
- fish processing
- logging and pulp manufacture
- marine transportation
- municipal discharges
- non-point sources.

Petroleum Hydrocarbon Pollution. Petroleum hydrocarbon pollution of the marine environment is a global problem. Petroleum hydrocarbons come from many sources besides oil and gas production activities. These sources include:

- bilge pumping from vessels
- marine accidents
- natural seepages
- loading and transfer operations
- refineries
- municipal sewage
- runoff
- atmospheric rainout (NRC 1985).

The nature of petroleum, its fate in the ocean, and its effects on organisms and ecosystems have all been the subject of intensive study during the past decade. Comprehensive general reviews include GESAMP (1977), Clark (1982), and NRC (1985). The fate and effects of petroleum spills in the ocean are summarized by Gundlach and Boehm (1981), Gundlach, Boehm, Marchand, Atlas, Ward, and Wolfe (1983), Teal and Howarth (1984), and Wolfe (1985).

Menzie (1982) describes the environmental implications of offshore oil and gas activities. Particularly pertinent are the reviews of oil weathering and its effects on the biota of the subarctic that were prepared by Malins (1977), Payne and Jordan (1979), Malins and Hodgins (1981), Griffiths, Caldwell, Broich, and Morita (1982), Malins (1982), Malins, Hodgins, Varanasi, Chan, McCain, Weber, and Brown (1982), Rice, Moles, Taylor, and Karinen (1979), and Rice, Moles, Karinen, Korn, Carls, Broderon, Gharrett, and Babcock (1984). Drilling discharges in the marine environment are reviewed by Houghton, Critchlow, Lees, Czapinski, Miller, Britch, and Mills (1981) and NRC (1983).

The concern over large-scale petroleum pollution in the Gulf of Alaska arises mainly from oil and gas production activities, oil loading, and tankering in Cook Inlet and Prince William Sound. Oil production in the Gulf began about 1900 at Katalla, 100 km east of Cordova. Between 1902 and 1933, this small field produced 1.54×10^5 bbl of oil (Davis 1984). Exploration elsewhere along the coast was unsuccessful until 1957 when the first commercial well was drilled near Swanson River in the Cook Inlet area. Subsequent intensive exploration in that area resulted in the discovery of seven oil fields and 13 gas fields, including fields in the Inlet proper (AGS 1970). By the end of 1984, Cook Inlet Basin had produced about 1.0×10^9 bbl ($\sim 1.6 \times 10^8$ m³) of oil and 3.7×10^{12} ft³ (1.1×10^{11} m³) of natural gas (AOGCC 1985). Annual production is now declining.

Exploratory drilling has occurred in coastal waters between the Alaska Peninsula and Yakutat. Six federal outer continental shelf (OCS) lease sales took place in the region between 1976 and 1984. Although over 20 offshore wells were drilled, no commercial finds have thus far been reported in either state or federally controlled waters. A summary of federal OCS sales and associated activities in the Gulf of Alaska is presented by Wiese (1984).

The main petroleum loading and shipping locations in the Gulf of Alaska are in Cook Inlet and at Valdez in Prince William Sound. The Drift River and Nikiski terminals serve Cook Inlet; volumes of petroleum products shipped from these terminals have reached as much as 8.0×10^7 bbl of oil and over 2.0×10^{11} ft³ of liquid natural gas annually (Davis 1984). The Valdez terminal—a much larger operation—receives some 1.6– to 1.7×10^6 bbl of oil daily from the North Slope fields via the Trans-Alaska Pipeline for loading on tankers for export. The annual throughput of the terminal was equivalent to 10% of the United States' total domestic consumption of 5.5– to 6.3×10^9 bbl per year in the early 1980s.

Spillage at the Valdez terminal has been only about one-half barrel for every million barrels handled. As of 1985, no spills exceeding 1,000 bbl and only one spill over 100 bbl had occurred (Lt. M. Dahl, U.S. Coast Guard, Valdez, pers. comm., 1985). Most of the petroleum hydrocarbons that enter Port Valdez harbor come from ballast water that is offloaded from incoming tankers. The water is treated to remove residual petroleum hydrocarbons and then discharged via a submarine diffuser into the inlet. Although the concentration of petroleum hydrocarbons remaining in the discharge is small (< 8 ppm), the absolute quantity that is released is significant—about 300 l of aromatic hydrocarbons and 170 l of dissolved organic compounds for the $\sim 3.8 \times 10^4$ m³ of ballast water that is processed daily (Lysyj, Rushworth, Melvold, and Farlow 1979).

Concerns about the chronic petroleum hydrocarbon discharges into Port Valdez, their potential for accumulation, and the effects they may have on the local ecosystem all prompted the EPA and the Alaska Department of Environmental Conservation to require oceanographic investigations both of the fjord and its biota as a condition of any discharge permit. An intensive four-year, pre- and post-operational study was undertaken by the University of Alaska; the project's results are described in Colonell (1980). It was concluded that, at least in the short term, no adverse effects on the fjord were evident. Monitoring of the treated ballast water effluent and receiving waters has continued under National Pollutant Discharge Elimination System (NPDES) permits.

Episodic releases of petroleum hydrocarbons into the Gulf of Alaska have come from vessel accidents, from bilge dumping, and from fish canneries. The heavy tanker traffic from Cook Inlet and Valdez thus far has not produced any massive oil spills. The only major oil spill in the region occurred in 1979 when an ore carrier, the *Lee Wang Zin*, capsized in Dixon Entrance. Several thousand barrels of bunker fuel and diesel oil from the vessel were carried northward by currents toward Ketchikan, where it washed ashore (Bayliss and Spoltman 1981). Evidence of vessel bilge dumping has

been observed on many occasions. In 1970, one such event reportedly killed an estimated 100,000 seabirds near Kodiak Island (Ohlendorf, Risebrough, and Vermeer 1978). Another somewhat unusual problem was encountered at a cannery near Cordova. Many years ago, waste oil was apparently disposed of in pits and then covered. The oil slowly percolated through the soil and entered the intertidal zone where it killed numerous organisms. Even this moderate quantity of oil was very costly to recover because it required months of effort that included trenching to collect the oil as it moved toward the beach.

Mining and Mineral Transfer Operations. Mining is an environmental issue for the Gulf of Alaska because mine tailings and processing water may be dumped into the Gulf, and pollution may arise from both loading and undersea mining operations. Potential environmental effects include:

- turbidity
- coastal erosion
- physical removal or smothering of marine organisms
- particle-size changes
- oxygen depletion caused by free sulfide releases (Baram, Rice, and Lee 1978).

The current state of knowledge about the effects of undersea mining on marine ecosystems is rudimentary. Little underwater mining has occurred in the Gulf of Alaska. A barite deposit at Castle Island was worked from 1967 to 1980 in order to provide oil-field drilling mud. About 2.25×10^6 mt of ore remain there (Baram *et al.* 1978). Future marine mining may exploit copper (Moore 1978; Heiner, Wolff, and Grybeck 1971), sand and gravel, placer, and sulfide deposits (Clague, Bischoff, and Howell 1984).

Two proposed onshore mining projects intend to discharge wastes into the marine waters of the Alexander Archipelago. The smaller one, the Greens Creek project, is an underground zinc, lead, silver, and gold mine located at the north end of Admiralty Island. The larger of the two is an open-pit molybdenum mine east of Ketchikan. The expected life of the Greens Creek mine is 11 years. Treated process water would be discharged from a marine outfall at a rate of about 2 m³/min. Potential pollutants in the effluent include milling-process chemicals such as sodium cyanide, copper sulfate, and other organic and inorganic salts (USDA 1983). Treatment would comply with the EPA effluent quality standards.

A major concern is the possible bioaccumulation of toxic metals and trace elements in those aquatic organisms that are near the outfall. The behavior of such chemical species in local waters is poorly understood, so it is not now possible to determine the environmental consequences of the proposed action (USDA 1983). The complexity of biological systems suggests that a simple relationship between the concentration and the nature of a sediment-metal and its bioavailability to various organisms in the ecosystem is unlikely (Warren 1981).

The proposed Quartz Hill open-pit molybdenum mine (located about 70 km east of Ketchikan) is one of the largest and richest known molybdenum ore bodies. Even though the ore is relatively rich, 99.875% of the extracted material

will be discarded after processing—this in addition to the overburden that must be removed (Snook 1982). If the mine's owners employ marine disposal, some $3.8\text{--}7.6 \times 10^4$ mt/d of tailings solids will be discharged through a submarine outfall into a nearby fjord for a period of 70 years (Ryan 1983). The projected annual discharge from Quartz Hill is equivalent to about 7% of the Mississippi River's sediment discharge and is roughly an order of magnitude greater than the total annual discharge of all dredging wastes that are dumped in the United States—according to data on the latter two sources in Gorsline (1979). Because the tailings have a low acute toxicity for organisms (Mitchell, Morgan, Vigers, and Chapman 1985), smothering and the alteration of the benthic community's composition are the primary concerns.

Coastal-water pollution may also result from ore—including coal—that spills at marine-shipment terminals. A terminal constructed at Skagway in the late 1960s served as a shipment point for both zinc and asbestos ore that was mined in the Yukon Territory. Peak annual shipments through the facility reached $\sim 7.0 \times 10^5$ mt (CSA 1982). The terminal is currently inactive. The effects created by ore that was lost during loading operations at Skagway have been examined by E.F. Robinson-Wilson (U.S. Fish and Wildlife Service, Juneau, unpubl. data) and G. Malinkey (Alaska Department of Environmental Conservation, unpubl. data). They found elevated lead, zinc, copper, mercury, and cadmium concentrations in the sediments as well as in some of the biota at the loading site. The ore terminal is one of several Alaska locations selected as long-term monitoring sites for NOAA's Status and Trends Program.

Coal exports from Alaska to Korea began in 1984. Because major deposits are located near the coast, it is likely that shipments of large quantities of coal from ports in southcentral Alaska to the Pacific Rim countries will occur. Annual exports could reach $1\text{--}2 \times 10^7$ metric tons. The two most important coal fields are the Beluga field on the west side of Cook Inlet and the Bering field east of Cordova. Identified resources in the Beluga field amount to at least 1.7×10^9 mt, of which at least 7.5×10^8 mt are economically extractable (Davis 1984). Alaskan coal has a low sulfur content (0.2%) (Davis 1984). Since this coal presumably has low toxicity for marine organisms, localized physical effects such as the smothering of infauna and habitat alteration may be the major issues.

Logging and Forest Products. Most of Alaska's lumber, wood chip, and pulp production takes place in the Tongass and Chugach National Forests. These Forests total about 9.3×10^4 km² and border much of the Gulf from Dixon Entrance to Kodiak Island. The primary timber species that are harvested include Sitka spruce and hemlock. While terrestrial environmental issues concerning the forest-products industry predominate, marine-related issues also are present. Localized pollution occurs in the vicinity of pulp mills. Log storage, transfer, and shipment activities cause physical damage to intertidal habitats, produce leachates, create biochemical oxygen demands, and smother biota with tree-bark accumulations (Hansen, Carter, Towne, and O'Neal 1971; Ellis 1973).

Log rafts are extensively stored and transported in the marine environments of the Gulf of Alaska. Loggers prefer creek mouths and other shallow embayments for log storage and transfer because they offer protection from both wind and waves, and they provide lower salinity and less exposure of the logs to air at low tide, thereby minimizing the damage caused by marine boring organisms. Such areas also often have the highest local habitat values and the most productive intertidal communities. They are concentration sites for anadromous fishes, waterfowl, and many other animals that frequently forage in the intertidal zone. The comparative richness of such habitats also makes them attractive for both subsistence and recreational use. Research on the effects of log storage and transfer practices on Alaskan intertidal and subtidal habitats has demonstrated that significant accumulations of organic debris may persist for long periods, and that marine organisms may become scarce in transfer and storage areas (Ellis 1973).

In 1967, the forests bordering the Gulf of Alaska contained 86% of the total volume of sawtimber in Alaska (Davis 1984). In 1979, the timber cut in Alaska's national forests—essentially the coastal forests—was about one-half of the allowable cut that would still maintain sustained yields. The allowable cut is now even less because land has been reclassified for wilderness areas and parks. Future cuts are unlikely to exceed the 1982 cut of $\sim 4.5 \times 10^8$ board feet, so little growth in the coastal lumber and pulp industry is expected (Davis 1984). Intertidal and subtidal habitat use by the industry should therefore be comparable in area to that in past years. In 1970, when the timber cut was about 5.6×10^8 board feet, log storage and transfer areas in southeastern Alaska totaled about 2.75 km² and mill storage areas totaled about 0.5 km² (ADEC 1971).

Questions remain concerning log storage and transfer areas:

- How much time is required for the intertidal communities to return to their original states?
- Are recovery rates sufficiently rapid to offset the damage that results from the establishment of new transfer sites as logging operations shift to new cutting areas?

Due to the slow growth rates of the region's commercial tree species, cutting rotations may be 100 years (Hutchinson and LaBau 1975, p. 36). Assuming that loading and transfer operations would take place at the same location during successive logging operations in a cutting area, it appears the perturbing episodes would reduce marine productivity for only a relatively short portion of the rotation cycle. However, this conjecture requires confirmation.

Public concerns about the impact of timber storage and transfer are being addressed in the Southeastern Tidelands Area Plan (SETAP) that is being developed by the Alaska Department of Natural Resources. SETAP is intended to resolve issues concerning use of state tidelands and submerged lands through improved coordination and by expediting the decision-making process that is associated with such usage. The plan will be a basis for State land classifications.

Two paper pulp mills are located in Southeast Alaska. One, in Ketchikan, began operation in 1954. The other, in

Sitka, started operating in about 1960. Both mills employ a dissolving sulfite process. In 1970–1971, the mills produced about 545 mt/d of pulp. At that production rate (following chemical recovery and screening), about 1.7×10^4 m³/d of sulfite waste liquor (SWL) were generated by each mill. The SWL is discharged into local marine waters along with wood chips and other waste materials.

When the water quality near the mills deteriorated, the pulp mill discharges were investigated by regulatory agencies (FWQA 1970; EPA 1971). Conditions observed near the mills included high concentrations of SWL, depressed dissolved-oxygen levels, sludge accumulations on the sea floor, and reduced numbers of littoral biota. Both investigations produced recommendations for secondary treatment of the SWL effluents to reduce pollutant discharges and to bring the mills into compliance with state and federal water-quality standards. Achieving compliance has been difficult, and the issue is replete with a history of appeals, hearings, and studies. In early 1985, the Ketchikan mill operators agreed to install equipment to achieve compliance with the Clean Water Act (Anonymous 1985). The Sitka mill has yet to receive an operating permit from the EPA.

Fish Processing Wastes. Marine dumping of fish-processing wastes has occurred in Alaska since the 1800s, but it only became a public policy issue when water quality deteriorated in certain coastal locations. Fish- and shellfish-waste discharges from both mobile and shore-based processors at Kodiak, Dutch Harbor, and Akutan have caused pollution. Statistics illustrating magnitudes of past discharges at those ports are presented in JSTT (1984a). At Dutch Harbor during the 1976 season, $\sim 2.1 \times 10^4$ mt of waste was discharged. Discharges at Kodiak amounted to $\sim 3.3 \times 10^4$ mt in 1971. The shore-based Trident Seafoods plant at Akutan released between 9 - and 11×10^4 mt of codfish and crab wastes into Akutan Harbor before the plant was destroyed by fire in 1983, after being in operation for about one year. Sidescan sonar surveys of the harbor bottom shortly after the fire showed that the Trident waste pile was about 7 m thick and 200 m in diameter. The survey also detected another waste pile in the harbor that was still identifiable five years after waste dumping had ceased.

Processing wastes consist mainly of highly biodegradable constituents such as tissue solids, oil and grease, along with fluids from viscera, heads, bones, and other discarded materials. Wastes are ground up before being discharged. The major constituents that are not highly biodegradable are crab and shrimp shells. Adverse effects from the wastes are coupled to dispersal regimes in the receiving waters. Noxious conditions occur when discharge rates exceed dispersion and biodegradation rates. When there is insufficient water exchange, the biochemical oxygen demand produced by the decaying wastes can cause anoxia. Elevated ammonia levels also may be present. Sedentary benthos are physically smothered by waste accumulations, and visible floating solids attract scavengers such as gulls or rodents, which may cause public health problems (Patten and Patten 1979). Finally, gull concentrations may be hazardous to aircraft in the vicinity of processors.

The amount of waste generated by fish processing operations depends upon processing rates, the species that is processed, and the type of processing that is used. The percent of waste ranges from between 30 and 35% for salmon, to between 73 and 85% for crabs (EPA 1983). Given those percentages and the recent regional fishery yields, the total annual tonnage of processing wastes discharged into the Gulf of Alaska appears to be 1.5 - to 2.5×10^5 metric tons.

In 1980, there were 302 applications for National Pollutant Discharge Elimination System (NPDES) permits to discharge fish processing wastes in Alaskan waters (EPA 1983). The heavy exploitation of currently important commercial fish and shellfish stocks indicates that on a regional basis, fish processing waste discharges will not increase much. Domestic processing wastes may increase if the United States industry gains control of the groundfishery. The rapid deterioration of many of the groundfish species soon after capture means that at least primary processing must occur quickly in order to maintain quality. Therefore, shore-based operations will be restricted to areas where the fish can be rapidly delivered from the grounds. Elsewhere, at least the primary processing has to be done at sea. Fish processing waste discharges may decrease if by-products such as meal and oil, fish silage, and chitin are made from the wastes (JSTT 1984b). The obstacles to by-product use in Alaska have included high production and shipping costs when compared with those of competitors that are located closer to markets, and lack of markets for the by-products. Both these obstacles could disappear if the demand increases.

Municipal Wastes. The world's oceans have traditionally been a repository for man's sewage, industrial byproducts, trash, and litter. Municipal wastes enter the marine environment in a variety of ways, the most prevalent being sewage outfalls, storm drains, streams, and ocean dumping. Some constituents of municipal wastes cause public health problems, adversely affect marine organisms, communities, and ecosystems, or result in aesthetic degradation. Synthetic organic compounds, chlorinated compounds, microorganisms, trace metals, biostimulants, and litter are among those constituents that are the most frequently implicated. A summary of types of wastes, their fates, and their effects is presented in Goldberg (1979).

Excluding the industrial wastes considered previously in this chapter, sources of municipal wastes in the Gulf of Alaska are relatively few, are dispersed, and are small in volume when compared with the waste in other coastal states. The municipality of Anchorage is the largest contributor. In 1981, Anchorage (population then 165,000) released about 9.1×10^4 m³/d of wastewater into Knik Arm. Discharges of Sitka (pop. 8,000) and Haines (pop. 1,350) (which typify smaller coastal communities) were 6,600 and 790 m³/d, respectively. The amount of sewage treatment also varies through the region, ranging from secondary treatment (*e.g.*, Kodiak, Wrangell, Haines) to primary treatment (Anchorage) to none (Sitka) (GAO 1981). Under section 301(h) of the Clean Water Act of 1977, the EPA can allow municipalities to discharge into marine waters sewage that

has undergone less than secondary treatment if the municipalities demonstrate that dispersion at the outfall will effectively dilute the wastewater.

The concentration of population in upper Cook Inlet has produced the only significant municipal waste pollution in the Gulf of Alaska region. In the early 1960s, Anchorage's raw sewage was discharged through several outfalls onto the broad apron of mudflats extending far offshore into Knik Arm. The outfall configurations caused serious bacteriological contamination and floating sewage solids (ADHW 1964). In the early 1970s, a municipal trunk and interceptor system, a primary treatment plant that provides wastewater screening and chlorination, and a submarine outfall extending 4.6 m below mean lower low water were constructed (EPA 1982). While the new system alleviated some problems, beaches east of the outfall remained contaminated. There was also concern that migrating salmon smolts would be affected by chlorinated compounds in the effluent. Due to the rapid population growth in the Anchorage metropolitan area, the existing system is nearing its design capacity and efforts are underway to improve it. The improvements include extending the outfall further offshore to reduce coliform bacterial contamination of the beaches. Stopping wastewater chlorination does not appear to be a viable alternative. Secondary treatment is considered unnecessary at present because the assimilative capacity of the Inlet is believed to be adequate for wastes produced by as many as 1.7 million people (EPA 1982).

Non-Point Source Pollutants and Litter. In addition to easily identified sources such as Anchorage, pollutants enter the Gulf of Alaska in a dispersed fashion from vessel discharges, upland runoff, and wind and ocean current transport. Well-known pollutants with ubiquitous distributions include polycyclic aromatic hydrocarbons, certain nitrogen and sulfur compounds implicated in 'acid rain', organochlorine insecticide residues, and petroleum tarballs. Common types of marine litter include polystyrene spherules and various other plastics. Mobile pollutants such as DDT and acid rain have stirred international controversies between 'exporter' and 'recipient' countries. Non-point source pollution will become a larger issue as human populations grow and more pollutants enter the biosphere.

Relatively few investigations have been made on non-point source pollutants in the Gulf of Alaska. Some effort has been directed toward petroleum hydrocarbons and marine litter. Shaw (1977, 1981) performed reconnaissance surveys to estimate hydrocarbon concentrations at the sea surface, in the water column, in sediments, and in selected biota. Most of the work was done in Cook Inlet and in the Gulf of Alaska between Yakutat and Unimak Island. Most of the non-biogenic hydrocarbons appeared to originate from natural oil seeps, coal outcrops, aeolian transport of combustion products, and local pollution sources.

Water samples collected in the Gulf indicated total hydrocarbon concentrations at or below the 1- $\mu\text{g}/\text{kg}$ level. There was no evidence of petroleum in the samples. Surface tows captured very little floating tar. The estimated arithmetic-mean concentration of tar over the continental shelf of the Gulf was $3.8 \times 10^{-4} \text{ g}/\text{m}^2$, two orders of magnitude

below the concentration levels found along major tanker routes in the world ocean. Petroleum hydrocarbons were not observed in water-column samples from Cook Inlet, presumably due to the intense tidal mixing in the upper and central portions of the Inlet, which rapidly disperses any hydrocarbons entering the system. However, fossil- and combustion-derived aromatic hydrocarbons were found in lower Cook Inlet sediment samples. Petroleum derived from previously identified oil seeps in the area was not encountered.

Litter is ubiquitous on Gulf of Alaska beaches and has been observed in trawl hauls by Jewett (1976). Much marine litter is attributable to fishing vessels and consists of long-lived plastic materials. Merrell (1984) found 122 to 345 kg/km of plastic litter of various kinds on 10 one-kilometer beaches of Amchitka Island in the western Aleutian Islands during a study period of 1972 to 1974 and again in 1982. Discarded trawl netting constituted the bulk of the litter in each year. The significant decline in litter between samplings was attributed to decreased numbers of foreign vessels operating in the Gulf by the 1980s. Discarded plastic materials such as netting and uncut strapping are a serious source of entanglement and mortality of marine mammals, birds, and fish. Fowler (1982) estimated that at least 5% of the fur seal population may die annually due to direct effects of fisheries, including entanglement in lost or discarded fishing gear. Over 200 salmon and 99 dead seabirds were found tangled in $\sim 1,500 \text{ m}$ of monofilament gillnet that was adrift south of the Aleutian Islands (DeGange and Newby 1982).

Multiple-use Conflicts

Marine mammals and commercial, subsistence, and sport fisheries are among the subjects of the numerous multiple-use conflicts present in the Gulf of Alaska.

Marine Mammal-Commercial Fishery Conflicts. Marine mammal-commercial fishery conflicts have existed as long as both users have competed for fish and shellfish. In the Gulf of Alaska, these conflicts are most evident in the salmon troll and gillnet fisheries, the halibut longline fishery, and the king crab pot fishery. They center around both gear damage and the loss or damage of fish captured by the gear (Mate 1980). The marine-mammal species most frequently involved are sea lions and harbor seals. Because of those depredations, there was a bounty on harbor seals in Alaska from 1927 until the 1960s. Control programs conducted in the Copper River Delta and the Stikine River areas during the 1950s removed about 35,000 seals (Matkin and Fay 1980).

Marine mammal-commercial fishery conflicts persist in the Copper River Delta. Matkin and Fay (1980) estimated that the monetary loss to the salmon fisheries in 1978 was about \$350,000, or about 4% of the gross potential value of the fishermen's catch for that year. Of the 1,000 marine mammals that were killed during the 1978 fishery, approximately 90% were harbor seals and sea lions.

Since protective legislation was enacted in the 1970s, many marine-mammal populations have grown rapidly, resulting in heightened conflicts. Predation on commercial

fish and shellfish is increasing (see Calkins, Ch. 17, this volume). For example, the burgeoning sea otter population in the Cordova area is believed to have markedly reduced local razor clam, Dungeness crab, and other invertebrate macrobenthos stocks. The Dungeness crab fishery in the area is depressed. Crab and clam stocks are unlikely to regain their former levels of abundance unless the number of sea otters decreases. Rosenthal (1977) predicted the current conflict between the crab fishery and the otters while studying otters and their habitats in Prince William Sound. Sea otters can forage to depths exceeding 40 m, and Rosenthal observed very intensive otter predation on both intertidal and subtidal invertebrates.

Additional marine mammal–commercial fishery conflicts will arise if forage species such as capelin and sand lance are commercially harvested. Trophic studies have shown that capelin and sand lance are among the most important prey species for both seabirds and marine mammals in the Gulf of Alaska (see DeGange and Sanger, Ch. 16, this volume; Calkins, Ch. 17, this volume).

Because public attitudes about marine mammals have changed and protective legislation has been passed, managers must use new approaches to fisheries management. Managers now must evaluate the impact of fisheries on mammals as well as the converse. Such complex considerations have helped spur the development of multi-species and ecosystem management models (see OCSEAP Staff, Ch. 14, this volume.)

Marine Mammal–Tourism Conflicts. Humpback whale use of certain areas in the Alexander Archipelago has allegedly decreased because of both disturbance and displacement by heavy vessel traffic. The Endangered Species Act mandates that no ‘taking’ of endangered or threatened species, such as the humpback whale, shall occur. The term ‘taking’ is broadly interpreted to include not only capture, killing, and injury, but also harassment and other activities that disturb the animals (Chapman 1979). Vessel traffic linked to whale displacement can be construed as harassment.

This controversy has been evident in Glacier Bay National Park and Preserve, where humpback whales traditionally feed in summer. The area has also become a popular cruise-ship destination. Whale numbers in the Bay have fallen during the past few summers (Baker, Herman, Bays, and Stifel 1982). Some believe that this change is related to the increased frequency of the cruise-ship visits, while others argue that it simply reflects the local availability of prey. Further details, both on the issue and on research efforts to resolve it, are presented in Baker, Herman, Bays, and Bauer (1983); Baker *et al.* (1982); and by Calkins (Ch. 17, this volume).

Recreational–Commercial Fishery Conflicts. Throughout the nation, the competition between commercial and recreational fishery users is growing, and conflicts are now commonplace. Alaska is no exception, but such conflicts are currently evident mainly in the more densely populated Cook Inlet area. The Kenai River salmon fishery is a notable example. The River is famous, both for its chinook salmon—which attain weights exceeding 40 kg—and for its prolific sockeye salmon runs, which attract anglers from

afar. Both salmon species are taken by contemporaneous commercial gillnet fisheries in the Inlet.

Because spawning runs for the two species overlap both in time and in space, an allocation scheme that favors a sport fishery for chinook and a commercial fishery for sockeye has been implemented with varying degrees of success. The commercial sockeye fishery invariably intercepts some Kenai chinooks. In order to maintain a viable stock, a certain minimal number of spawners must escape. This means that the anglers’ catch must sometimes be reduced. Restriction of the sport fishery in the River imposes economic hardships on guides and others who cater to sport fishermen. Restrictions are also perceived by the anglers as inequitable, because they believe they have been denied an equal opportunity to harvest an open-access (*i.e.*, common-property) resource.

As a partial solution to the problem, fish traps could be installed at the mouth of the Kenai River that would selectively release enough chinook and sockeye for a sport fishery as well as meet spawning management goals. This would also provide an economic substitute for the existing commercial fishery. Fish traps were outlawed in Alaska soon after statehood. But, as noted by Straight (1980), there are powerful economic and resource-management arguments in favor of their use, and perhaps one day they will become legal again.

Subsistence-related Conflicts. Subsistence is perhaps the most volatile open-access resource issue in Alaska. Since passage of ANILCA, both federal and state fish and game management policies as well as court decisions have given preference to rural residents because the opportunities to earn a cash income are limited and purchased foods may be supplemented with wild fish and game (see Kelso 1981a, 1981b, 1982). Also, living off the land is a traditional way of life in many rural Alaskan communities. However, many urban Alaskans believe that their rights are being abridged by the current policies. In response, the Alaska Department of Fish and Game has formed a Subsistence Division to deal with this complex and controversial issue.

The subsistence issue is not yet a major concern with respect to the marine environment, but it relates to allocation of salmon. Large numbers of salmon are captured for subsistence after they enter the rivers. This means that subsistence users compete with both commercial and sport fishermen for the resource. One potential consequence of an excessive ocean catch is the restriction or the closure of subsistence fisheries to ensure that spawning-escapement requirements are met. The subsistence issue has thus far focused on big game such as moose and caribou; however, it seems inevitable that as the population and the competition for resources continue to grow, subsistence issues will extend to the coastal areas as well.

Environmental Hazards

Various environmental hazards are present in the Gulf of Alaska. Seismicity, volcanism, storms, and other geophysical phenomena present significant threats to both people and property.

Large and relatively frequent earthquakes are characteristic of essentially the entire coastline (see Jacob, Ch. 6, this volume). This hazard is exemplified most vividly by the Great Alaskan Earthquake of 1964, which caused 115 deaths and an estimated \$330 million in damages in the coastal region. The Great Alaskan Earthquake is extensively documented in an eight-volume, National Academy of Sciences-sponsored report (NRC 1972). A comparably large event may occur soon in the Shumagin seismic gap (Jacob 1983).

Continued population growth in the Railbelt will increase the potential for a catastrophe if another great earthquake occurs. The rupture zones of major regional earthquakes often extend for hundreds of kilometers (Sykes, Kisslinger, House, Davies, and Jacob 1980), so the epicenter need not be close to produce damaging results. While regional seismotectonics are fairly well understood, additional, more localized information is needed in order to develop intelligent land-use policies, building codes and practices, and public safety plans that will mitigate the consequences of a major seismic event (see Jacob, Ch. 6, this volume).

The tsunamis and seiches generated by the Great Alaskan Earthquake of 1964 caused 90% of the deaths in Alaska, along with heavy property damage and fatalities as far away as Crescent City, California. The tsunami produced by the Earthquake was even observed in Antarctica (Selkregg 1974). Landslides and icefalls in coastal embayments also cause loss of life and property in the Gulf. In Lituya Bay, a landslide in 1958 produced a wave with a runup that reached 530 m above sea level and drowned two fishermen. In 1845, approximately 100 Natives were killed in Yakutat Bay by a wave that was apparently produced by an ice-fall at the head of the Bay (Cox and Pararas-Carayannis 1976).

Volcanism is a significant environmental hazard owing to the large number of active, violently eruptive volcanoes similar to Mount St. Helens in Washington State. The Katmai eruption of 1912 and eruptions of Mount Augustine in Cook Inlet were comparable events. The social impacts of past eruptions have been limited because there were few people in the danger zones of the events. As the volcanic zone becomes more populated, the potential for a catastrophe will grow. The hazards associated with volcanism both in Cook Inlet and on the Alaskan Peninsula have been described by Pulpan and Kienle (1981), Kienle and Swanson (1983), McNutt (1983), and Jacob (Ch. 6, this volume).

Near-field volcanic hazards such as pyroclastic flows, dry debris avalanches, wet debris flows, and flood deposits present the greatest threat. Far-field hazards include ashfalls, acid rain, and tsunamis caused by mass wasting. For example, some of Mount Augustine's eruptions have produced tsunamis in Cook Inlet. Flash flooding can also result when ice and snow are rapidly melted by subglacial heating. This is a serious hazard in some areas; such volcano-glacier interaction has occurred at Mounts Katmai and Redoubt (Pulpan and Kienle 1981).

Sediment has been deposited at high rates during the Holocene period, and this has led to unstable sediments in the Gulf of Alaska (Hampton, Carlson, Lee, and Feely, Ch. 5, this volume). Unstable sediments are especially prevalent in the northeastern Gulf, where submarine slumps and slides

are commonplace. Some cover areas, exceeding 100 km², have thicknesses of hundreds of meters, and occur on slopes of less than one degree. Unstable sediments are of major concern for the offshore petroleum industry because they can shift and cause structural damage or even failure of the bottom-founded production platforms and pipelines.

Many parts of the Gulf of Alaska coastline are undergoing rapid change due to ongoing tectonic, glacial, and erosive processes. Such activity has been documented in Prince William Sound, Cook Inlet, near Icy Bay, and elsewhere (NRC 1968; Peterson 1979, 1980; and Hampton *et al.*, Ch. 5, this volume). The implications of rapid coastal erosion or accretion can be considerable. Remedial measures such as the construction of jetties and groins to stabilize beaches, the use of maintenance dredging, or the use of rip-rapping are not only costly, but are often ineffective measures that may themselves produce unforeseen adverse changes. The Alaska Coastal Management Plan denotes areas of significant geophysical hazard as "areas meriting special attention."

Hazards produced by the weather must be included here because the Gulf of Alaska is one of the stormiest oceanic regions in the world. Conditions that are dangerous to mariners occur frequently; they include large seas, high winds and, during winter, vessel icing. The same weather also often affects the coastal areas, as documented by Wise, Comiskey, and Becker (1981). During the winter of 1984-1985, high winds and high tides combined to cause extensive damage and property loss along the waterfronts of Juneau (the state capital), and several other communities in southeastern Alaska.

The Future

Having described the underlying factors and issues that have affected oceanographic research in the Gulf of Alaska, it remains to look to the future. A review of two of Alaska's growth forecasts (APU 1984; Morehouse 1984) suggests the following:

- Fisheries will remain a major issue—with perhaps some shift of emphasis from 'traditional' fisheries to the groundfisheries and the fisheries for currently unexploited species.
- The forest-products industry is expected to experience slow growth, so both logging and pulp-production issues will remain essentially unchanged.
- Oil production in Cook Inlet will decline; however, the level of activity at Port Valdez will remain high into the twenty-first century.
- Mining and associated transfer operations could become very important issues if large-scale coal exports or hard-rock mining projects occur.

Development in any of these areas will depend on both favorable national and favorable international market conditions.

The continued population growth in the Cook Inlet area will exacerbate the existing multiple-use conflicts between subsistence, commercial, and recreational fishery users and

will likely generate other open-access resource conflicts. Municipal waste discharges into the marine environment will not assume significantly greater near-term importance because most population growth is expected in upper Cook Inlet where dispersion is highly efficient. Pollution from fish wastes should not significantly increase. Litter is presently the most evident and obtrusive form of non-point source pollution in the Gulf of Alaska. It will become less of a problem only if public attitudes change, regulation and enforcement improve, and use of recalcitrant materials such as plastics for containers and other disposable items decreases. Non-point source pollution will become a larger issue as both regional and global populations grow.

Energy systems in the coastal zone may become a major regional issue because the Gulf is rich in potential power sources, and the population growth in Cook Inlet will increase the demand for energy. Possible energy technologies include plants that use coal, the tides, or geothermal energy to generate electricity. These potential energy systems are described in Davis (1984). Coal-fired electricity generation is particularly attractive because the Beluga coal field is nearby and Cook Inlet offers a virtually unlimited supply of cooling water. Exporting Beluga coal to the Far East would introduce economies of scale in fueling the plant and would improve the economic aspects of both projects. The environmental problems that would arise from a coastal coal-fired power plant could include air pollution, ash disposal, thermal pollution, entrainment of organisms, and the formation of toxic chlorination products (Hall, Howarth, Moore, and Vörösmarty 1978).

Upper Cook Inlet, with its large tidal range (~7.5 m), is among the world's best sites for tidal power generation. Preliminary studies suggest that up to 7.5×10^4 gigawatt-hours of energy could be produced annually (Davis 1984). Such a project would raise issues concerning sediment transport through the Inlet, seasonal ice, anadromous fish migration, and navigation.

Geothermal activity is commonplace in the northern Gulf of Alaska due to active tectonism and volcanism. Preliminary evaluations of the geothermal energy potential have been conducted by the state and federal agencies. The volcanoes of the Aleutian Island chain are obvious examples of energy sources that could be tapped. Their remoteness now precludes their consideration as a viable alternative to more conventional methods of electrical power generation. As the region's population grows and the cost of fossil fuels continues to rise, geothermal energy generation may become economical. Potential problems associated with the marine waste-water discharges that come from geothermal plants include localized temperature increases, the toxic constituents of the effluent, and anoxia.

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ABSTRACT

The United States government has played a key role in sponsoring research in the Gulf of Alaska, particularly since the passage of the National Environmental Policy Act in 1970. Much of this research was focused on environmental issues pertaining to offshore oil and gas development. The scientific data pertaining to management needs are described for three broad subject areas: 1) environmental hazards, 2) pollutant transport, and 3) biological production and resources.

Present information is adequate to identify both the areas and the phenomena that are hazardous to industrial structures and operations, to calculate oil-spill trajectories and weathering states, to identify those shoreline segments that have the potential to retain spilled oil, and to describe important marine bird, mammal, and fish habitats. Six critical coastal habitats are described in the chapter.

Data are inadequate to compare the biological productivity of different parts of the Gulf. Data are also insufficient to describe regional ecosystems or to undertake a holistic approach to marine environmental assessment.

Newly acquired data have progressively improved both the environmental descriptions and the analyses in those environmental impact statements prepared during the period from 1975 to 1984 for oil and gas lease sales in northern and western parts of the Gulf, in Cook Inlet, and in Shelikof Strait. These data may have been instrumental in several resource management decisions.

The observations in the existing data base are not uniform in their comprehensiveness for different parts of the Gulf. There is the least amount of data available for southeastern Alaska.

Introduction

From the exploratory surveys aboard the United States fisheries vessel *Albatross* in the 1890s to the current fisheries oceanography study in Shelikof Strait under the sponsorship of the National Oceanic and Atmospheric Administration, the United States government has played a dominant role in sponsoring research in the Gulf of Alaska. Much of the research has focused—and continues to focus—on resource management. In this context, the government's role can be broadly divided into four categories: 1) to conserve, 2) to predict, 3) to mitigate, and 4) to compensate.

The years 1969 and 1970 are the most significant milestones in the government's involvement in research pertaining to national policy and priorities. These two years marked the institutionalization of commitments by the gov-

ernment to improve the quality of public decision-making by means of a more integrated, interdisciplinary use of scientific information and methods. The National Environmental Policy Act (NEPA) of 1969 (P.L. 91-190, 83 Stat. 852, January 1, 1970) declared a national environmental policy and committed all government agencies to using a systematic and interdisciplinary approach that would ensure that both natural and social sciences, as well as engineering design criteria, be used in any decision-making process that might lead to an impact on man's environment. In 1970, the Council on Environmental Quality (CEQ) was established by statute, and the Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) were established by Executive Reorganization Plans 3 and 4, respectively. These actions further expanded the government's role in relevant scientific research and the use of scientific data in the decision-making process.

The significance of the period 1969 to 1970 and of the statutory and administrative framework it provided became clearly evident in 1974. On January 23, 1974, President Nixon directed a three-fold expansion of the Department of Interior's outer continental shelf (OCS) oil and gas development efforts. The continental shelf from Dry Bay to Montague Bay (beyond the 3-mile State jurisdiction) was the first Alaskan area to be included in the OCS oil and gas leasing schedule. The CEQ, at the request of the President, undertook a study of the potential environmental risks and outlined a number of factors (stated below) relating to oil and gas development in the Gulf:

- There is a high probability that oil spills will come ashore from a number of hypothetical production locations.
- There will be slow weathering of crude oil in this region due to temperature and sunlight conditions.
- There is a high degree of importance attached to biota, particularly bird nesting and fish spawning areas.
- There are frequent storms in the area.
- There is a potential hazard to industrial installations and facilities from earthquakes and tsunamis.

The council stated that there was little or no scientific information available to properly evaluate these factors.

Following the CEQ's study and recommendations, the Bureau of Land Management (the bureau within the Department of the Interior that was responsible for oil and gas leasing at that time) requested NOAA to conduct an environmental study and assessment program in the Gulf. The program was established in 1974 by an interagency agreement between BLM and NOAA. It initially responded to the specific needs, goals, and objectives of BLM in the OCS leasing decisions. In 1975, it was expanded to include research in nine Alaskan OCS areas as well as non-area-specific (generic) studies. This program, known as the Outer Continental Shelf Environmental Assessment Program (OCSEAP), became the largest marine environmental research program ever undertaken. It emphasized both the acquisition and the analysis of data as part of the assessment of those environmental factors identified by CEQ.

OCSEAP-sponsored research—particularly the research conducted during the period from 1974 through 1980—is largely responsible for increasing our current scientific knowledge of both the physical environment and the biological resources of the Gulf. Other agencies such as the United States Geological Survey, the United States Fish and Wildlife Service, the National Marine Fisheries Service (and other elements of NOAA), and the State of Alaska have also contributed significantly to this knowledge.

Other comprehensive and multidisciplinary environmental studies have also been conducted in the Gulf (on a much smaller spatial scale) in order to fulfill NEPA requirements and to obtain mandated scientific information for both State and federal regulatory agencies. Two of these more prominent studies were 1) an evaluation of the possible effects that wastewater discharge from a ballast-water treatment plant would have on the biological resources of Port Valdez (located in Prince William Sound) (Hood,

Shiels, and Kelley 1973; Colonell 1980); and 2) an investigation of how mill tailings and other waste products from a proposed molybdenum mine near Boca de Quadra fjord (southeastern Alaska) would affect the environment in the fjord if those wastes were discharged into the water (Ellis 1982).

The significance that the scientific data base holds in allowing informed and rational resource management decisions to be made or in facilitating selection of a particular engineering design is illustrated in Figure 20-1. Certain formalized concepts of pollution control strategies (Freeman, Haverman and Kneese 1973) and risk-benefit analyses (Whyte and Burton 1980) are implicit in this figure, developed by Dr. Rudolf J. Engelmann, Director of OCSEAP from 1975 to 1979. The figure was described as an 'Engelmann Curve' by Dr. T. Neil Davis in a Fairbanks newspaper (*Fairbanks Daily News-Miner*, May 26, 1979). Because the figure actually consists of two separate curves, it will be referred to as the 'Engelmann Diagram' in this chapter to avoid any semantic confusion.

According to Figure 20-1, if no consideration is given to 1) the sustainable exploitation level of a resource, 2) the accommodative capacity of a natural body of water, or 3) the safety provisions in an engineering design (each of the three requiring scientific data and their interpretation), then the project is likely to fail—resulting in economic loss (Point 1). A much greater loss to society would occur if the project failure also results in other damages such as the loss of a resource, irreparable damage to the environment, or loss of human life (Point 2).

The cost of a project with its own desired safety provisions (and minimum expenditure) is shown at Point A. But societies demand greater than the minimum safety margin and a higher safety margin brings a higher cost (Point B). Neither the project nor the society benefits if the safety and

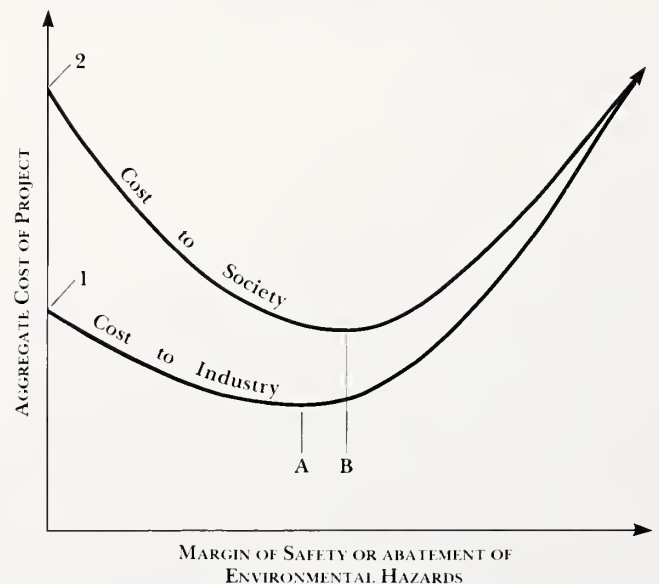


Figure 20-1. Engelmann Diagram showing the generalized relationships between the costs and the margins of safety in a given project.

abatement considerations are far lower than Point A or far higher than Point B. Our society has remained willing to pay for the additional safety margin that lies between points A and B in Figure 20-1. These margins currently take the shape of emission controls for automobiles or factories, traffic diversions away from bird nesting colonies or mammal rookeries, or the curtailment of industrial operations in order to reduce the disturbance of a valued species.

There are a number of techniques one can use to interpret and evaluate scientific data when making resource management decisions. These techniques range from the relatively simple, subjective, and qualitative interaction matrices, such as the Leopold matrix (Leopold, Clarke, Hanshaw, and Balsley 1971), to more objective and complex numerical analyses, such as simulation modeling (Holling 1978).

Simulation modeling relies on precise identification of relevant variables and their interrelationships. It is a powerful and readily adaptable technique which can be used both to mimic natural systems and to compare alternate management schemes (Holling 1978). The principal disadvantage of simulation modeling is that its results do not reflect the adequacy of assumptions that go into the calculations and can only be as good as the input data. There is also danger that results of simulation modeling may be too readily believed by the decision maker.

Although there are ample techniques one can use to evaluate scientific data, and there are clear guidelines for making a management decision (Holling 1978; Wolfe, in press), it is usually not obvious that scientific data are adequately used as part of the management decision process. This is because most management decisions are not made on the basis of scientific considerations alone; certain economic criteria, the prevailing socio-political environment, and prevalent institutional tendencies also play a significant role. Furthermore, if scientific analysis is not included as an integral part of the decision-making process from the beginning, the evaluation of scientific data will not play a prominent role in the decision (Holling 1978). Under circumstances where scientific study is an afterthought, research and evaluative studies are likely to be either too broad and unfocused to respond to future information requirements, or too narrowly focused on those aspects of the program that are easily quantifiable (Lowry 1980).

This chapter describes both those scientific data and models that play a role in the previously stated management concerns. Most of these concerns are focused on environmental issues and resource-use conflicts discussed in the previous chapter (Jarvela, Ch. 19, this volume). The text is organized into three areas for which data are available: 1) environmental hazards, 2) pollutant transport, and 3) biological production and resources.

No attempt is made to judge either the extent or effectiveness of use of scientific data in management decisions. In recent years, such decisions in the Gulf have included:

- selecting the site for the ballast-water treatment plant
- selecting and excluding tracts for petroleum development
- allocating fisheries resources

- designating critical biological habitats
- governing vessel traffic near marine bird and mammal habitats.

For those interested, there is a case study of Port Valdez in which scientific data were used both to allow for and to monitor wastewater discharge (Shaw and Hameedi, in press).

Environmental Hazards

Coastal facilities, bottom-founded structures, and sub-bottom installations in the Gulf of Alaska are at risk due to the geologic setting. Surface vessels in the Gulf are subject to frequent storms and high waves. Extremes in meteorologic and oceanographic conditions and other environmental factors pose risks to human life, construction vessels (pipelayers, dredges), support vessels, and industrial installations.

A number of environmental factors must be considered before a decision to install a bottom-founded or sub-bottom facility can be made. In the case of petroleum production platforms, such factors may include:

- water depth
- tides and currents
- storm-wind velocities
- storm-wave heights
- tsunamis and seiches
- ground acceleration due to earthquakes
- instability of sea floor sediments
- impact load caused by sea ice that impinges upon the structure.

Site-specific data are required in order to characterize a particular location as being suitable for the development and operation of an offshore installation. There is also a need for reliable data with broader spatial resolution to facilitate evaluation of the hazards that the environment poses to any structure. Such broader-scope data provide an essential framework with which to evaluate site-specific information and help guide safe and orderly industrial development.

The offshore petroleum industry is probably the only industry likely to commit vast resources to the design and the placement of structures on or below the sea bottom. There are petroleum production platforms in Cook Inlet, off the California coast, and off Japan that have been exposed to numerous earthquakes. According to Dunn (1982), the design criteria for Cook Inlet petroleum platforms have included deck loading ($8-10 \times 10^3$ mt), wave height (12-15 m), ground acceleration (0.2 gr), and ice loading (1 m). The industry experience and data base in this field are growing, but more extensive and longer-term data are needed because some environmental parameters must be described in statistical terms (Dunn 1982).

Seismic Hazards

Jacob (Ch. 6, this volume) has described the seismotectonic setting of the Gulf of Alaska. The high level of tectonic

activity, coupled with the expectation of a large earthquake within the next two to three decades, presents a substantial hazard to human life and property. Three of the ten largest earthquakes in the world since 1904 have occurred in the Gulf of Alaska/Aleutian region. The Great Alaskan Earthquake of 1964 was perhaps the most significant event in terms of its magnitude and the extent of damage it caused. The Shumagin and Yakataga seismic gap areas are identified as the most likely sites for the next great earthquakes in the Gulf (Savage, Lisowski, and Prescott 1986).

A number of tectonic models have been developed to describe the seismotectonic framework for the Gulf. These models are based on an evaluation of historic earthquake records, the regional geology, and an analysis of data obtained from both regional and worldwide seismograph networks. The synthesis of data in the form of a seismic-exposure analysis is an important and useful step in assessing environmental hazards. Woodward-Clyde Consultants (1982a, b) modified existing software and applied it to seismic-exposure analysis and mapping for the Gulf of Alaska region. The modification was made in order to account for seismic gaps, to use newly acquired data on ground-motion attenuation, and to establish initial seismicity conditions and source geometries that would be consistent with recent observations. A schematic representation of the seismic-exposure model is shown in Figure 20-2.

The results of the Woodward-Clyde study can be used to obtain single-point values of seismic exposure at a given site. They can also be used in combination with a grid of sites to create seismic exposure maps. Six such maps have been produced. These maps show the probabilities of exceedence (at the 33% level) for typical ground-motion parameters such as maximum horizontal acceleration. The exceedence probabilities were calculated for the 1981 to 2021 period. Maximum ground-acceleration contours that

showed high values in seismic gap areas are presented by Jacob (Ch. 6, this volume: Figs. 6-31 and 6-32).

Seismic-exposure maps are very useful to resource managers for tasks such as establishing seismic zones and creating design guidelines. Offshore industries' personnel use the maps for planning site-specific studies and for determining engineering design specifications. Researchers also use the seismic-exposure maps for evaluating the reliability of input data and model parameters. The use of these maps is currently limited by: 1) the lack of integration of the seismicity records from great earthquakes in the analysis, 2) the lack of any recent redefinition of seismic-gap zones, and 3) the need for substantive additional data on ground-motion attenuation and scaling factors that can be applied to the Gulf (Jacob and Hauksson 1983).

Volcanic Hazards

Another manifestation of the tectonic setting of the Gulf and, in particular, of the subduction of the Pacific Plate under the North American Plate, is the nearly forty volcanoes both on the Alaska Peninsula and in the Aleutian Islands. A number of these volcanoes have erupted during this century (*e.g.*, Katmai-Novarupta in 1912, and Mount Augustine in 1883, 1963-1964, and 1976) (Kienle and Shaw 1979)—Mount Augustine also erupted again in 1986. The following phenomena that are commonly associated with volcanic eruptions pose substantial hazards:

- 1) violent explosive eruptions, directed blasts, volcanic bombs, glowing avalanches and *nuées ardentes*, heavy debris falls, and tectonically induced sea waves
- 2) hazardous atmospheric phenomena, including turbulent ash clouds, noxious gas clouds, and corrosive rains
- 3) pyroclastic flows, lava flows, mud falls, and flash floods in river valleys.

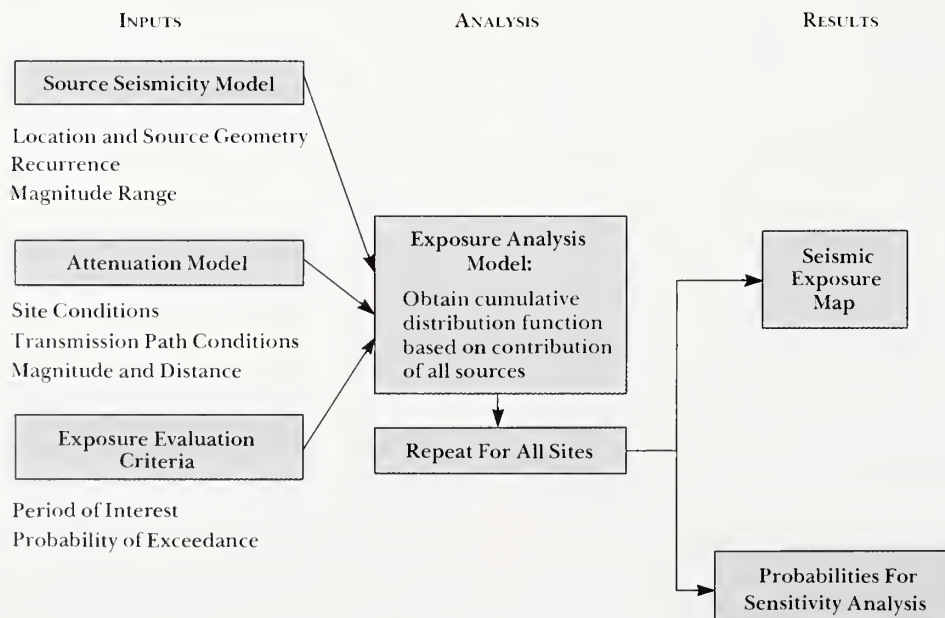


Figure 20-2. Schematic diagram of the elements of a seismic-hazard evaluation, as implemented in a seismic-exposure software package by Woodward-Clyde Consultants (1982a).

At present, the area of highest risk to human life and property as a result of falling volcanic bombs, pyroclastic flows, and tephra accumulation in the Gulf has been (and is likely to be) restricted to the immediate vicinity of St. Augustine Island. The volcanic gas plumes and ash from the 1986 eruption spread northward and eastward to a much larger area. This was predicted by Kienle and Swanson (1980).

In comparison with seismic hazard studies, research on volcanic hazards has not been extensive; however, events that have led to major volcanic eruptions and the areal extent of damage from those eruptions are well documented (Kienle and Shaw 1979; Kienle and Swanson 1980; and McNutt 1983). The geophysical precursors to the eruptions of Mount Augustine volcano have been described by Kienle and Swanson (1980), and seismicity appears to be the most reliable predictive sign. These authors also produced a volcanic hazard map in the event of future eruptions (such as that in 1986) of the volcano. Four hazard zones were delineated, from very high to very low hazard areas.

Offshore oil and gas lease sale blocks in Cook Inlet were located outside the high hazard zone in which there could be potential loss of life and property from pyroclastic flows as well as from volcanic gases and tephra accumulations (Fig. 20-3). The low hazard zone—an area in which there was only low ash accumulation—extended about 1,000 km eastward to Sitka and 400 km northward to Talkeetna. The areal extent of this zone was determined by the prevailing high-latitude westerly winds. After the 1986 eruption, actual ash-fall patterns were found to be precisely as predicted. McNutt (1983) also produced maps of potential ash accumulation from 'once-per-hundred-year eruption' probability data for major volcanoes located on the Alaska Peninsula.

Sediment Instability and Erosion

Hampton, Carlson, Lee, and Feely (Ch. 5, this volume) have described both the distribution and the properties of sea-floor sediments as well as having delineated areas where there are potential instabilities on the sea floor. Two of the most striking and well-studied sediment-slump and sediment-slide areas are located on the northern portion of Kayak Trough and in the area seaward of Icy Bay. The sediment slide near Kayak Trough covers an area of over 250 km² and has a volume of nearly 6 km³ (Molnia, Carlson, and Bruns 1977). This slide could have been triggered recently by an earthquake. A sediment slide near Icy Bay that covers an area 90 km long and 10 to 20 km wide is also believed to have occurred recently. It could have been caused by rapid sediment accumulation combined with an increase in the slope angle (Carlson 1978).

Sediment sliding is not known to occur in the western Gulf of Alaska, although the shallow troughs that intersect the shelf off Kodiak Island have slopes that should be conducive to slides (Hampton *et al.*, Ch. 5, this volume; Fig. 5-4). Sediment distribution data and the high-resolution maps produced by the United States Geological Survey were very useful in selecting lease tracts in the northeastern Gulf (U.S. Department of the Interior 1980).

Sediment sliding or slumping is not considered a hazard in Cook Inlet. Rather, potential bedform movement such as

the sand waves or sand ripples that result from tidal currents or storm waves may pose hazards to bottom-founded installations. Under present hydraulic conditions in Cook Inlet, large sand waves—some of which are 5 to 10 m high and 500 to 1,000 m long—are believed to move very slowly, perhaps only tens of centimeters per year (Hampton *et al.*, Ch. 5, this volume). The superimposition of bedforms of different sizes and their respective orientations suggest that the time scale for different bedform movements may vary widely—from daily to episodic or even geologic. Such movements should be evaluated before installing bottom-founded or sub-bottom structures such as drilling platforms or pipelines.

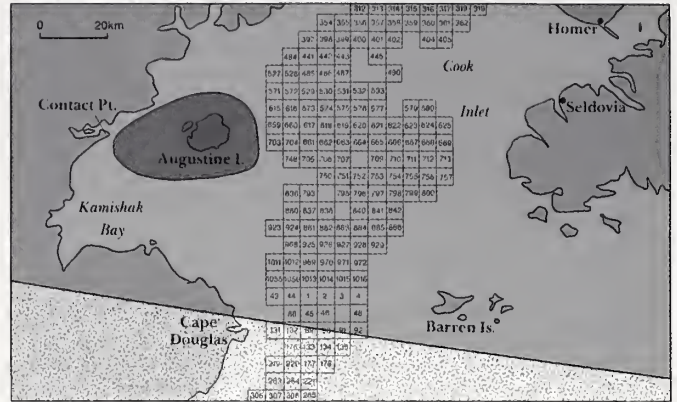
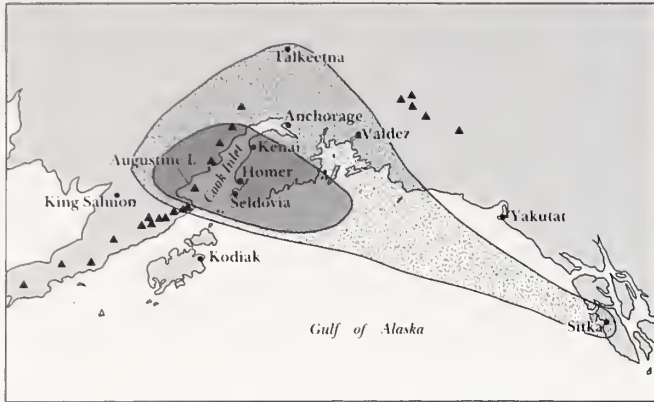
A large portion of the sediment that is brought into Cook Inlet by rivers remains suspended due to strong tidal mixing and is subsequently transported out of the Inlet. The most important of the river systems that empty into Cook Inlet in terms of sediment load is the Susitna/Knik/Matanuska system. Depending upon the sediment grain characteristics and the prevailing current regime, sediment leaving the Inlet may be deposited in Shelikof Strait or in the region of the Kennedy and Stevenson Entrances. Sediment accumulation within Cook Inlet occurs only in protected, semi-enclosed embayments such as Tuxedni, Chinitna, Kachemak, and Kamishak Bays. The high concentration of suspended sediment in water, coupled with strong currents that exceed 300 cm/s in certain locations, has the potential to be highly abrasive and could damage protective coatings. However, such hazards are relatively unimportant, even though they could be expensive to counteract.

Oceanographic Hazards

High winds, large waves, and accumulating or drifting sea ice all pose hazards to facilities and their operations. It is usually not the normal events that cause concern, but rather the extreme events that may cause loss of life and damage to property.

Brower, Searby, Wise, Diaz, and Prechtel (1977) calculated values for maximum sustained winds, maximum significant wave heights, and extreme wave heights for six segments of the Gulf ranging from southeast Alaska to Unimak Pass. The oceanic area south of the Kodiak Archipelago is expected to have stronger winds and higher waves than the other areas. Winds approaching 47.6 m/s (87 kt), waves with maximum significant heights of 17 m, and extreme waves over 30 m high can have 25-y cycles over most of the Gulf. The 100-y or 'engineering design' events are a 54.7 m/s (100 kt) wind, a maximum significant wave height of 22 m, and an extreme wave height of 39 meters. This implies that the probability in any given year for a 54.7 m/s (100 kt) wind or an extreme wave height of 39 m is one percent.

Sea ice occurs in Prince William Sound, Cook Inlet, along smaller stretches of coastline south of the Alaska Peninsula, and in Shelikof Strait. Shallow embayments and coves may be seasonally covered with ice, although in most areas ice formation and break-up occur several times during the winter. Small segments of ice broken off glaciers (called 'bergy bits') have been found floating several kilometers from their origin. Except for small craft, they rarely pose any danger to marine transportation and shipping.



- Area of very high risk to human life and property associated with falling volcanic bombs, pyroclastic flows, volcanic gases, thick tephra accumulation and mudflows (on or nearshore only).
- Area of high risk to human life and property caused by pyroclastic flows, volcanic gases and tephra accumulation. (Extent uncertain in striped area.)
- Area of low risk to human life and moderate risk to property caused by volcanic gases and tephra accumulation.
- Area of no risk to human life and low risk to property caused by volcanic gases and tephra accumulation.
- Area of no risk to human life or property.
- Extent of 1976 pyroclastic flows.
- Extent of offshore pyroclastic deposits based on bathymetry.
- Extent of volcanic bomb fall for 1976 eruption. (Fragments >15cm diameter.)
- Offshore lease blocks.
- Volcanoes.

Figure 20-3. Regions of volcanic hazard from both current and future eruptions of Augustine volcano. Planned oil and gas lease sale tracts are also shown. (Modified from Kienle and Swanson 1980.)

Nearly 200 vessel-icing incidents were recorded during the period of 1979 through 1984 in the Gulf, most of them occurring in the western part (Pease and Comiskey 1985). Ice accretion can increase a vessel's weight, elevate its center of gravity, or decrease its metacentric height, causing it to lose balance, capsize, and eventually sink. Structural icing may be a more serious hazard to vessels operating in the Gulf than was previously thought. Nomograms that are used to calculate icing rates under different air-temperature, wind-speed, and seawater-temperature conditions have been recently revised (Pease and Comiskey 1985; see also Wilson and Overland, Ch. 2, this volume).

Pollutant Transport

The ability to describe both the mechanisms and the processes that govern the transport of water-borne pollutants is critical to predicting the consequences of oil spills or waste discharges. Predicting pollutant trajectories and mapping exposure fields can only be done reliably if the scientific data regarding currents and meteorological conditions are reliable. Any conceptual or numerical model that describes contaminant transport in the marine environment should be able to describe both the amount and the weathering state of a pollutant on the sea surface, in the water column, and on the sea bed—both along and at the end of its trajectory or plume. Such models should also provide:

- data that can help minimize the risk to environmentally sensitive areas
- information on probable trajectories and landfalls in the event that pollutants are accidentally released
- information that can be used during pollutant containment and clean-up operations both in coastal and in nearshore areas.

Basic data for such models may be acquired from sources such as:

- literature summaries
- hydrographic data
- current-meter and pressure-gauge records
- drift-buoy trajectories
- satellite and other remotely sensed imagery
- local and regional wind fields
- pollutant weathering or removal rates.

Advective and Dispersive Regimes

Wilson and Overland (Ch. 2, this volume), and Reed and Schumacher (Ch. 3, this volume) have reviewed data from a large number of studies on meteorology and physical oceanography, respectively. Major features of the Gulf of Alaska circulation are shown in Reed and Schumacher's Figure 3-1. It is now possible to make general statements on the

advective and mixing processes that are likely to be responsible for shaping pollutant trajectories or plumes.

A comparison of the relative magnitudes of the kinetic energy components (mean flow and its fluctuations) shows that currents seaward of the continental shelf (dominated by the Alaska Current and Alaskan Stream) are characterized by a strong mean flow and moderate-to-weak high-frequency fluctuations. This implies that there would be a rapid transport of pollutants in the direction of the mean flow. On the other hand, currents on the continental shelf are characterized by a weak mean flow (as much as an order of magnitude lower than those off the shelf), but they have a high-energy tidal component. This means that pollutants are likely to remain on the shelf for a longer period of time, but their concentration will be more rapidly reduced by strong tidal mixing.

Off the Kodiak Archipelago—where shallow banks are separated by deep troughs—tidal variance in currents over the banks is higher than the variance in the troughs (Reed and Schumacher, Ch. 3, this volume). The fact that high-salinity water occurs in the Kodiak Archipelago troughs (values $>33\text{‰}$ have been observed in Kiliuda Trough) strongly suggests that the source of this water is the shelf-edge portion of the Alaskan Stream. Current-meter records show flow events that might transport shelf-edge waters (and associated pollutants) shoreward into Kiliuda Trough. The influence of the Alaskan Stream on circulation in these troughs is demonstrated by a shoreward flow on the upstream side and seaward flow on the downstream side (Lagerloef 1983). Pollutants released on the outer shelf could impinge upon shorelines and bays, particularly those that lie at the head of troughs.

The mechanisms that are responsible for eddies, such as those located west of Kayak Island, off Sitka, and off Vancouver Island, are potentially significant to pollutant retention and transport. Except for the eddy off Vancouver Island (which is frequently initiated by local alongshore winds), such mechanisms have not been studied in detail (Thomson and Gower 1985).

Pollutant transport, particularly spilled-oil trajectories, is greatly influenced by both prevalent wind conditions and episodic meteorologic events. Oil spilled on the North Albatross Bank would be pushed offshore into the Alaskan Stream by strong southwesterly winds and then advected out of the area. However, if the winds were strong and northeasterly, spilled oil would be advected into Chiniak Bay. A review of offshore-wind records shows that either of these winds—as well as other winds—can occur in the Kodiak region during any given period (Brower *et al.* 1977).

Along the coast, pollutants would be transported by the coastal current (known as the Kenai Current off the Kenai Peninsula) in a counterclockwise direction at different speeds, but would be contained within a narrow band. The current speed off Kenai Peninsula varies between 20 and 100 cm/s. Local bathymetry and topographic features will modify this transport pattern, causing oil to smear long stretches of coastline and causing oil and other pollutants to be retained in eddies and deposited in bays.

Cook Inlet's water circulation is dominated by strong tidal currents, and its winds are modified by both the local orography and the Inlet's configuration (Greisman 1985). Water from the Gulf of Alaska flows into the Inlet through Kennedy Entrance. This water—which is characterized by low turbidity, high salinity, and a high concentration of inorganic plant nutrients—flows north along the eastern side of the Inlet. Its northward extent varies with the seasons and is largely determined by the degree to which it mixes with the southward-flowing, turbid, low salinity water from upper Cook Inlet. During fall, when outflow from the upper Inlet is reduced, the Gulf water can still be identified as far north as the Forelands. The southerly flowing water along the west side of the Inlet is readily recognized by its heavy suspended-sediment load, with high suspended-sediment concentrations occurring in Tuxedni Bay, the Forelands, and upper Cook Inlet.

Within Shelikof Strait, the outflowing Cook Inlet water mixes with Gulf water that is flowing through Kennedy Entrance. This mixing creates a complex hydrographic structure that includes strong surface-temperature and suspended-particulate gradients. The flow through Shelikof Strait is predominantly southerly. Winds are greatly influenced both by the coastal mountain range and by the gaps between the coastal mountains.

Two fjords have been extensively studied: Port Valdez in Prince William Sound, and Smeaton Bay in Southeast Alaska. Water circulation in Port Valdez is typically that of a positive estuary: brackish water flows seaward in the surface layers and saline water flows landward at depth. Current speeds range between 20 and 25 cm/s with a mean, non-tidal component of about 2 to 3 cm/s (Muench and Nebert 1973). Nebert (1982) suggested that the circulation in Smeaton Bay might be opposite that found in typical positive estuary. Thus, materials added in upper waters would be mixed downward into the outward-flowing layer. Such a pattern may be advantageous for dumping marine tailings at depth since it would be less likely that turbidity would be carried into the upper, biologically productive layers. However, field data in support of the suggested circulation scheme in Smeaton Bay are few and not conclusive. More research, including numerical modeling of circulation, is in progress.

Both regional ocean-circulation data and meteorology data are used extensively to describe the environments that would be affected by OCS oil and gas development. These data are also used to calculate hypothetical oil-spill trajectories and assess environmental risks associated with the development. This information is contained in several environmental impact statements for leases in areas of the northern Gulf of Alaska, in lower Cook Inlet, and in the Kodiak region. Site-specific data, including dispersion estimates, were obtained in Port Valdez. These data were used to delineate the type of mixing zone that would be required to achieve a sufficient oil and grease dilution for the effluent that would be discharged from a ballast-water treatment plant (Colonell 1980; Hood, Shiels, and Kelley 1973). Other studies are gathering field data and formulating dispersion models for Port Valdez, Smeaton Bay, and Boca de Quadra

to predict mine-tailing plumes and their associated pollutant discharges.

Numerical Modeling

Numerical modeling of the ocean circulation in the Gulf has been conducted for a number of purposes, including:

- to diagnose the Gulf's salient features (Galt, Overland, Smyth, Han, and Pease 1977; Galt and Watabayashi 1980)
- to simulate tidal heights and the associated currents (Mungall 1973; Harding 1976)
- to calculate hypothetical oil-spill trajectories for use in environmental impact analyses and assessments (Schlueter and Rauw 1981).

Each of the numerical modeling studies varies markedly in terms of the areas covered and the primary focus. The oil-spill trajectory model is a series of algorithms that use data on regional winds, currents, geography, and bathymetry. The model then predicts the movement of a floating oil mass and presents the results in both digital and graphic formats. Many terms and coefficients in each algorithm require either actual time-series observations or a statistically generated data set for the oil-spill trajectory simulation period.

Most of the resource assessment reports and environmental impact statements for OCS leases in the Gulf of Alaska were prepared before 1984. Although capability exists to do so now, the earlier documents did not include data on petroleum-hydrocarbon dispersion and weathering in either the oil-spill trajectory calculations or the oil-spill risk assessments. The environmental impact statements include the probabilities that spilled oil would reach a certain shoreline segment or biologically important area—probabilities that are based solely on meteorologic and oceanographic data. In addition, they provide combined probabilities that spilled oil would contact either the shore or other biologically important areas at some point during the production period of an oilfield, given the resource estimate and probable oil-spill rate (U.S. Department of the Interior 1984). For OCS leases in the Bering Sea, Liu and Leendertse (1985) provide a more comprehensive accounting of those factors that determine oil-spill trajectories, factors that include sea-ice cover, stochastically generated wind fields, dispersion, and weathering. The oil trajectory and weathering models, including a trajectory model developed by NOAA to support federal response to marine spills of hazardous substances (Torgrimson 1984), were successfully applied to both the movements and the weathering state of 750 m³ of JP-5 jet fuel that spilled from the *M/V Cepheus* near Anchorage in January 1984.

In those instances where numerical modeling was intended to serve a diagnostic purpose, it has been possible to simulate major circulation features for both the continental shelf and the slope that agree with observations. It has also been possible to identify regional responses that are associated with different forcing mechanisms such as density- or wind-driven circulation. The diagnostic model shows that the coherence-length for currents—which is

controlled by the conservation of potential vorticity along isobaths—is typically ~30 km over the shelf and ~300 km over the slope (Galt *et al.* 1977; Galt and Watabayashi 1980).

Spilled Oil Retention Potential

The coastline extending from Cross Sound to the southern extent of the Kodiak Archipelago has been surveyed to characterize and classify its segments in terms of their oil-spill retention potential and their habitat vulnerability. Vulnerability indices (usually ten) have been developed based on a number of factors that include:

- beach morphology
- sediment grain-size distribution
- prevailing wave patterns
- inferred alongshore transport
- major biotic assemblages.

According to this classification, about 23% (or 410 km) of the shoreline between Dry Bay and Hinchinbrook Entrance has the potential to retain spilled oil for more than ten years (Ruby 1977).

It is noteworthy that vulnerable segments of the coastline, such as the Copper River Delta, include some very important biological habitats. In contrast, only about 2% (or 110 km) of the Kodiak Archipelago is classified as having a potential to retain spilled oil for ten years or longer (Hayes and Ruby 1979). Sand and gravel beaches—comprising 70% of the Archipelago shoreline—may allow deep burial of spilled oil. These beaches were classified as having moderate risk for spilled-oil retention (vulnerability index between 6 and 8). This coastline mapping has been useful to various agencies in their evaluation of coastal development projects, their preparation of coastal management plans, and their preparation of contingency plans for oil-spill cleanup operations.

Oil Weathering

Scientists have completed a major crude-oil weathering study that culminated as a computer model (Payne, Kirstein, McNabb, Lambach, Redding, Jordan, Baxter, and Gaegel 1984). During the study, they used kinematic and thermodynamic data on crude oils extracted from the literature, then they obtained new data from a series of experiments they conducted in test chambers, flow-through aquaria, and wave tanks. These experiments simulated conditions typical of the Gulf of Alaska. Many experiments were conducted at the Kasitsna Bay Laboratory, located near Seldovia in Cook Inlet. The weathering study provided data on a number of processes, including:

- evaporation/dissolution
- surface slick formation
- oil-droplet dispersion
- dispersed and dissolved oil adsorption on suspended particulate matter
- water-in-oil emulsion (*mousse*) formation
- microbial degradation.

The oil-weathering model takes into account the oil's composition in terms of its boiling-point/distillation-cut data. The model focuses on those major oil-weathering processes that determine the mass balance of any spilled oil. Microbial degradation is not considered because of its low significance in affecting the mass balance. The sedimentation of oil is also not included as part of the model.

Both the nature and the amount of oil that is transported to the sea bottom depend greatly on 1) the oil's composition, 2) the sediment's affinity to accumulate oil, and 3) physical factors such as water depth, tidal mixing, and wave-induced turbulence. In the open waters, transportation of oil to the sea bottom is likely to be widely spread and may not result in high concentrations.

Biological Production and Resources

The Gulf of Alaska's continental shelf and overlying waters are highly productive, sustaining an abundance of flora and fauna. The living marine resources are (and have been for centuries) of central importance to both the existence and the way of life of the people in this region. For decades, salmon, crab, shrimp, halibut, clams, and scallops have been exploited either commercially or for subsistence and sport fishing. Until recently, commercial exploitation of marine mammals was common. The importance of commercial fishing to the regional economy is underscored by the annual value of the catch, which was estimated at \$350 million in 1984. There is currently no commercial harvest of marine mammals or birds, although subsistence use may occur in some areas.

The shelf is heavily used as a feeding area in the spring and summer by birds such as the black-legged kittiwake, the tufted puffin, and others. Winter residents such as the malarl, the oldsquaw, and the Steller's eider, as well as transient populations of short-tailed and sooty shearwaters, also feed in the shelf waters. Shearwaters dominate the spring/summer pelagic bird community, constituting about 84% of the numbers and 83% of the biomass (DeGange and Sanger, Ch. 16, this volume). Both the deltaic and intertidal areas are heavily used by migrating birds. Nearly 10 million birds—consisting largely of western sandpiper and dunlin—feed on the rich biota of the Copper River Delta for a short period each year.

Marine mammals both feed and breed throughout the region (Calkins, Ch. 17, this volume). Steller sea lions, harbor seals, and sea otters are common and probably dominate ecologically. Several species of cetaceans, including some listed as endangered species, migrate through and feed on the shelf or offshore. Dall's porpoises and humpback whales may also use the shelf area for calving.

The sustenance and the growth of these large and varied animal populations require not only large quantities of food but also effective mechanisms for partitioning the resources in both the pelagic and the benthic environments. Because greater emphasis has been placed on research on marine birds, mammals, and fisheries in the Gulf, data on lower trophic levels—particularly plankton—are relatively meager. It is, however, possible to speculate on the basic func-

tional aspects of the shelf ecosystem by considering the food habits of those species which have been studied. This information can be coupled with knowledge of the circulation and mixing regimes, and further information can be extrapolated from data on the biological productivity of similar areas of the world. However, the lack of data precludes using community structure analysis to evaluate those ecosystem properties such as resilience and stability.

Primary Productivity and Trophic Links

The data on the Gulf's primary productivity are sporadic in terms of both time and space, but suggest that its seasonal cycle is typical of most subarctic marine environments. This contention is supported by phytoplankton productivity, biomass, and inorganic plant nutrient data obtained at a variety of locations, including: 1) in the open ocean at Station P (McAllister 1969), 2) over the continental shelf (Larrance, Tennant, Chester, and Ruffio 1977), 3) in fjords (Goering, Shiels, and Patton 1973; Iverson, Curl, O'Connors, Kirk, and Zakar 1974), and 4) in estuaries (Larrance and Chester 1979). This subject is treated in detail by Sambrotto and Lorenzen (Ch. 9, this volume).

The effects that water-column stratification, sunlight, and nutrient levels have on primary productivity in lower Cook Inlet are reported by Larrance *et al.* (1977) and Larrance and Chester (1979). Their observations were made at stations along a transect between Kachemak and Kamishak Bays. Maximum productivity occurred in Kachemak Bay in early May, in mid-Inlet in late May, and in Kamishak Bay in July. They reported primary productivity rates in Kachemak Bay (which receives nutrient-rich waters from the open shelf) that ranged from 1 to 8 g C/m²d during May through August. In Kamishak Bay, which is usually turbid, primary productivity rates were between 0.1 and 7 g C/m²d. Any primary productivity values that exceed 5 g C/m²d are considered exceptionally high.

A single phytoplankton bloom cannot sustain the variety of life forms and trophic levels in the Gulf and adjoining coastal regions throughout the year. On the Kodiak Archipelago—as on other highly productive continental shelves that have shallow banks—primary productivity takes place in late spring and continues into the summer. Productivity increases often occur that are both of short duration and of limited spatial extent. These increases depend on the same three parameters as those governing the vernal increase in phytoplankton productivity: 1) mixing of the water column followed by stabilization, 2) an adequate supply of inorganic plant nutrients, and 3) the availability of sunlight. Such primary productivity increases on the Kodiak shelf may be facilitated by vertical mixing that is induced by storms in a situation similar to that found in the eastern Bering Sea (Sambrotto, Niebauer, Goering, and Iverson 1986).

The importance of frontal zones to the enhancement of both biological richness and productivity is well recognized in many areas. These features are characterized by locally intense gradients in hydrographic properties, circulation, or biological features (Bowman 1978). Frontal zones exist in Shelikof Strait, in Cook Inlet (commonly known as the 'trash line'), and off the Kodiak shelf break. The increase in phy-

toplankton biomass (or of other biota) in frontal zones could result from 1) matter that accumulates due to convergence, 2) increased productivity when divergence occurs on one side of the front, or 3) admixing of the water masses on opposite sides of the front (Savidge 1976).

Iverson, Coachman, Cooney, English, Goering, Hunt, Macauley, McRoy, Reeburgh, and Whitledge (1979) demonstrated the significance of both fronts and interfrontal zones to the pelagic trophic structure in southeastern Bering Sea. There are no published data from the Gulf of Alaska that correlate the physical dynamics of the fronts with the biological richness or the productivity of the area. Field data with horizontal resolutions of from 0.1 to 1.0 km and vertical resolutions of from 0.5 to 5.0 m are usually required to adequately hypothesize (or observe) front domains in either along-front (*ca.* 30–300 km) and cross-front (*ca.* 60–600 m) directions (Bowman 1978). The importance of frontal-dynamics research as it relates to understanding the Gulf's productivity (and taking into account productivity's spatial-resolution and data synopticity requirements) has not been widely acknowledged.

The physical environment also exerts an influence on both the taxonomy and the size composition of the planktonic primary producers. This influence is enforced via size-selective feeding at succeeding trophic levels and it has important implications in terms of the yield available to apex predators (Landry 1977; O'Brien 1979). The predominant phytoplankton size and the trophic structure of various plankton communities are fundamentally different in areas where there is either a high or a low fisheries yield. This difference is due to the trophic position of fish relative to the primary production source (*i.e.*, whether the source is diatoms or flagellates).

The relatively high abundance of large phytoplankton species—particularly pelagic diatoms in nutrient-rich waters—leads to desirable food chains in terms of fisheries. Decreased nutrients and increased stratification shift the growth advantage to dinoflagellates and microflagellates, often leading to food chains that culminate in jellyfish and chaetognaths (Greve and Parsons 1977).

The degree to which the water column primary production is used by herbivores (and the succeeding trophic levels) is important in determining the overall economy of the sea. There seem to be energetic benefits derived from preferential feeding on larger prey. Both the seasonal presence of large, oceanic copepods, such as *Neocalanus plumchrus* and *Neocalanus cristatus*, and the timing of their grazing cycle result in an efficient transfer of organic matter to higher trophic levels. In such cases, there is no time lag between intensive grazing pressure and phytoplankton primary production. Consequently, only relatively small amounts of organic matter are lost to the water column. The onshelf advection of oceanic water over the shelf, which is documented for some areas of the Kodiak shelf (Lagerloef 1983), probably accounts for the presence of these large copepods inshore (Vogel and McMurray 1986).

Smaller neritic and oceanic copepods usually predominate on the shelf and in coastal areas. Such copepods (*Pseudocalanus* sp., *Acartia* sp., and *Oithona* spp.) breed following intensive feeding, and their brood size depends on the

amount of food they have consumed. Maximum grazing occurs from two to six weeks after the spring phytoplankton growth. The delay in the maximum use of the phytoplankton results in 1) an unbalanced plankton cycle, 2) the loss of a large quantity of organic matter that falls to the bottom, and 3) an inefficient use of the resources in the water column.

Energetic benefits to fish from preferential feeding on large prey have been demonstrated both theoretically and experimentally (Kerr 1971; O'Brien 1979). For example, salmonid juveniles can obtain between 5 and 10 times their daily ration from large copepods compared with small copepods. They showed a 4% per day growth rate when fed on *Neocalanus plumchrus* which averaged 3 mg each, compared with no growth when fed on cycloids that averaged 0.1 mg each. These copepods were both available at the same concentration (LeBrasseur 1969).

Large copepods are not preferred by jellyfish such as *Pleurobrachia* sp., which has a much higher food intake and growth rate when feeding on small copepods (Greve and Parsons 1977). Maximum abundance of planktivorous fish (mainly young salmonids) occurs in the Strait of Georgia, British Columbia, either after or in association with the maximum abundance levels of *Neocalanus plumchrus*. Small copepods, such as *Pseudocalanus minutus*, occur in summer when ctenophore and jellyfish populations are also at high levels (Parsons, LeBrasseur, and Barraclough 1970). It appears that trophic pathways leading toward jellyfish and ctenophores are favored where nutrient concentration and supply are low.

In addition to copepods, amphipods and euphausiids are important and, in some cases, are the dominant food in the pelagic environment. They are consumed by Pacific salmon juveniles, herring, capelin, Atka mackerel, and Pacific sand lance juveniles, as well as by pelagic birds and marine mammals (see Science Applications, Inc. 1980 for a review of data for the Kodiak region). Food webs where euphausiids are the principal intermediate element may be similar to those based on large copepods. The importance of amphipods to shelf predators has only recently been recognized. Cross, Fresh, Miller, Simenstad, Steinfort, and Fegley (1978) showed that 53 out of 55 nearshore fish species preyed upon gammarid amphipods. These amphipods accounted for more than 50% of the total Index of Relative Importance (IRI) for 31 different species, and accounted for more than 75% of the IRI for 9 of those species.

The relative role of a carnivorous amphipod, such as the genus *Parathemisto*, is not well known. Food webs leading to or including carnivorous amphipods are distinct from (but probably exist concurrently with) food webs involving large copepods. The webs may involve: 1) small phytoplankton, 2) protozoa, small copepods, and larvae, 3) carnivorous amphipods, or 4) larger carnivores (Nemoto 1970). Such food webs may allow for increased food resources for animals of both commercial and aesthetic value and may counteract the formation of food chains culminating in jellyfishes. It is not known whether such alternative trophic pathways exist over large areas of the Gulf.

Both the richness and the productivity of the benthos depend on primary productivity both in the water column

(in the form of plankton and fecal pellets sinking to the bottom) and on the sea bottom (in the form of bacteria, microalgae, and macrophytes). The flux of organic matter to the sea bottom is higher in shallow waters, due in part to inefficient phytoplankton grazing by small copepods (Parsons, Ch. 18, this volume). Such data from the Gulf are few.

Larrance and Chester (1979) showed that the daily loss of phytoplankton to the sea bottom was 8% of the standing stock in both Kachemak Bay (less than 100 m deep) and in Kamishak Bay (less than 50 m deep). These values are rather low for the neritic environment and suggest that herbivore grazing rather than algal cells sinking to the bottom represents the major loss of phytoplankton from the water column in these bays. Organic matter sinking from the water column combined with other detrital and living food sources forms an important source of nutrition for suspension- and deposit-feeding fauna. King crab, Tanner crab, Dungeness crab, and pink shrimp are all primarily carnivorous, and obtain a large part of their food by consuming detritus and detritivores. Pacific halibut, Pacific cod, and walleye pollock are also carnivores that use both benthic and demersal fauna such as shrimp and flatfish. Both shrimp and flatfish either directly or indirectly feed on detritus.

Organic matter produced by benthic microalgae and bacteria is expected to make a significant contribution to the overall trophodynamics of a coastal marine ecosystem. Atlas and Griffiths (Ch. 8, this volume) have discussed both the possible mechanisms and the magnitudes of organic production by bacteria in lower Cook Inlet. Quantitative data are not available, but bacterial production can be utilized in conventional food chains through a microbial loop: photosynthesized organic matter to bacteria—bacteria to heterotrophic flagellates—heterotrophic flagellates to microzooplankton.

Brown algae, including kelp (*Alaria* spp., *Agarum cribrosum*, *Laminaria groenlandica*, and *Nereocystis luetkeana*)—and in some intertidal areas, the rockweed *Fucus* sp.—are widespread on rocky shores throughout the Gulf of Alaska. In dense patches, plant biomass can be very high: 10 to 20 kg wet weight/m² off Kodiak (Calvin and Ellis 1978) and approaching 30 kg wet weight/m² in Prince William Sound (Lees, Houghton, Erikson, Driskell, and Boettcher 1980). These biomass values are comparable to values from some of the richest seaweed-producing areas of the world such as Nova Scotia and Scotland.

Macrophyte productivity estimates, based on a few data obtained during summer 1978, ranged from less than 0.2 kg C/m²y to over 4 kg C/m²y. The highest values were for *Nereocystis* sp. and *Laminaria* sp. in Prince William Sound (Lees *et al.* 1980). Macrophyte production may be an order of magnitude higher than primary productivity in the water column on a unit-area basis. However, very little of the macrophyte production (probably less than 10%) enters the food web through the grazing pathways because only a few animals—both in terms of species and numbers—feed directly upon macroalgae (Velimirov, Field, Griffiths, and Zoutendyk 1977).

The detritus produced by macrophytes forms an important substrate for a variety of fauna and flora (including bac-

teria), which are, in turn, consumed by larger animals and eventually contribute to the production of apex predators (Mann 1972). There is evidence that organic matter originating with macrophytes is transported to the shelf areas—notably to the shallow banks where it can be retained and recirculated by currents that are predominantly tidally driven. A strong storm can uproot as much as 10% of the primary producer stock (Velimirov *et al.* 1977). Although actual data are lacking (only a few visual observations have been reported over the Kodiak shelf), significant algal drift and leaf litter can be predicted from the high wind waves and the frequent storms that are typical for the area.

A plausible scenario for the decomposition and the use of macrophyte leaf litter may be as follows. First, epiphytic communities are torn off along with leaf blades and fronds and are removed from the region. Then, initial autolysis results in the release of dissolved organic matter, which is acted on by bacteria (and possibly fungi). Next, small predators such as nematodes and ciliates build up on the drifting material, and animals that are feeding on the detritus strip off the fauna—then their subsequent feces are recolonized by bacteria. Finally, detritivores are consumed by larger, benthic predaceous species, some of which are commercially harvested. In this scenario, the cumulative role of the microorganisms is making macrophyte energy stores available to the higher forms. This may be an important trophic pathway that is responsible for the high biological productivity of the Kodiak shelf.

Annual Production and Fisheries Yield

The most easily recognizable results of the biological production in a region are the economic value of its harvest and the wildlife that region can sustain. In the nutrient-rich waters of upwelling areas, there may only be 1.5 to 2 trophic levels between algal production and planktivorous fish production. The overall efficiency of a food chain that has two trophic levels and 20% efficiency at each level would be 4%, and the yield to fisheries would be quite high in proportion to primary production (Crisp 1975).

In the less fertile waters of oceanic areas, there are usually five or more trophic levels, each with lower efficiencies (about 10%). These conditions lead to an overall trophic efficiency of ~0.001 percent. Ryther (1969) demonstrated that because of this low efficiency (and lower primary production), oceanic areas—despite their huge extent—contributed less than 1% of the world's total fish production. The remaining fish production came from areas of the continental shelf (54% of the total) and from upwelling areas (44% of the total).

As noted earlier, the daily primary productivity rates in the Gulf are high. Accurate annual production estimates for much of the Gulf have not been made. Annual production estimates are only available for two areas in Prince William Sound: 1) Port Valdez (150 g C/m²) and 2) Valdez Arm (220 g C/m²) (Goering, Shiels, and Patton 1973). Data tabulated by Larrance and Chester (1979) can be used to calculate primary production values for the phytoplankton growth season (March to August) that exceed 500 g C/m² in Kachemak

Bay, 240 g C/m² in the middle portion of lower Cook Inlet, and 250 g C/m² in Kamishak Bay.

Koblents–Mishke (1965) estimated (from little data) annual primary production rates of 100 g C/m² for open shelf waters of the Gulf. Larrance (1971) reported values ranging from 20 to 200 g C/m² for the northern North Pacific Ocean along the 176°W meridian during a three-year period from 1966 to 1968. The average annual primary production at Station P (located at 50°N and 145°W), during 1961 through 1966 was 48 g C/m² (McAllister 1970). Data on macrophyte and kelp production are even more sparse; a representative figure for annual production in the littoral zone is 500 g C/m².

The 1984 commercial finfish and shellfish harvests in the Gulf of Alaska were over 50×10^4 mt and nearly 2×10^4 mt, respectively (Alaska Department of Fish and Game, unpubl. data; National Oceanic and Atmospheric Administration 1985). The finfish catch consisted of groundfish (68%), Pacific salmon species (25%), herring (4%), and halibut (3%). The shellfish catch consisted of Tanner crab (51%), Dungeness crab (23%), shrimp (23%), king crab (2%), and razor clam (1%).

Based on these data, we can make a tenuous attempt to relate the commercial fish catch to the total primary production for the Gulf of Alaska. The continental shelf area of the Gulf is 3.62×10^5 km² (McRoy and Goering 1974), about 1.8×10^5 km² of which is open shelf, and the remaining area is fjords, embayments, and estuaries (Rand–McNally 1977). If one assumes that 100 g C/m² is representative of the annual primary production for the open shelf and 200 g C/m² is representative of production for inshore waters, the total annual water column primary production is 5.4×10^7 mt of carbon. Macrophyte production can be estimated at 6×10^5 mt of carbon if one assumes that 80% of the 75,680-km-long tidal shoreline of Alaska is located in the Gulf and that the average width of the littoral zone where macrophyte production takes place is 20 meters. This means that the sum of both water column and macrophyte production is equivalent to 5.5×10^7 mt of carbon.

The commercial finfish and shellfish catch data, given as wet weight and usually referred to as biomass, can be converted into organic carbon equivalent amounts using conversion factors and ratios from Winberg (1956), Nishiyama (1975), and Crisp (1975). Using these conversion factors, the 1984 commercial finfish catch is equivalent to 5×10^4 mt of carbon, and the shellfish catch is 5.9×10^2 mt of carbon, resulting in a total catch value of slightly over 5×10^4 mt of carbon.

The proportion of the total primary production (~ 5.5×10^7 mt of carbon) that is represented in the Gulf commercial fisheries catch is very small—0.09 percent. This is only slightly higher than the value given for oceanic regions by Ryther (1969). Parsons (Ch. 18, this volume), using a primary production value of 300 g C/m², gives a percentage of apex production (not commercial catch) to primary production that ranges from 0.8 to 1.0 percent. His corresponding values for the open ocean are not included. In the North Sea, where the fishery consists of fish such as herring from lower trophic levels and where fishing is more intense, a much

higher proportion (0.8%) of the primary production is harvested. In the southeastern Bering Sea, where the fishery consists of both invertebrate apex predators and zoophagous fish (capelin and herring), the harvest was estimated at 0.4% of the total primary production (Walsh and McRoy 1986).

The relatively low level of commercial fisheries catch in the Gulf of Alaska in relation to total primary production may be explained by one or more of the following reasons:

- 1) A large proportion of the commercial fisheries catch is composed of Pacific salmon species along with a minor amount of halibut. These species are carnivorous, and their high respective positions in the trophic structure are characterized by low overall trophic efficiencies. Conversely, it can be stated that the salmon catch in coastal waters also represents—to an unknown extent—production that is imported from the open ocean.
- 2) Much of the fisheries resource is not harvested. In 1984, the total catch allowed for foreign fishing in the Gulf was set at 320,686 mt, of which 119,910 mt remained unallocated. The 1984 total foreign catch amounted to 123,079 mt—77,697 mt less than was allocated and 197,607 mt less than was allowed (NOAA 1985).
- 3) The region's mammal and bird populations are very significant consumers. Their yearly consumption—based on estimates from DeGange and Sanger (Ch. 16, this volume) and from Calkins (Ch. 17, this volume)—is $\sim 6.5 \times 10^4$ mt for birds and 7.7×10^5 mt for mammals. This amounts to $\sim 8.4 \times 10^5$ mt of carbon each year for both groups, with birds accounting for less than 10% of the total. This amount is 16 times the amount of carbon removed by the commercial fisheries, and accounts for 1.5% of the total carbon that is fixed in the system.
- 4) Primary production estimates may be too high, and efficient trophic pathways are not widespread in the region.

Critical Habitats

The biological richness of the Gulf of Alaska makes this region invaluable as a fish and wildlife resource area. For example, one of the world's largest harbor seal concentrations is at Tugidak Island. Large numbers are also found at Sitkinak Island, Geese Island, Aiaktalik Island, Ugak Island, and Shuyak Island—all in the western part of the Gulf. Very large Steller sea lion rookeries and hauling-out grounds are located on Sugarloaf Island, Marmot Island, Chirikof Island, and on Chowiet Island as well as in Puale Bay. Each of these major rookeries contributes pups to other distant areas of the Gulf. Sea otters—which had been hunted to very low levels by the turn of the century—have recovered as a result of legal protection. Moderate to high sea otter population densities are building at many locations such as Marmot and Chiniak Bays, and the species is expected to reinhabit its previous range throughout the Gulf.

The largest seabird colonies—located on the Barren Islands—are dominated by three species: 1) the fork-tailed storm petrel (300,000 birds), 2) the common murre (60,000 birds), and 3) the tufted puffin (950,000 birds). Another large bird colony that is dominated by black-legged kittiwakes (160,000 birds) is located on Middleton Island. The large bird colonies of Cook Inlet (nearly 80,000 birds) are located in Tuxedni Bay and are composed of black-legged kittiwakes, common murrelets, horned puffins, and glaucous-winged gulls. Numerous other bird colonies have been identified and mapped by the United States Fish and Wildlife Service (Sowls, Hatch, and Lensink 1978).

Millions of shearwaters from the Southern Hemisphere visit the western Gulf of Alaska during spring and summer where they feed intensely in the pelagic zone. In addition, most of the world's population of western sandpipers and the entire western-Alaska breeding population of dunlin are believed to migrate through the Copper River Delta.

All nearshore and shelf waters, embayments, coastal streams, and rivers are used by both finfish and shellfish either as migratory pathways or as preferred habitats for feeding, breeding, spawning, or rearing of young. Kelp beds are particularly important because they are protective habitat for many species, including the larval and juvenile stages of the commercially valuable Pacific salmon as well as king and Tanner crabs.

Given the widespread distribution of biota throughout the Gulf and the sporadic nature of the existing database, it is difficult to designate certain areas as biologically more significant than others. The biological productivity (and the species richness that results) appears to be higher in the central and western parts of the Gulf than it is in the eastern part, but this observation could be the result of a greater number of studies conducted in the Cook Inlet and the Kodiak regions.

In coastal areas under its jurisdiction, the State of Alaska defines biologically sensitive areas in the context of its resource management policies (Kramer, Clark, and Canelos 1978). Accordingly, sensitive areas include (but are not limited to):

- estuaries
- wetlands
- river deltas
- fish spawning grounds
- intensive-use habitats
- bird-nesting areas
- waterfowl and shorebird staging areas
- migration routes
- wildlife wintering habitat
- sea-mammal rookeries and hauling-out grounds.

Under Alaska Statutes Title 16, Chapter 20 (Conservation and Protection of Alaska Wildlife), the State has designated certain areas as critical habitats to protect and preserve habitats that are especially crucial to the perpetuation of the fish and wildlife, and to restrict all uses not compatible with that purpose. To date, six critical habitats are identified in the coastal areas of the Gulf (Figure 20-4). Additional critical

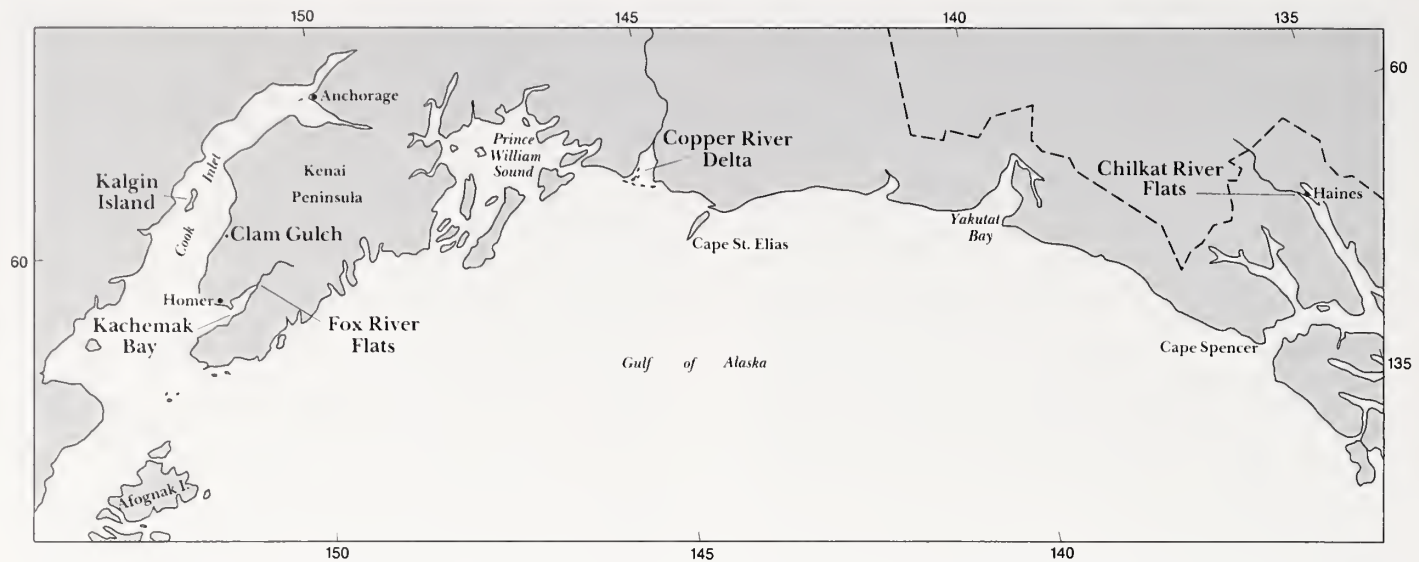


Figure 20-4. Locations of the six critical biological habitats that have been designated by the State of Alaska.

habitats can be added by legislative approval. No critical habitats have been designated by the Federal government in this region.

Characteristics of critical habitats. Key features of the currently designated State of Alaska critical habitats are noted below:

Copper River Delta. (a) One of the world's most important waterfowl and shorebird concentration and feeding areas. The tidal flats and marshes of the Delta—which encompass 500 km²—are host to more than 20 million birds during the peak of the spring and fall migration. (b) A migratory and staging area for most of the world population of western sandpiper and the entire western Alaska breeding population of dunlin. (c) An important breeding and nesting area for many waterfowl species, especially dusky Canada goose and trumpeter swan. (d) The waterfowl found in the Delta include such trans-Pacific migrants as the pintail and the American widgeon. (e) A major fishery for Dungeness crab, king salmon, sockeye salmon, and coho salmon. (f) An important habitat for harbor seals during summer, particularly in the Barrier Islands seaward of the Delta.

Clam Gulch. A large concentration of razor clams used heavily for both recreation and subsistence.

Fox River Flats. (a) A foraging area for thousands of waterfowl and shorebirds. (b) A feeding area for chum and pink salmon, shrimp, and Dungeness crab. (c) A breeding area for about 800 geese and ducks. (d) A heavy-use area for sport fishermen, hikers, and recreationists during summer and fall.

Kachemak Bay. (a) An extensive commercial fishery for king crab, Tanner crab, Dungeness crab, shrimp, Pacific salmon, Pacific herring, and Pacific halibut. (b) The single most important fish spawning area in Cook Inlet during spring (the inner portion of the Bay). (c) An abundance of larval and post-larval stages of king crab, Tanner crab, Dungeness crab, and various species of pandalid shrimp throughout the year. (d) A number of important seabird

colonies on Gull Island, Sixty-foot Rock, and Grass Island. (e) A wintering area for approximately 10,000 white-winged scoters. An important concentration area for marbled and Kittlitz murrelets during summer. (f) A high density of sea otters in the kelp beds. Harbor seal, Steller sea lion, harbor porpoise, Dall's porpoise, and killer whale are also frequently found here.

Kalgin Island. (a) A spring staging area (because the wetlands here thaw early) for migratory waterfowl that include dabblers, snow geese, Canada geese, and swans. (b) A habitat for breeding waterfowl such as pintails, mallards, and teals. (c) A high density area for harbor seals during summer. (d) An important moose habitat.

Chilkat River Flats. (a) A fall and winter gathering area for northern bald eagles, representing the largest known concentration of the species (2,500 or more birds) in the world. (b) An important habitat for the northern bald eagle for feeding (on chum, coho, and sockeye salmon), for nesting (primarily in cottonwood trees), and for breeding (approximately 30% active nests).

Endangered Species

Seven species of whales and two species of birds that occur in the region either seasonally or at irregular intervals have been designated as endangered species (Federal Register, 48 (145), 1983). The Endangered Species Act as amended (P.L. 97-304, 96 Stat. 1411, October 13, 1982), defines 'endangered species' as any species in danger of extinction throughout all or a significant portion of its range. Such danger can be due to: 1) destruction, modification or curtailment of its habitat or range, 2) overuse of the species for commercial or other purposes, 3) disease or predation, 4) inadequacy of existing regulatory mechanisms, or 5) other natural or manmade factors affecting its continued existence. These species, their habitats, and their migratory range must be protected from adverse impact due to human activities.

The populations of the endangered cetacean species were greatly diminished as a result of commercial whaling. Even though protected by the Endangered Species Act, other acts, and by international agreements, only the gray whale population—which was almost exterminated early in the century—appears to have recovered to its pre-exploitation level. Its North Pacific population is estimated at about 13,000 to 17,000 animals, most of which use the Gulf (Reilly 1984). Populations of some other endangered whale species are still very small (Wolman 1978; Calkins, Ch. 17, this volume).

Because of the whales' cosmopolitan nature and their extensive seasonal migration, scientific data bases for most species are both sporadic and unsatisfactory. The present knowledge of the distribution and the biology of the gray whale, which migrates close to the shore, is the best available among endangered species that occur in the Gulf (Jones, Swartz, and Leatherwood 1984). The population distribution, habitat use, and feeding data that do exist for other species are scant and, for the most part, are based on extrapolations from other areas of the North Pacific Ocean (Calkins, Ch. 17, this volume).

Glacier Bay (southeastern Alaska) is the only area where site-specific studies have been done on habitat characterization, food resources, and the impact that motorized vessel traffic has on the occurrence and behavior of the humpback whale (Baker, Herman, Bays, and Bauer 1982).

The Aleutian Canada goose is probably not found in the Gulf. Its known breeding ground is Buldir Island, and it is suspected that during migration, the geese fly east to Unimak Pass and then across the Pacific Ocean to their wintering grounds in California. Sightings of short-tailed albatross have been recorded at certain sites in the Gulf, but sufficient data do not exist to establish their migratory routes or habitat use in the Gulf of Alaska.

Other Data

It is evident from the above account that those species that have a high visibility, are susceptible to environmental pollution, have commercial value, or are under legal protection have received priority for research. We know the composition of both the bird and mammals faunas as well as the location and the approximate size of the seabird colonies and the marine mammal rookeries and haul-out areas. Data on both pelagic and non-colonial birds are relatively few but are sufficient to describe the species distribution, the population sizes, and the habitat use for many areas.

Data concerning the food and the feeding habits of selected species have also been obtained, and some calculations have been made for their energetics and their growth rates. Fecundity rates, breeding phenologies, and other life-history information are also available for a number of species such as the harbor seal, the Steller sea lion, the black-legged kittiwake, the tufted puffin, and others.

Benthic macroinvertebrate distributions have been established for some areas, and the food webs have been described for a few species. This improved data base is reflected in progressively better environmental descriptions and issues analyses in the several environmental

impact statements that were prepared during the period from 1975 to 1984 for planned OCS oil and gas lease sales in the Gulf. Special considerations can now be offered that can minimize the impacts from industrial installations and other activities on a number of species.

Commercial- and sport-catch statistics, estimates of population- or stock sizes, and the general life-history data of the commercially important finfish and shellfish have been obtained and maintained by the fisheries management agencies of the State of Alaska and the Federal government for a number of years. These data are mostly for the adult forms, but data on the early life history, including the larval and the juvenile forms, are far more scant and sporadic, and are generally inadequate to describe the population dynamics of any given species. The overall fisheries data are spatially very limited when viewed in light of the expanded U.S. Fishery Conservation Zone (FCZ), and in light of increasing efforts to harvest larger quantities of groundfish (pollock, cod, sablefish, and Pacific ocean perch) on the continental shelf and slope.

Estimates of both the size of the fish population and the maximum allowable commercial catch (maximum sustainable yield [MSY]) that will still ensure perpetuation of the species exist for only a few species. Such species include those whose life histories, population dynamics, and ecology are well known and for which resource management policies exist (*e.g.*, the Pacific salmon species and the Pacific halibut). In most cases the calculated MSY is modified by ecological, economic, and social factors so that catch allowances are actually based on optimum yield (OY). Special considerations are given to aquaculture, extended jurisdiction, coastal-zone management policies, international negotiations, employment, and market conditions.

Multispecies numerical models are intended to provide both quantitative recruitment assessments and population forecasts for particular fisheries. These assessments and forecasts are aimed at facilitating decisions made by resource managers and by the fishing industry. Results from numerical simulation tests, particularly those for which the data base is limited, are usually based on simplified assumptions and inadequate understanding of variability. While they may provide considerable insight into the adequacy of the data base, they often have little predictive value. There are extremely serious deficiencies in the often-used strategy of hierarchical arrangement of trophic levels—which aggregates species at the level of a guild—when describing ecosystems or when modeling multi-species interactions (Cousins 1985). Such approaches are not suitable for developing resource management strategies, *i.e.*, for fisheries (Beddington 1986).

Continued, but preferably more intensified research is needed on the biology of target species and on pertinent environmental parameters in order to monitor variability and forecast abundance of fish and shellfish populations. Without such efforts, the goal of preventing over-fishing, rebuilding overfished stocks, and realizing the full potential of the United States fishery resources—notably in the expanded Fishery Conservation Zone—will remain elusive (Fishery Conservation and Management Act, P.L. 94-265, 90 Stat. 331, April 13, 1976).

Conclusion

Our understanding of the Gulf of Alaska's environment and its biological resources has greatly improved during the past 15 years. The investigations that were carried out during this period were aimed at providing a scientific framework to use in making resource management decisions and in preparing environmental impact statements. Environmental issues, particularly those pertaining to petroleum development and transportation, have figured prominently in both the planning and the funding of research. As a result, existing data are not uniform either in their scope or in their comprehensiveness for different parts of the Gulf. In addition, a substantial amount of the biological and physical data gathered over the last 15 years remains either unanalyzed or unreported.

Even within the limits of the existing data base, it is possible to identify those areas and phenomena that are hazardous to industrial structures and to operations in the marine environment. For example, prominent ocean-circulation features are documented well enough to let us do spilled-oil trajectory and oil weathering-state calculations. The entire coastline, with the exception of Southeast Alaska, has been surveyed and its various segments categorized for their spilled-oil retention potential. However, seasonal variability (in many cases) and annual variability (in nearly all cases) have not been established for the phenomena and processes that have been studied so far. Even in those cases for which many years of data are available, the problems of interannual variability in both the oceanographic features and the biological populations remain unresolved (Frost 1983).

Both spatial spottiness in the data and an imbalance in the disciplinary coverage pose significant impediments to a comprehensive or holistic approach to marine environmental assessment (Holling 1978). The present data are inadequate to evaluate the biological productivity of many different areas within a region as is required by the OCS Lands Act as amended (P.L. 95-372, 92 Stat. 629, September 18, 1978). Data are also inadequate to estimate the biological community's diversity, its productivity, or its stability as required by the Federal Water Pollution Control Act (or Clean Water Act) as amended (P.L. 95-576, 92 Stat. 2467, November 2, 1978). The importance of having a comprehensive understanding of the various marine ecosystems is also underscored by the Marine Protection, Research, and Sanctuaries Act as amended (P.L. 95-153, 91 Stat. 1255, November 4, 1977).

There are many research needs—stated along disciplinary lines and each with its own scientific merit—that have been noted by the authors who have contributed to this volume. The uneven nature of the existing data, both in terms of location and in terms of various disciplines, is also reflected in the relative comprehensiveness and scope of individual chapters.

The contentious interpretations of the same data set—"sufficient information exists to safeguard the environment" versus "major gaps in existing information preclude an adequate assessment of environmental impacts"—can best be viewed in the context of the Engelmann Diagram

(Fig. 20-1). While a convincing argument can be made to strive continually to reduce the overall risks to society, the increased role of the government in such endeavors (at greatly increased expenditure of public funds) should be viewed in light of its effectiveness—both in terms of cost and attainment of objectives.

The criteria for determining the significance of environmental impacts—even in a relative sense—are not clearly defined, although Duinker and Beanlands (1986) have recently discussed four perspectives on impact significance. These perspectives are related to 1) statistical, 2) ecological, 3) social, and 4) project-induced changes.

Research continues in an effort to assess the resource potential in the United States' Exclusive Economic Zone, to guide future industrial development both in offshore and coastal areas, and to help improve scientific understanding of the physical environment and biological resources of this region.

Disseminating scientific information to the public and publishing research papers in scientific journals have been a major part of the research programs conducted in the Gulf. Research reports and publications that resulted from OCSEAP funding are listed in a bibliography (NOAA 1984). Environmental data were reviewed and summarized periodically between 1974 and 1980. Synthesis meetings among scientists were attended by government and industry representatives, and by individuals from various interest groups. The meetings provided a forum to present both newly acquired data and the interpretation of those data as they related to OCS lease sale decisions for the northern and western Gulf, for Cook Inlet, and for Shelikof Strait.

Proceedings from synthesis meetings became widely read source documents for those seeking environmental information. It is to the credit of the management of the research programs conducted in this region that a number of single-source reference volumes have been prepared (AEIDC 1974; Hood *et al.* 1973; Colonell 1980; Ellis 1982). The publication of this volume is another step in that direction.

Acknowledgments

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Glossary

The terms defined in this section were selected from the text of the 20 chapters in this book. Definitions of some terms are general and comprehensive in nature, whereas others are specific and relate only to the subject matter of the chapters from which they were taken. For more general definitions of some terms, and for definitions of terms not included in this glossary, the reader is encouraged to refer to other glossaries or dictionaries of scientific/oceanographic terms such as:

Baker, B.B., Jr., W.R. Deebel, and R.D. Geisenderfer,
editors

1966 Glossary of Oceanographic Terms, 2nd edition. U.S. Naval Oceanographic Office, Washington, D.C. 204 pp.

Considine, D.M., editor

1983 Van Nostrand's Scientific Encyclopedia, 6th edition. Van Nostrand Reinhold Co., New York, NY. 3,067 pp.

Accretion—The addition of crustal material to existing crust.

Acid rain—Rain that has a depressed pH due to presence of hydrolyzed end products from oxidized sulfur-, nitrogen-, or halogen-containing compounds.

Acoustic anomalies—Variations in sound velocity, refraction, or reflection from that expected in a continuous medium; a phenomenon of great importance in geophysical studies.

Acoustic surveys (biological)—The use of reflected sound to determine the relative distribution or density of schooling fish or plankton.

Advection—Differential motion within a fluid; changes in properties (e.g., temperature, salinity) that take place in the presence of horizontal or vertical flows of seawater (i.e., currents) represent advective changes.

Age structure—The distribution of the various age groups within a stock or population of animals.

Alaska Coastal Management Program—A state program, mandated by the Alaska Coastal Management Act of 1977, which seeks to balance utilization and protection of the coastal area.

Alaska National Interest Lands Conservation Act (P.L. 96-487, 16 U.S.C. 3101 *et seq.*)—This act is the last stage of a process begun in 1958 with the passage of the Statehood Act and followed by conveyances of federal lands to state and native ownership. It sets aside federal lands for national parks, preserves, wildlife ranges, and wilderness areas.

Alaska Native Claims Settlement Act of 1971 (P.L. 92-203, 43 U.S.C. 1601 *et seq.*)—This law provides for the conveyance of about 44 million acres of land and almost one billion dollars to Alaska's natives in exchange for the extinguishment of all further claims to lands. In addition, it establishes twelve regional native corporations and a thirteenth region's corporation for Alaskan Natives residing out of state.

Alaskan Gyre—The dominant circulation feature in the Gulf of Alaska formed by the counterclockwise flow of the Subarctic Current and its continuation as the Alaska Current.

Alcid—Any of 16 species of diving seabirds (Alcidae) that are found exclusively in the northern hemisphere (e.g., murre, puffin, and auklet).

Aleutian Canada goose—*Branta canadensis leucopareia*, a small subspecies of Canada goose that nests in the Aleutian Islands.

Aleutian Tern—A medium-small fish- and plankton-feeding seabird (Laridae, *Sterna aleutica*) that nests in scattered locations in coastal Alaska and presumably winters in the western North Pacific.

Alevin—A young fish in which the egg sack has been absorbed.

Algorithm—In computer science, a detailed logical process (or an analysis procedure) which generates the solution of a particular problem.

Allele—Abbreviation for allelomorph; any one of the alternative forms of a gene. A single gene may have several alternative forms, called multiple alleles.

Allochthonous carbon—Carbon derived from outside the area or ecosystem being considered; the converse of autochthonous, which is carbon produced within a designated ecosystem.

Allochthonous microorganisms—Foreign microorganisms that do not occupy the functional niches of that ecosystem.

Amphiboreal—Occurring in the north temperate zones of the Atlantic and Pacific Oceans.

Amphipoda—Small, laterally compressed crustaceans commonly occurring in marine benthic and planktonic communities. There are also some freshwater and semi-terrestrial species.

Anadromous fishes—Fishes that migrate from the sea to spawn in freshwater.

Ancient murrelet—A small burrow- or crevice-nesting diving seabird (Alcidae, *Synthliboramphus antiquus*), with precocious young, that nests throughout the Gulf of Alaska.

- Anova**—The abbreviation for ‘analysis of variance’, a statistical technique used to test whether two or more sample means could have been obtained from populations with the same parametric mean.
- Anoxic**—Without oxygen; converse of oxic.
- Anticline**—A geological term referring to a fold with strata sloping downward on both sides from a common crest.
- Anticyclone**—An extensive system of winds spiraling outward from a high-pressure center, circling clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.
- Apex carbon budget**—Carbon budget taken to the top (apex) of the food chain.
- Apex predators**—Predators located at the top of a food chain.
- Apparent oxygen utilization**—The difference between the saturation oxygen concentration and the measured oxygen concentration; used as a measurement of respiration in the subsurface waters of the ocean.
- Aragonite pteropod test**—The hard shell of certain species of free-swimming gastropod mollusk (Pteropoda; see pteropods). Aragonite is one of the two common crystal forms of calcium carbonate found in the marine environment.
- Arctic fox**—*Alopex lagopus*, a small fox of open arctic habitats that was introduced by fox farmers on many islands in the Aleutian chain and western Gulf of Alaska.
- Arrowgrass**—*Triglochin* sp., a grass-like wetland plant in the rush family that is a favorite food of geese.
- Artificially propagated salmon**—Salmon that are produced from the egg to the smolt stage under the direct control of man, thereby reducing natural losses due to predation, disease, and physical factors.
- Aseismic**—Pertaining to the property of a portion of the earth to be free of earthquakes.
- Aseismic front**—The line or locus in subduction zones more or less parallel to the trench, at which the plate interface between the subducting and overriding plates has a transition from seismic-brittle behavior at depths shallower than about 40 km to aseismic (ductile) behavior at greater depths.
- Assimilation efficiency**—The amount of energy retained by an organism divided by the amount consumed.
- Assimilative capacity**—The capacity of a water body to receive, dilute, and carry away wastes without harming water quality. In the case of organic matter, it includes the capacity for chemical and biological oxidation.
- Asthenosphere**—See mantle.
- Atmospheric input function**—The rate (over time) at which a substance is added to the ocean from the atmosphere.
- Austral winter**—Winter in the Southern Hemisphere.
- Autochthonous carbon**—Carbon produced within a designated ecosystem; the converse of allochthonous, which is carbon imported into the system.
- Average carbonaceous compound index (UAI)**—A numerical descriptor of the ability of microbial populations in a community to utilize different classes of compounds; essentially identical to nutritional versatility index.
- Baleen whales**—Whales of the suborder Mysticeti containing a horn-like material (also known as whalebone) on their upper jaws that functions to filter food from the water. Unlike the toothed whales (suborder Odontoceti), which have one external blowhole, the baleen whales have two external blowholes.
- Baroclinic flow**—A flow that exists where surfaces of uniform density (isopycnal surfaces) are inclined to surfaces of uniform pressure (isobaric surfaces). This is the flow traditionally computed by the geostrophic method.
- Baroclinic wave**—A wave in which the isopycnals follow a wave motion but the surface is relatively undisturbed (*e.g.*, an internal wave).
- Barotropic flow**—A flow where surfaces of uniform density and pressure are parallel. Such a system has the same speed and direction throughout the water column and usually must be measured.
- Bathylagids**—Small fishes called deep-sea smelts (family Bathylagidae) which have an adipose fin, large eyes, and a small mouth.
- Bathymetry**—The shape or relief of the ocean bottom, especially depth contours as obtained from a map or nautical chart.
- Bathythermograph**—An instrument that provides a continuous trace of temperature versus depth, usually only in the upper 300–500 meters. The older instruments were mechanical devices that obtained data on a coated glass slide. The newer system uses expendable thermistors that transmit data by a thin wire to shipboard recorders.
- Beaked whales**—Toothed whales (suborder Odontoceti) ranging in length from 4 to 13 m, whose jaws are more or less attenuated, forming a narrow beak.
- Bed-load**—Pertains to the amount of solid material carried by moving water, such as a current, stream, or river.
- Benthic autotroph**—An organism that dwells on the bottom of a river, lake, or ocean and assimilates energy from either sunlight (*e.g.*, most plants) or inorganic compounds (*e.g.*, sulfur bacteria).

- Bergy bits**—Small chunks of ice, generally less than 5 m high, which have broken off from coastal glaciers.
- Bioavailability**—The ability of a substance to be taken up and incorporated into the cells of an organism through ingestion, respiration, or absorption. Extrinsic factors that control bioavailability include the chemical nature of the substance, the amount of substance present, and the nature of the site at which the exposure occurs. Intrinsic factors include the organism's susceptibility to the substance (*i.e.*, rejected, accepted, or metabolized).
- Biogenic particle flux**—The rate at which the biologically produced fraction of suspended particles settle to greater depths in the ocean.
- Black mat syndrome**—A fungal disease affecting crabs.
- Blastocyst**—The blastodermic vesicle; the blastula stage in early mammalian development which becomes the embryo.
- Blue mussel**—A common intertidal bivalve mollusk (*Mytilus edulis*) that attaches to the substrate with short, filamentous 'byssal threads'.
- Bolus**—An approximately spherical mass of water, often with physical characteristics (*e.g.*, salinity, temperature) which distinguish it from the surrounding water mass.
- Boreal fauna**—Animals that inhabit the north temperate zone.
- Bottom drifter**—A device, often a bottle or plastic card, which is designed to drift in the bottom several meters of the water column.
- Boundary current**—A current which occurs on the periphery of a large-scale circulation system such as the subarctic gyre.
- Box model**—A method of describing mass flow or flux of constituents within a system by defining homogeneous sub-compartments or 'boxes'.
- Brittle (geophysical)** — The sudden localized loss of shear strength in an otherwise elastic solid material.
- Browser**—An animal that feeds on the shoots, twigs, and leaves of trees and shrubs or, in the marine environment, on algae.
- Bubble net feeding**—A feeding method observed in humpback whales in which a chain of bubbles is blown as the whale swims in a circular pattern, causing food (*e.g.*, euphausiids) to mass in the center of the ring. The whale then rises to feed in the resulting concentration.
- Bubble-phase gas**—A volatile material trapped in sediments or rock in the form of clathrates or liquids that has formed a small globule of gas trapped in the liquid or solid medium.
- By-catch**—Species of fish caught incidentally in the fisheries for other species; also called 'incidental catch'.
- Cackling Canada goose**—*Branta canadensis minima*, a small subspecies of Canada goose that nests in western Alaska and stages in Cook Inlet during spring migration.
- Calanoid copepod**—Member of the crustacean class Copepoda, order Calanoida; often the most common taxon of small crustacean comprising the marine zooplankton community.
- Canadian Ocean Weather Station 'P'**—The site in the North Pacific (50°N, 145°W) of weather and oceanographic monitoring since the early 1950s.
- Capelin**—*Mallotus villosus*, an abundant, small schooling smelt (family Osmeridae) that is an important prey of several kinds of fish, marine mammals, and seabirds throughout coastal Alaska.
- Carrying capacity**—The maximum number or weight of individuals in a species which can be maintained in a habitat without depletion of food or other ecological factors.
- Catch per unit effort (CPUE)**—A statistic, based on catches taken per unit of fishing effort, which is sometimes used to estimate the relative abundance of a species.
- Central Subarctic Domain**—One of the water masses identified by Dodimead *et al.* (1963) and typical of much of the eastern Gulf of Alaska.
- Cephalopods**—The molluscan taxon comprising the squids and octopuses.
- Chaetognaths**—Small, torpedo-shaped carnivorous invertebrates of the phylum Chaetognatha, often termed 'arrow worms'.
- Chinook salmon (*Oncorhynchus tshawytscha*)**—A common name for the largest of the salmon species of the genus *Oncorhynchus*; also called king, quinnat, or tyeec.
- Chlorophyll *a***—A pigment, found in all plant chloroplasts, that absorbs visible light as the first step in photosynthesis.
- Chlorophyll degradation products**—A multiplicity of products formed when chlorophyll is decomposed.
- Choanocyte**—Collar cell; a type of cell peculiar to sponges. The cells form an epithelium in certain chambers and passages through the sponge; each cell has a funnel-shaped, mucus covered, gelatinous collar and a single flagellum originating from the cell in the center of the collar.
- Choanoflagellates**—Small (<5 μm) phytoplankton characterized by the presence of a collar-like structure at the base of the associated flagella.
- Chum salmon**—A common name for fish of the salmon species *Oncorhynchus keta*, which is also known as dog salmon.
- Cladocerans**—Small crustaceans of the suborder Cladocera, most commonly occurring in freshwater, but with representatives in coastal marine waters.

- Clast**—A fragment of a detrital (or clastic) rock, often used as a synonym for a megaclast, a larger clastic particle within a rock of prevailing finer grain.
- Cloud streets**—Approximately parallel lines or streaks of clouds with clear spaces in between and with width scales from 1 or 2 km to 20 kilometers. Clouds are organized into these lines by instabilities in the atmospheric boundary layer.
- Cluster analysis**—A process of classifying or grouping variables, subjects, or sampling units by combining similar units to form small classes, then combining small classes into larger classes, and so on.
- Clutch**—The number of eggs laid by a female bird during one nesting attempt.
- Cnidaria**—A phylum containing the jellyfishes, sea anemones, and corals; also called Coelenterata.
- Coastal wind jets**—Winds along mountainous coastlines that, in adjusting to the inability to flow through a mountain wall, turn from their offshore geostrophic orientation to a new direction aligned closer to the direction of the pressure gradient and to a new speed that allows for the conservation of mass and momentum for the onshore flowing air mass.
- Coastal Zone Management Act of 1972 (P.L. 92-583, 16 U.S.C. sec. 1451 *et seq.*)**—This law defines the national policy concerning the nation's coastal zone by declaring that it is in the nation's interest to preserve, protect, develop, and, where possible, to restore or enhance the resources of the coastal zone. It also promotes federal-state cooperation in matters concerning the coastal zone and the establishment and implementation of state coastal zone management programs.
- Coccolithophores**—A family of planktonic dinoflagellates characterized by an external covering of calcareous plates.
- Coherence**—The existence of a correlation between the phases of two or more phenomena, so that coupling or interference effects may be produced between them.
- Commercial extinction**—In the context of fisheries, a species or stock reduced to such small numbers that it no longer makes an economic contribution to the fishery.
- Community composition**—The species of organisms making up a biological assemblage at a given time and location.
- Compensation light intensity (I_c)**—The light intensity at which the rates of photosynthesis and respiration are equal.
- Competitive exclusion**—A situation resulting when one individual or species uses or defends a resource to the extent that the resource becomes unavailable to other individuals or species.
- Conservative constituent or parameter**—A constituent or parameter whose concentration or value may be affected by mixing of different water masses, but not by physical-chemical reactions or biological processes.
- Conservative tracer**—A material whose concentration in seawater is not changed by chemical or biological processes.
- Consumption rate**—The amount of prey ingested by an organism in a given period of time.
- Convergence**—Act of approaching the same point from different directions; see also plate tectonics and downwelling.
- Copepod nauplii**—The first stage after hatching in the development of copepod crustaceans from eggs to adults.
- Copiotrophs**—Microorganisms that grow at high nutrient concentrations.
- Coralline algae**—Calcareous red algae of the family Corallinaceae.
- Coriolis Force**—The deflecting force of the earth's rotation; a fictitious force used mathematically to describe motion relative to a noninertial, uniformly rotating frame of reference such as the earth.
- Cosmogenic**—Originating in space or in the upper regions of the earth's atmosphere.
- Council on Environmental Quality**—A three-person council of experts created in the Executive Office of the President under Title II of the National Environmental Policy Act of 1969 (NEPA, 42 U.S.C. 4332 *et seq.*) to assist and advise the President.
- Crested auklet**—A small plankton-feeding alcid (*Aethia cristatella*) common to the Bering Sea and Aleutian Islands.
- Critical depth (Z_{cr})**—The maximum depth of surface water mixing that will sustain net water column photosynthesis.
- Crust**—The outer rocky layers of the earth with seismic P-wave velocities less than about 8 km/s. Oceanic crust is usually less than 10 km thick; continental crust is typically between 20 and 40 km thick.
- CTD stations**—Sampling, at discrete sites, with continuous profiling devices that electronically sense conductivity, temperature, and depth.
- Ctenophores**—Small jelly-like forms of the phylum Ctenophora, distinguished from the true jellyfishes (phylum Cnidaria) by having eight rows of swimming cilia and two tentacles.
- Cyclonic gyre**—An air or water mass that circulates counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

DDT—Dichlorodiphenyltrichloroethane; a chlorinated hydrocarbon that has been widely used as a pesticide. Due to its toxicity to a variety of non-target organisms, and to its mobility and persistence in the environment, use of DDT is now tightly controlled in the United States and many other countries.

Decapods—Members of the crustacean order Decapoda, including shrimps and crabs.

Deep sections—Cross sections of vertical properties (*e.g.*, temperature, salinity) at ocean depths greater than 1,000 meters.

Demersal fishes—Bottom-dwelling fishes.

Dendrogram—A diagram showing the relationships produced by a hierarchical classification; that is, a classification in which the classes are ranked such that every unit belongs to a class, and every class to a higher-ranking class, up to the highest class, which is the totality of all units.

Denitrification—The conversion of fixed forms of nitrogen, such as nitrate ions, to atmospheric nitrogen (N_2).

Density gradient—The change in density per unit horizontal (or vertical) distance.

Density slope—The slope (change in depth divided by distance) of a constant-density surface.

Detrital food chain—A food chain based on the consumption of detritus (*i.e.*, particulate organic debris).

Diagenesis—Changes that take place in the conversion of a sediment to a rock, and the processes that bring about these changes.

Delta ^{13}C —Three common forms of carbon are found in the atmosphere— ^{12}C , ^{13}C , and ^{14}C . Marine primary producers have a less negative ratio of $^{13}C/^{12}C$ than do terrestrial primary producers. Therefore, the tissues of animals which prey on marine primary producers should also have a less negative ratio. The unit of $\Delta^{13}C$ has been developed as a means of discriminating very small differences between two large numbers.

$$\Delta^{13}C = \frac{^{13}C/^{12}C \text{ Sample}}{^{13}C/^{12}C \text{ Standard}} - 1 \times 1,000$$

Diamict sediment—Sediment consisting of particles of two classes or modes; usually large clasts in a finer-grained matrix.

Differential Ekman pumping—An effect of spatial variations in local wind-stress curl that results in horizontal differences in vertical velocity. These differences in vertical velocity cause changes in the depth of density surfaces that change geopotential anomaly and geostrophic flow.

Dinoflagellate resting cysts—Typically, a part of the life cycle of coastal marine dinoflagellates that allows them to survive periods unfavorable for growth.

Dipteran larvae—Worm-like immature stage in the life cycle of flies of the insect order Diptera.

Direct count—A method for enumerating microorganisms based upon direct microscopic observation, often after staining with a fluorescent dye such as acridine orange.

Diversity index—A numerical descriptor that reflects the number of different species and their relative abundances within a community.

Double-crested cormorant—A large, diving, fish-eating seabird (Phalacrocoracidae, *Phalacrocorax auritus*) that has two small crests on its head during the breeding season.

Downwelling—Vertical sinking of upper ocean layers which may result from either convergence of ocean currents or increased water levels along the coast owing to wind stress; opposite of upwelling.

Drag (transfer) coefficient—When momentum is transferred from the atmosphere to the earth's surface, a drag force per unit area (stress) is exerted on the surface. The drag coefficient is a convenient, dimensionless number that relates the momentum transfer (stress) to the near-surface wind speed.

Drogued drifter—A device used to follow ocean currents, consisting of a surface float connected to a subsurface drogue (parachute, panel, or vane) used to couple the assembly to the subsurface current.

Ductile—Pertaining to the plastic, flow-like deformation of materials without breaking.

Dusky Canada goose—*Branta canadensis occidentalis*, a dark subspecies of Canada goose that nests exclusively on the Copper River Delta.

Dynamic centimeters—A unit used for computing values of geopotential anomaly. It is derived from the vertical (pressure) integral of specific volume anomaly and equals 10 ergs per gram. It is approximately equivalent to 0.98 linear centimeters.

Eared seal—A member of the pinniped family Otariidae (fur seals and sea lions) that has rolled-up external pinnae (ears).

Earthquake—The sudden shear failure of a stressed elastic-brittle portion of the earth. Earthquakes are the manifestation of a dynamic slip on a fault that radiates seismic waves.

Ecological efficiency—A ratio: the amount of energy extracted from a lower trophic level by an upper level, divided by the amount of energy supplied to the lower level.

- Eddy heat flux**—A flux or transfer of heat resulting from correlated deviations of current and temperature.
- Eddy kinetic energy**—Energy per unit mass at frequencies higher than the mean of net flow; determined by computing the variance of velocity, and taking one half of it over the record length.
- Ekman transport**—Wind stress (or drag) on the ocean surface produces motion in the upper, mixed layer of the ocean (usually between 10 and 100 m deep). This oceanic response to the wind is termed Ekman transport.
- El Niño**—An intermittent event (typically every 3–7 years) of about one year's duration that produces marked warming of upper ocean waters in the central and eastern equatorial Pacific. The events may interrelate with atmospheric systems globally, and they may affect temperature and sea level along the eastern Pacific margin as far north as the Gulf of Alaska.
- Elastic (geophysical)**—The behavior of solid matter in which stresses and strains relate linearly to each other.
- Emery and Hamilton pressure index**—An index that compares winter mean pressure south of the Aleutian Islands to that over coastal California (pressure at 40°N, 120°W minus the pressure at 50°N, 170°W; Emery and Hamilton, 1985). High values of the index correspond to low relative pressure near the Aleutians, which relates to more intense and/or frequent cyclone activity in the Gulf of Alaska.
- Emperor goose**—A medium-sized goose (*Chen canagica*) that nests in western Alaska and is the only abundant goose that winters in Alaska.
- Endangered Species Act (of 1973) (P.L. 93–205, 16 U.S.C. 1531 et seq.)**—This act provides for the conservation of endangered and threatened species of fish, wildlife, and plants.
- Endogenous**—Originating within the organism.
- Engelmann diagram**—A schematic illustration showing relationships between costs and margins of safety in a project.
- Environmental degradation**—A change in the environment that is harmful to the environmental systems or aesthetically displeasing to a majority of people.
- Environmental hazards**—Those elements in the physical environment harmful to man and caused by forces extraneous to him.
- Epibenthos**—Organisms occurring on (but seldom in) the sea floor.
- Epicenter**—Position of the nucleation point of an earthquake projected on the earth's surface. Its coordinates are given by geographic latitude and longitude.
- Epipelagic zone**—The surface layer of the ocean where photosynthesis and seasonal changes in temperature and salinity occur; the upper 200 meters.
- Equitability index (J')**—A measure of diversity that describes the evenness of distribution of species within the community.
- Errantiaetes**—A classificatory grouping of polychaete worms that includes free-living species.
- Eulachon**—*Thaleichthys pacificus*, a species of smelt (family Osmeridae), commonly called candlefish, that is an important prey species for several kinds of fish and sea birds throughout coastal Alaska.
- Euphausiids**—Small, active, shrimp-like crustaceans of the order Euphausiacea.
- Euphotic zone**—The uppermost layer of a body of water receiving sufficient light for photosynthesis.
- Euryhaline**—Able to tolerate wide fluctuations in salinity.
- Eutrophic**—A description of relative water column productivity referring to the most productive of conditions.
- Exceedence probability**—The probability that a given level of ground motion, expressed as a given parameter (*e.g.*, ground acceleration), will not be exceeded within the period of interest.
- Exclosure**—An area from which intruders (*e.g.*, predators) are excluded, especially by fencing.
- Exclusive economic zone (EEZ)**—The contiguous zone extending offshore 200 nmi from the United States and its territories, proclaimed by President Reagan on March 10, 1983. The intent of the proclamation was to set forth the United States' sovereign rights to the mineral resources of the zone.
- Extreme wave height**—In oceanography, an empirical estimate equaling 1.8 times the average height of the highest one-third of all observed waves.
- Fastidious**—Term used to describe microorganisms that grow only under very restricted nutritional and environmental conditions.
- Fault**—An internal surface in the earth's crust across which repeated slip has occurred. A normal fault occurs when the hanging (upper) wall has apparently moved down with respect to the foot (lower) wall. A thrust or reverse fault occurs when the hanging wall has apparently moved up relative to the foot wall.
- Fault plane**—A plane that contains the surface of slippage during an earthquake. One of the two orthogonal nodal planes in the P-wave radiation pattern of an earthquake coincides with the fault plane.

- Fecal pellets**—Particles voided from an animal's digestive tract; often discussed with respect to zooplankton (*e.g.*, copepods).
- Fecundity**—The potential reproductive capacity as measured by an individual's production of young.
- Federal Water Pollution Control Act of 1972 (FWPCA)** (33 U.S.C. 1251 *et seq.*)—This act sets forth policy concerning the restoration and maintenance of the quality of the nation's navigable waters and the elimination of discharges of pollutants into the waters.
- Fetch**—The distance the wind has blown over a surface.
- Five hundred millibar height**—The height above mean sea level of the 500 mb constant pressure surface, typically near 5.5 km altitude. Since the average surface pressure is ~1,000 mb, about half of the mass of the atmosphere is above this height and half is below. At mid-latitudes this is the approximate height of the winds that steer the motion of the large high and low atmospheric pressure systems.
- Fjord**—A deep (and frequently long, narrow, and steep-sided), high-latitude estuary excavated or modified by land-based ice; usually, but not necessarily, bounded seawards by a sill.
- Flagellate**—Members of the protozoan subphylum Mastigophora, which possess one or more filiform appendages (flagella) as adult locomotor organelles.
- Fledging success**—The proportion of young birds that successfully leave the nest relative to the number of young that hatch.
- Flick feeding**—A feeding method observed in humpback whales in which the flukes are suddenly flexed forward, creating a wave that concentrates planktonic food.
- Fluorometer**—An instrument that can detect the presence of fluorescent materials; most commonly used in oceanography to measure the concentration of chlorophyll in seawater.
- Fluorometry**—An analytical technique in which the stimulated emission of light from a substance (usually in solution) is measured.
- Fluvial**—Pertaining to, or inhabiting, a river or stream formed by action of flowing water.
- Food chain**—The theoretical flow of energy from plants through a series of other organisms; members of each link in the chain feed upon the members of the one below and are consumed by the members of the one above.
- Free sulfide**—Uncombined sulfide ions often present under anaerobic conditions in marine waters.
- Freshet**—Freshwater snow-melt discharge, usually in the spring.
- Frontal systems**—Ocean areas in which relatively sharp horizontal gradients in properties are found, usually associated with temperature or salinity.
- Frustules**—The two siliceous plates that enclose a diatom; composed mainly of silica.
- Fugitive species**—A species adapted to colonize newly disturbed habitats. A fugitive species often has a life history characterized by short life span, short development time to reach maturity, and many reproductive periods per year.
- Fulvic acid**—A functionally defined fraction of humic material soluble at low pH values (see humic acid).
- Gadwall**—*Anas strepera*, a species of duck that nests in wetlands bordering the Gulf of Alaska.
- GAK line**—Acronym for Gulf of Alaska. The GAK line is a series of oceanographic stations transecting the continental shelf from a point at the mouth of Resurrection Bay. This series of stations has been monitored at irregular intervals since 1970 by scientists at the Institute of Marine Science, University of Alaska.
- Gap winds**—Air motion from an area of higher pressure to an area of lower pressure through a region restricted by the terrain.
- Genotype**—The genetic constitution of an individual, without regard to its outward appearance (phenotype).
- Geopotential anomaly**—For a mass of water at a given pressure, the difference between the depth of the water mass as calculated from its potential energy and the actual geometric depth of the water mass; most often used to infer the direction of water movement at different depths in the ocean.
- GEOSECS**—An acronym for geochemical ocean sections, a large multi-institutional program, supported by the National Science Foundation, that conducted a coordinated mapping of chemical concentrations in the world's oceans during the period from 1972 to 1977.
- Geostrophic flow**—Flow that assumes a balance between the pressure gradient and deflective or Coriolis forces in the equation of motion. This is the component of flow computed from geopotential anomalies derived from hydrographic casts.
- Geostrophic relation**—An assumption that pressure gradients and the earth's deflective forces balance locally; used to compute geostrophic flow.
- Geostrophic winds**—Air flow that is necessary to balance the force of a pressure gradient and the effects of a uniformly rotating reference frame (see Coriolis force). The geostrophic wind is always parallel to contours of constant pressure (isobars) and has a magnitude inversely proportional to the distance between adjacent isobars.

- Geothermal energy**—Energy available from heated vapors or water from sources beneath the earth's surface. In Alaska, many potential geothermal energy sources are associated with volcanoes and volcano-like features.
- Gill net**—A fixed vertical net, having the head rope buoyed and the bottom rope weighted, in the meshes of which fish become entangled by their gill covers. Set gill nets have one end anchored to shore; drift gill nets float free in the water.
- Glacial-fluvial sediments**—Pertaining to sediments derived from or associated with glaciers.
- Glaucous-winged gull**—A large seabird (*Larus glaucescens*) that nests in the Gulf of Alaska.
- Gonatid squid**—Any of several species of abundant oceanic squids of the family Gonatidae.
- Graben**—An unusually elongated depression of the earth's crust between two parallel faults.
- Gram-negative bacteria**—Bacteria with a complex cell wall containing murein and an envelope containing lipopolysaccharides; bacteria that decolorize and therefore appear pink using the Gram stain procedure.
- Gyre**—A very large-scale ocean circulation system whose currents impart a tendency to clockwise or counterclockwise rotation. The Pacific subarctic gyre has a counterclockwise rotational tendency.
- Half-saturation constant**—Term applicable to uptake of a limiting nutrient by an organism; the concentration of the limiting nutrient when the uptake rate is half of the maximum rate observed for that particular organism and nutrient.
- Halocline**—Region of maximum change of salinity per unit depth.
- Harpacticoid copepods**—Small benthic copepods of the order Harpacticoida.
- Hatching success**—The percent of eggs that hatch relative to the number laid.
- Haulouts**—Areas where marine mammals rest on a beach.
- Hematopoietic necrosis**—A disease condition evidenced by bloody, dead tissue.
- Hemolymph**—The nutritive circulatory fluid, similar to blood or lymph, of invertebrates.
- Herbivorous grazing**—Selective consumption of plants; often used to designate consumption of phytoplankton by herbivores, mainly zooplankton.
- Heterotrophic activity**—A measure of relative bacterial productivity, based upon the uptake of radioactive isotope-labeled organic compounds.
- Hippolytid shrimp**—Any of several species of shrimp in the family Hippolytidae.
- Holoplankton**—Organisms that are a permanent component of the zooplankton community.
- Horizontal divergence**—Movement, in a horizontal plane, away from a common point.
- Hot spot**—The spot-like locus of persistent upwelling of mantle-derived magma.
- Humic acid**—A functional fraction of humic material soluble at high pH, but which precipitates on acidification (see fulvic acid).
- Humic substances**—High molecular weight, acidic organic polymers containing active hydrophilic phenolic and oxylic groups; generally resistant to chemical and microbiological degradation.
- Hybridize**—The sexual crossing of genetically dissimilar individuals.
- Hydrocarbon degraders**—Microorganisms capable of metabolizing hydrocarbons.
- Hydrocast**—A vertical sampling of oceanic water at a fixed site. Until the development of CTD sensors, hydrocasts were made by lowering bottles (with reversing thermometers) on a wire to obtain temperatures and samples for analyses of salinity and other properties.
- Hydrographic time series**—A time series of any oceanographic property (at discrete depths or continuous in the vertical) at a fixed site.
- Hydromedusae**—The free-swimming medusoid forms of some species of hydroids (phylum Cnidaria, class Hydrozoa).
- Hypocenter**—Position (depth, latitude, longitude) of the nucleation point of an earthquake.
- Ice scour**—Removal of attached organisms by moving ice.
- Ichthyoplankton**—The eggs or larval stages of fish that drift or swim weakly in the water column.
- Imbricate**—In structural geology, pertaining to the shingling arrangement of thrust faults that form thrust belts with inclined stacks of thrust sheets.
- Incubation period**—The period in the reproductive cycle of egg laying animals which occurs after egg laying and before hatching.
- Interception fishery**—A fishery that catches fish in migratory paths; often refers to salmon caught as they return to their home streams to spawn.

- International North Pacific Fisheries Commission (INPFC)**—A research and coordinating body, composed of representatives from the United States, Canada, and Japan, which establishes management measures to conserve stocks of fishes in the North Pacific Ocean. The commission sponsors relevant fisheries research and publishes the results in the INPFC Bulletin.
- International Pacific Halibut Commission (IPHC)**—Formed in 1923 with the United States and Canada as the only members, this body carries out research and establishes the management measures under which halibut catches by the two countries are regulated.
- International Pacific Salmon Fisheries Commission (IPSF)**—Created by treaty in 1937, the goal of the commission is the restoration of the Fraser River sockeye salmon runs and equal division of catches between Canadian and United States fishermen.
- International Whaling Commission (IWC)**—This commission was established in accordance with the International Convention for the Regulation of Whaling, which entered into force in 1948. The commission is responsible for amending the regulations that govern the conduct of whaling by the contracting governments.
- Interstitial water**—Water occurring in the interstices between particles.
- Isochron**—A line or contour of constant age.
- Isohaline**—A surface of constant salinity.
- Isopycnal surface**—A surface of constant density.
- Isotopic fractionation**—Small separations between the isotopes of an element that occur during chemical and biological processes.
- Jacks**—Members of the fish family Carangidae; also sexually precocious male salmon.
- Katabatic winds**—Winds that flow down slopes that are cooled by radiation, the direction of the flow being controlled almost entirely by orographical features.
- Killer whale**—*Orcinus orca*, toothed whales with tall, wide dorsal fins and body length up to 9.5 meters.
- Kinematics**—In fluid dynamics, the characteristics of different kinds of pure motion; that is, without reference to mass or the causes of motion.
- Kuroshio water**—Water resulting from the continuation of the Kuroshio Current into the western North Pacific.
- Larvaceans**—Small, free-swimming members of the subphylum Urochordata (Tunicata), which feed primarily by filtering particulate matter from seawater.
- Latent heat flux**—The quantity of heat transferred between the earth's surface and the atmosphere through evaporation.
- Leachates**—Liquids that have percolated through a medium and have extracted dissolved or suspended materials from it.
- Lead-210 (or ^{210}Pb) analysis**—Lead-210 is an unstable, alpha-emitting product of U-234 with a half-life of 21.4 years. Lead-210 measurements may be used to determine either the age of sediments or sedimentation rates.
- Leopold matrix**—A tabulated arrangement of a set of possible developmental actions with a set of potentially impacted indicators, sometimes used as an environmental assessment technique.
- Lesser Canada goose**—*Branta canadensis parvipes*, a subspecies of Canada goose that nests in southcentral and interior Alaska.
- Light extinction coefficient**—The proportion of light absorbed per meter in water. This varies from 0.04/m in the clearest ocean water to 0.4/m or more in very turbid water.
- Light saturation**—That amount of light beyond which there is no increase in productivity by plants.
- Limpet**—Any of several species of dorso-ventrally compressed (Chinese hat shaped) gastropod mollusks which hold tightly to rocks.
- Lipid reserves**—Special triglycerides that many zooplankton store for use as energy reserves during times of food shortage (*i.e.*, winter).
- Liquefaction**—The property of unconsolidated sediments to lose their shear strength during shaking, rendering them capable of flowing like a liquid.
- Listric**—Pertaining to the orientation of faults whose dip angles decrease with depth.
- Lithosphere**—The outer shell of the earth that maintains relatively high rigidity and integrity of matter during tectonic processes. Its thickness can measure a few tens of km for young oceanic lithosphere and in excess of 100 km for old continental lithosphere. The lithosphere contains both brittle crust and the partly seismogenic and partly ductile (but strong) portions of the upper mantle.
- Litter**—Scattered rubbish; considered herein to consist of materials discarded by man.
- Littoral zone**—The expanse of shoreline between high and low tides.

- Longline**—A long, negatively buoyant fishing line, having many short subsidiary lines attached to it, each with one or more baited hooks. Longlines may extend for several miles.
- Loon**—Any of four species of large, fish-eating birds (Gaviidae) that nest primarily on freshwater and winter at sea.
- Lumpfish**—A group of small- and medium-sized fishes of the family Cyclopteridae.
- Lunge feeding**—A feeding method observed in humpback whales in which the animals lunge forward with their mouths open to collect food.
- Lymphocystis**—A viral disease that affects flatfish.
- Macrofauna**—Fauna (animals) larger than 0.5 millimeters.
- Macrophagus detritivore**—An organism that feeds on relatively large particles of freshly dead or partially decomposed organic matter.
- Macrophyte**—An individual plant large enough to be seen easily with the unaided eye. In marine biology, this term is often used to refer to the large kelp species which are abundant in northern coastal waters.
- Macrozooplankton**—Zooplankton large enough to be retained by a net with 183 μm mesh.
- Magnitude**—A logarithmic measure of the source size and source strength of an earthquake, usually inferred from quantities that can be measured on seismograms.
- Magnuson Fishery Conservation and Management Act of 1976** (16 U.S.C. 1801 *et seq.*)—This law established the United States' 200-nmi fisheries conservation zone, and created eight regional fisheries management councils to regulate the take of fish within their geographic areas of concern.
- Mantle**—The ~2,800-km thick, compositionally dense portion of the earth that lies between the less dense crust and the much denser liquid core of the earth. Relatively rigid portions of the upper mantle are part of, and move with, the plate-like lithosphere, which overlies the weak ductile asthenosphere, which in turn overlies the lower mantle at depths beneath about 650 kilometers. The lower mantle is sometimes also referred to as mesosphere.
- Marbled murrelet**—A small, coastal alcid (*Brachyramphus marmoratus*) usually seen in pairs.
- Marine Protection, Research, and Sanctuaries Act of 1972** (33 U.S.C. 1401 *et seq.*)—This act prohibits unregulated dumping of material into ocean waters, and requires permits for the dumping of dredged materials.
- Maximum sustainable yield**—The largest annual commercial and sport catch, in terms of weight of fish, that can be taken continuously from a stock under existing environmental conditions.
- Mean kinetic energy**—Energy per unit mass associated with the mean or net flow; proportional to one-half the product of its mass and the square of its speed.
- Mechanistic approach**—Involving the study of the processes underlying the organization of natural communities.
- Medusae**—Bell-shaped, usually free-swimming forms of many members of the classes Hydrozoa and Scyphozoa of the phylum Cnidaria.
- Megazooplankton**—Zooplankton larger than 1.0 centimeter.
- Meiofauna**—Fauna in the size range 0.05 to 0.5 millimeters.
- Meroplankton**—Organisms that are only temporary members of a zooplankton community.
- Mesosphere**—See mantle.
- Metabolic rate**—The rate at which an animal chemically converts food into body tissues, carbon dioxide, and waste products.
- Metacentric height**—The distance of the metacenter above the center of gravity of a floating body. Metacenter is the point of intersection of a vertical line through the center of buoyancy of a floating body and a vertical line through the new center of buoyancy when the body is modified or displaced.
- Microaerophilic marine environments**—Regions of reduced oxygen tensions where microorganisms that require oxygen, but are also sensitive to it, can live.
- Microflora**—Plants or bacteria smaller than 50 microns (0.05 mm).
- Micronekton**—Small, free-swimming animals that have the ability to swim against weak vertical and horizontal currents.
- Microzooplankton**—Zooplankton smaller than 183 microns (0.183 mm).
- Milt**—The mass of sperm released by a male fish.
- Mineralization**—The conversion of organic matter to inorganic compounds such as carbon dioxide and water.
- Mitigation**—A system of programmatic measures to reduce or minimize the damaging effects from an unwanted occurrence.
- Mixed layer depth (MLD)**—The depth of surface wind-mixing, usually taken as the depth at which a significant temperature change from the surface value takes place.

- Mixed-stock fishery**—A fishery in which different stocks of the same fish species are taken.
- Mixing rates**—The rate at which water masses are mixed with each other by physical processes such as diffusion or tidal flow.
- Mysids**—Small shrimp-like crustaceans of the order Mysidacea, distinguished from euphausiids by the presence of a small 'balancing organ', or statocyst.
- Mysticetes**—See baleen whales.
- Naked flagellates**—Small (<5 microns) planktonic cells possessing at least one flagellum, but without any hard covering such as coccolithophorids or silicoflagellates have.
- Nanoplankton**—Plankton in the size range of 5 to 20 microns (0.005 to 0.02 mm).
- National Environmental Policy Act of 1969 (P.L. 91-190, 42 U.S.C., 4321 *et seq.*)**—This act promotes efforts to prevent or eliminate damage to the environment.
- National Pollutant Discharge Elimination System (NPDES)**—Embodied in subsection 1342 of the Federal Water Pollution Control Act of 1972, NPDES sets out guidelines which control the discharge of pollutants into navigable waters.
- NEGOA** —An acronym for the northeast Gulf of Alaska, used mostly in connection with OCSEAP studies of the region of the North Pacific lying on the continental shelf between Hinchinbrook Island and Yakutat Bay.
- Nepheloid layer**—A layer in a liquid containing large amounts of suspended particles; usually found in the ocean where near-bottom turbulence is sufficient to maintain a layer of suspended sediments.
- Nephelometer**—An instrument used to measure the transmission of light through a water sample. Its main application is in estimating the concentration of suspended particles in seawater.
- Nereid polychaetes**—Segmented benthic marine worms of the genus *Nereis* (phylum Annelida, class Polychaeta) that produce a sexually ripe swimming stage for reproduction.
- Neritic species**—Marine forms that are found in nearshore habitats.
- Net photosynthesis**—The organic matter produced by plants after adjusting gross photosynthesis for losses due to respiration.
- New nutrients**—Exogenous nutrient supply for phytoplankton production; contrasted with regenerated supply from *in situ* consumption and degradation.
- New production**—Phytoplankton fixation of carbon based on the use of NO_3^- as the nitrogen source. When nitrogen in the form of NH_4^+ is used, this is considered recycling, since NH_4^+ is only present when fixed carbon is being consumed and regenerated by respiring organisms.
- Nitrogen fixation**—The conversion of atmospheric nitrogen (N_2) to fixed forms of nitrogen, such as ammonium ions.
- Nitrogen-15 (^{15}N)**—A heavy isotope of nitrogen that can be used as a tracer in studies of marine productivity.
- NO**—A computed chemical parameter ($9 \times$ nitrate concentration plus the dissolved oxygen concentration) that is conservative if Redfield stoichiometry is approximated.
- Nodal plane**—A theoretical plane through a seismic source that contains directions in which the radiation pattern for a specified type of seismic wave has zero amplitude; see also fault plane.
- Nomogram**—A graphical representation of numerical relationships among three or more variables.
- Non-point source**—Any unconfined area from which pollutants are discharged.
- Nanoplanktonic heterotrophic flagellates**—Very small non-photosynthetic flagellates that occur within planktonic communities.
- Normal fault**—See fault.
- NORPAC**—Acronym for North Pacific; an informally organized group of scientists responsible for collating and publishing much of the oceanographic data collected in the North Pacific Ocean during the period of approximately 1930 to 1965. These data were published in several volumes by the University of California Press. This data set is collectively known as the NORPAC data.
- North Pacific oscillation index**—A measure of the difference in mean winter air temperature anomalies between St. Paul Island in the southern Bering Sea and Edmonton, Canada. An intensified Aleutian low pressure area in the eastern North Pacific occurs when there is a cold anomaly in winter temperatures at St. Paul and a warm anomaly at Edmonton.
- Nuee ardente**—In volcanology, an extremely hot gaseous cloud of volcanic ash released during an explosive eruption; may flow downslope like an avalanche at high speeds.
- Numerical taxonomy**—An approach used for classifying organisms based upon sets of phenotypic characteristics rather than upon a hierarchical scheme.
- Nutricline**—Region of maximum change in a nutrient with depth.

- Nutrient mass balance**—A quantitative measurement of the amount of nutrients in a system; it involves computing the amount in organic form (biomass), inorganic form, and supply through advection or diffusion; a method recently used to estimate primary production.
- Nutritional versatility index**—A numerical descriptor of the ability of microbial populations in a community to utilize different classes of compounds, a property presumably related to the substrates that are naturally available. Separate indices are calculated for different classes of substrates; the indices have a scale of 0 to 1 and are calculated by determining the proportions of representative microorganisms that can grow on various individual substrates within each class of compounds.
- Ocean Weather Station 'P'**—See Canadian Ocean Weather Station 'P'.
- OCSEAP**—An acronym for the Outer Continental Shelf Environmental Assessment Program. OCSEAP is an Alaskan research program managed by the National Oceanic and Atmospheric Administration and funded by the Minerals Management Service of the Department of Interior.
- Odontocetes**—Dolphins, porpoises and whales of the sub-order Odontoceti that have teeth but no baleen, and a single external blowhole.
- Oligotrophs**—Microorganisms that grow at low nutrient concentrations.
- Ontogeny**—Developmental history of an organism from zygote to maturity.
- Open-access resource**—A resource that is not owned.
- Optimum yield**—In the context of the United States fisheries policy, the amount of fish that will provide the greatest overall benefit to the United States; prescribed on the basis of maximum sustainable yield for a fishery as modified by any relevant ecological, economic, or social factors.
- Orography**—Study of the physical geography of mountains and mountain ranges.
- Osteichthyes**—The class to which bony fishes belong.
- Ostracods**—Small marine crustaceans of the class Ostracoda which possess a bivalved carapace (shells) that partially encloses the body.
- Ovoviviparous**—Producing eggs that hatch within the body of the female.
- Oxygen minimum**—Those depths in the ocean where the oxygen concentration is less than that at both shallower and greater depths. In the Gulf of Alaska, the oxygen minimum generally occurs at a depth of about 1,000 meters.
- P/B ratio**—Ratio of production to biomass.
- Pacific intermediate water**—That mass of water typically occurring at depths of 200 to 800 m in the North Pacific Ocean which formed as a result of the cooling of surface waters along the coast of the U.S.S.R. during winter months.
- Pandalid shrimp**—Any of several species of shrimp of the genus *Pandalus* (order Decapoda) that are highly sought in commercial fisheries in Alaska.
- Papillomatosis**—A viral disease resulting in formation of benign tumors.
- Paralytic shellfish poisoning (PSP)**—A human pathological condition caused by the ingestion of shellfish that have previously accumulated toxins from dinoflagellates in the surrounding water. While apparently not harmful to the shellfish, these toxins can cause death by respiratory failure in mammals.
- Particulate flux**—The rate of sinking of particulate material from the surface waters of the ocean.
- Patchiness**—Variability (in space and/or time) of biological populations.
- Pathogen**—A microorganism that causes disease.
- Pathogenicity test**—A test conducted to determine whether a particular microorganism causes a specific disease condition.
- Peak uptake**—The maximum utilization of nutrients, especially nitrogen, by phytoplankton during photosynthesis.
- Pelagic**—Free-living in the water column.
- Pelagic amphipods**—Amphipods that complete their life histories entirely in the water column.
- Pheopigments (or phaeopigments)**—Degraded forms of chlorophyll (*e.g.*, via acidification).
- Photosynthesis**—The conversion of light energy to chemical energy during the synthesis of organic material by plants.
- Physiological tolerance index (P)**—A numerical descriptor of the ability of microbial populations in a community to tolerate deviations in particular environmental parameters such as variations of temperature and salinity from ambient conditions at the time of sampling. Separate indices are calculated for different environmental factors; the indices have a scale of 0 to 1 and are calculated by determining the proportions of representative microorganisms that can grow under various fixed conditions.
- Phytodetritus**—Detritus derived from plants.
- Phytoplankton**—Typically, microscopic, single-celled plants that grow in surface waters.

- Piedmont glacier**—A glacier formed by the coalescence of two or more valley glaciers behind the base of a steep slope.
- Pigment budget**—A method to measure phytoplankton growth and sinking and grazing losses based on pigment changes in the surface layer and the rate of pigment deposition in subsurface traps.
- Pink Salmon**—A common name for fish of the salmon species *Oncorhynchus gorbuscha*, which are also known as humpy or humpback salmon.
- Pioneer species**—See fugitive species.
- Piscivorous**—Fish-eating.
- Planktivorous**—Plankton-eating.
- Plantigrade**—The young postlarva of the bivalve molluscan family Mytilidae (mussels).
- Plasma volume**—The volume of cell protoplasm within a plant cell. This may be significantly less than the volume contained by the cell wall.
- Plastic limit**—The point at which the capability of a plastic to be continuously deformed is exceeded.
- Plate count**—A method for enumerating microorganisms based upon the reproduction of individual, viable microbes to form macroscopic colonies that can be counted.
- Plate tectonics**—A largely kinetic working hypothesis that assumes that the earth's lithosphere is broken up into several distinct plates (about 100 km thick) that internally deform very little (are rigid) but can move readily with respect to each other.
- Pleuronectid**—Any of several species of flatfishes (family Pleuronectidae) in which both eyes appear on the right side of their body. In contrast, flatfishes of the family Bothidae have both eyes on the left side of their body.
- Poll**—An estuarine area at the end of a fjord separated from the main body of the fjord by a shallow inner sill.
- Polychaetes**—Segmented marine worms of the class Polychaeta (phylum Annelida).
- Pre-recruits**—Fish that are too small, too young, or otherwise unavailable to a fishery.
- Primary carnivores**—The first level of herbivore-eating predators in the food chain. Predators that eat primary carnivores are secondary carnivores.
- Prodelta**—The marine area immediately in front of the delta, usually at the mouth of a river.
- Progradation**—A seaward advance of the shoreline resulting from the nearshore deposition of sediments brought to the sea by rivers.
- Propagule**—The minimal number of individuals of a species capable of successfully colonizing a habitable island.
- Proteolytic**—Capable of degrading proteins.
- Pseudocomponents**—In petroleum engineering, refers to fractionation of oil in a true-boiling-point distillation column yielding components of the oil characterized only by boiling point and density.
- Pseudomonads**—A group of metabolically versatile bacteria that are Gram negative, motile by polar flagella, and obligately respiratory.
- Psychrophiles**—Microorganisms with optimal growth temperatures below 15°C that generally can only grow at low (<20°C) temperatures.
- Pteropods**—Small mollusks (order Opisthobranchiata) which are modified for pelagic life.
- Pycnocline**—Region of maximum change in density with depth, typically 50 to 200 m in the subarctic Pacific.
- Pyranometer**—An instrument that measures the amount of sunlight received at a given place.
- Pyroclastic flows**—Volcanic materials that have been explosively or aerielly ejected from a volcanic vent and that move downslope under the influence of gravity.
- Recruits**—The supply of fish that becomes available at some particular stage in the life history of the species.
- Red tides**—Reddish appearance of inshore waters owing to blooms of dinoflagellates or other protozoans; paralytic shellfish toxins are sometimes associated with red tides.
- Refractive index**—The ratio of the speed of light in a vacuum to the speed of light in the medium under consideration.
- Regenerated production**—Primary production that results from utilization of nutrients derived from respiration and recycling of organic matter in the euphotic zone.
- Relict**—An organism or material of earlier time surviving in an environment that has undergone considerable change.
- Reproductive success**—Refers to the number of offspring produced per egg during a breeding attempt.
- Residence time**—Volume of water in an environment (e.g., an estuary) divided by the input or removal rate. In chemistry, the residence time of an element is the average time that it remains in sea water before removal by some precipitation process.
- Reverse fault**—See fault.

- Reversing thermometer**—A specialized thermometer used for recording water temperatures at discrete depths. Reversing thermometers were the primary instruments for temperature measurements in physical oceanographic research from about 1900 to the 1960s, when they were replaced by electronic instruments (*e.g.*, CTD).
- Rheology**—The quantitative description of the relation between strain and stress in earth materials.
- Ridge push**—One of the fundamental driving forces for plate motion; ridge push is a gravitational force that points in the direction of a gradient from high to low topography near mid-ocean ridges.
- River otter**—*Lutra canadensis*, a semi-aquatic carnivore of the weasel family.
- Roe-herring fishery**—A seine and gillnet fishery directed toward the capture of ripe female Pacific herring (*Clupea harengus pallasii*) in order to obtain their roe. Most of the roe is exported to the Orient, where it is considered a delicacy.
- Rorqual**—Whales of the genus *Balaenopteridae* (suborder Mysticeti) that possess numerous ventral grooves and a dorsal fin.
- Rosby radius of deformation**—The horizontal scale at which rotational effects become as important as buoyancy effects. Near a mountainous coastline, it is the distance offshore within which the flow adjusts to the presence of a mountain barrier.
- Runs**—Groups of fish, particularly those ascending a river from the sea.
- S distribution**—The horizontal and vertical salinity field.
- Sac roe**—Eggs of fishes held in a soft-walled membrane; used to designate the roe of herring.
- Saccharolytic**—Capable of degrading carbohydrates.
- Salmonids**—Members of the fish family Salmonidae, which includes the salmon, trout, and whitefishes.
- Salps**—Pelagic tunicates of the class Thaliacea.
- Scutum**—One of the anterior, paired, movable plates which, along with the paired terga, form the operculum that covers the aperture of an acorn barnacle.
- Sea stack**—A small, steep-sided, rocky projection above sea level near a coast.
- Sea-level pressure**—The atmospheric pressure exerted on a unit area at mean sea level from the weight of the atmosphere directly over the unit area.
- Seamount**—A submarine mountain, usually of basaltic magma, emplaced onto an oceanic crust of generally younger age.
- Seasonal thermocline**—A discontinuity in the vertical temperature profile caused by surface heating in the summer.
- Secchi disk**—A simple instrument used to measure the light extinction properties of surface waters by measuring the depth at which the disk disappears from view.
- Secondary bloom**—A phytoplankton bloom of lesser intensity, and usually occurring later in summer, than the primary spring bloom in temperate-boreal regions.
- Sedge**—Fresh- or brackish-water plants of the family Cyperaceae which resemble grasses but have solid rather than hollow stems.
- Sediment failure**—A term used to designate the point when sediment moves under stress.
- Sediment traps**—Containers, open at their upper end, which are suspended at selected depths to measure the amount of sinking material.
- Seiche**—A standing wave in a confined body of water, such as a lake, bay, or fjord, which continues oscillating after the cessation of the originating atmospheric or seismic force.
- Seismic (seismogenic)**—The property of brittle rock to fail suddenly under stress, thereby causing earthquakes.
- Seismicity**—The occurrence of earthquakes as quantified by their patterns in space, time, and magnitudes.
- Semidemersal**—Refers to animals that often occur near the bottom, but which may be caught in the water column.
- Senescence**—That period in the life of an individual when its powers are declining prior to death.
- Sensible heat flux**—The quantity of heat (thermal energy) transferred between the earth's surface and the atmosphere.
- Seston**—A general term referring to all suspended matter in water.
- Set gill net**—A gill net that is anchored to shore.
- Sexual dimorphism**—A difference in appearance, such as size, between the male and female members of a species.
- Shannon index (H')**—An index used to describe the diversity of organisms within a community.
- Shelf break**—The outer edge of the continental shelf; marked by an increase in slope as the bottom descends to the abyssal plain.
- Siblicide**—The killing of a brother or sister by a sibling.

- Sigma-t**—A term used to describe the density of seawater. Because the significant part of a seawater density measurement is usually beyond the third decimal, a conversion has been adopted: $\text{Sigma-t} = (\text{density} - 1) \times 1,000$; thus a density of $1.02750 \text{ g/cm}^3 = \text{sigma-t}$ of 27.50.
- Significant wave height**—The average height of the one-third highest waves measured in a given wave group.
- Siliceous ooze**—A type of marine sediment composed largely of diatom frustules.
- Silicic acid**—The soluble form of silicon in seawater that is conventionally analyzed ('soluble reactive silica').
- Silver salmon**—A common name for fish of the salmon species *Oncorhynchus kisutch*, which is also known as coho salmon.
- Simulated *in situ* incubations**—A method used to measure phytoplankton growth rates by incubating bottles of water from selected depths on the deck of a ship. The bottles are covered with various light filters to simulate the light conditions at the depths from which the water was collected.
- Slab pull**—One of the fundamental driving forces of plate tectonics, which arises during plate convergence when the negative buoyancy of a cold, dense slab exerts a downward directed force onto the slab as it descends into the warmer, and hence less dense mantle.
- Smectite**—A green clay.
- Sockeye salmon**—A common name for fish of the salmon species *Oncorhynchus nerka*, which is also known as red salmon.
- Southern ocean**—Refers to the Antarctic Ocean.
- Spawning aggregation**—Large numbers of a species that gather together for the act of spawning.
- Specific growth rate**—A growth rate in terms of the uptake of a selected element (*i.e.*, carbon or nitrogen). This may or may not correspond to the actual growth rate of the organism, depending on whether or not growth is balanced.
- Sphagnum bog**—Freshwater, acidic wetland characterized by an abundance of mosses of the genus *Sphagnum*.
- Spring bloom**—A rapid increase in the growth of phytoplankton; usually observed at mid- to high latitudes during spring, due to the increase in daylight coupled with decreased surface-water mixing.
- Squamish wind**—Local Canadian name for a katabatic wind.
- Standing crop**—The amount of plant material present at a given point at a given time.
- Station 'P'**—See Canadian Ocean Weather Station 'P'.
- Stochastically**—In mathematics, pertaining to random variables.
- Stock**—Generally pertaining to commercially caught fish that are genetically of one line of origin.
- Stock density**—The number of individuals of the target species available per unit volume or area.
- Stratification**—The restriction of vertical mixing in water columns caused by density differences between water layers.
- Streamline**—A fluid line having the property that the tangent at every point on the line is aligned with the fluid's local velocity.
- Strike slip**—Movement in which the slip across a steeply dipping fault is mostly horizontal.
- Subduction**—The 'pulling under' of one lithospheric plate beneath another.
- Submarine diffuser**—A device at the terminus of an outfall in which a high-velocity, low-pressure stream of fluid is converted into a low-velocity, high-pressure flow to promote rapid mixing and dilution of the discharge with receiving waters.
- Subsistence fisherman**—A person whose primary motivation to fish is to obtain food, in contrast to a commercial fisherman, who is motivated by economic gain, and an angler, who fishes mainly for sport.
- Supralittoral fringe**—In the Stephenson Universal Zonation scheme, the highest zone on the shore bounded below by the upper limit of barnacles and above by the upper limit of *Littorina*.
- Surface gill net**—A gill net that floats on the surface and is free to move with the currents (*i.e.*, drift net).
- Surge channel**—A deep channel in the seaward face of a rock or coral reef or platform through which water moves freely.
- Suspended load**—The total weight of particles suspended in a volume of water.
- Sustained winds**—Winds averaged over a period of one minute.
- Sympatric**—Pertaining to two or more populations of closely related species that occupy identical or broadly overlapping geographical areas.
- Sympatric speciation**—Speciation which occurs within the same range.
- Synoptic survey**—An areal grid of observations occupied over a brief period of time. There is no precise definition of what is and is not 'synoptic'.

- Synopticity**—In oceanography, relating to or displaying oceanic conditions as they exist simultaneously over a broad area.
- T distribution**—The horizontal and vertical temperature field.
- Taku wind**—An Alaskan term for cold air draining from interior glacial or ice-field regions.
- Talus slope**—Slopes of unevenly sized rock debris produced by the fracturing of rock faces.
- Tectonics**—The study of the processes that form the large-scale structures of the earth.
- Teleseismic**—Pertaining to the distance far from the hypocenter of an earthquake, usually more than 1,000 m away.
- Tephra**—A general term for all fragmented rock material formed by volcanic eruption.
- Terpenes**—A complex variety of organic compounds found in many plant and animal materials. Most terpenes found in ocean water are presumed to have originated in the terrestrial environment, and thus have the potential for identifying marine waters that have been directly influenced by continental inputs.
- Terrane**—A fault-bound piece of the earth's crust with a geologic record of evolution that is clearly distinct from now adjacent pieces of crust.
- Terrigenous**—Derived from the land, especially by erosion.
- Thalweg**—The line joining the deepest points of a stream channel, often used as a synonym for the profile of a valley.
- Thermocline**—The region in a thermally stratified body of water in which the temperature decrease with depth is greater than that of the water above and below.
- Thirty-five hour filter**—A computational procedure for smoothing and removing high-frequency fluctuations in data. This filter is mainly used in physical oceanographic calculations to remove tidal energy; more than 99% of the amplitude of fluctuations of periods less than 25 hours is removed by the procedure.
- Thrust fault**—See fault.
- Tidal prism**—In an estuary, the volume of water between high and low water levels.
- Time series**—A series of measurements made at the same geographic area so that seasonal and longer time-scale trends can be resolved.
- Toothed whale**—Whales of the suborder Odontoceti; all of these animals (including porpoises and dolphins) have teeth instead of baleen, and have a single blowhole.
- Tower counts**—Fish counts made from a tower which permits the observer to look down into the target area.
- Trammel net**—A form of gill net consisting of two taut outer nets of large mesh and a larger slack middle net of finer mesh, all three being attached to each other at the head, foot and ends.
- Transfer efficiency**—The fraction of biomass actually used for growth by trophic level i as obtained from the trophic level just below it ($i-1$).
- Transition waters**—Ocean waters intermediate in character between two recognized water masses.
- Trench**—A long, narrow depression of the deep-sea floor having relatively steep sides; ocean trenches can be up to 11 km deep and are usually found at an active plate boundary where an oceanic lithospheric plate subducts.
- Triple junction**—The locus where three plate boundaries meet. Depending on the type of boundaries that meet, the triple junction is named accordingly (*e.g.*, a trench-ridge-transform triple junction).
- Trophic studies**—Investigations of food chain phenomena; that is, investigations of the relationships among predators and their prey and/or herbivores and the plants they utilize for nutrition.
- Trophodynamic modeling**—Modeling of an ecosystem based on transfer of energy (food) through the food chain.
- Try net**—A small trawl, about 4 to 5 m wide, with comparatively small meshes (< 5 cm).
- Tsunami**—A large sea wave caused by an earthquake or volcanic eruption.
- Tule goose**—*Anser albifrons gambelli*, a large subspecies of the white-fronted goose which nests on marshes in western Cook Inlet.
- Tunicates**—Soft-bodied animals belonging to the subphylum Urochordata, characterized by the presence of an enclosing mantle.
- U.S. Fishery Conservation Zone**—A zone contiguous with the territorial seas of the United States and extending seaward 200 nmi; see Magnuson Fishery Conservation and Management Act of 1976.
- Ultraplankton**—Plankton too small (< 5 microns) to be seen with ordinary microscopes.
- Ulvoid**—Characteristic of the green algal family Ulvaceae; most species have broadly expanded, membranous, green blades.

Upwelling—The replacement of surface water with deeper, cooler and usually more nutrient-rich water; can result from diverging ocean currents or decreased water level along the coast owing to wind shear; opposite of downwelling.

Variance—The square of the standard deviation from the mean value. For current velocity, one-half the variance equals the fluctuating or eddy kinetic energy per unit mass.

Verrucaria zone—The zone that commonly forms in the lower part of the supralittoral fringe and is distinguished by black crusts composed of blue-green algae, or by lichens of the *Verrucaria* type.

Vertical eddy diffusivities—The rate at which waters, or materials dissolved or suspended in them, are mixed with those at greater or shallower depths by diffusive processes.

Vertical stability—The resistance of a water column to mixing.

Volcanic front—A theoretical linear locus in a subduction zone drawn along strike, and seaward of, a volcanically active arc. In map view, it separates the areas with and without active volcanoes.

Voles—Small, mouse-like rodents (*e.g.*, *Microtus* spp.) having short limbs and a short tail.

Vorticity—A tendency for spin or shear in motion. Planetary vorticity exists because of the earth's deflective force; relative vorticity results from local shear or curvature in the flow. In oceanography, refers to the horizontal circulation of a fluid particle about a vertical axis.

Wadati-Benioff zone—The dipping zone of subcrustal earthquakes in a subduction zone which occurs in the cold and brittle stressed portions of a subducting lithospheric plate as it descends into the otherwise aseismic mantle.

Wandering tattler—A shorebird (*Heteroscelus incanus*) that nests in alpine tundra and winters along rocky shorelines.

Weir—A fence set in a stream or in a channel to capture fish.

Weir counts—Counts of migrating fish (*e.g.*, salmon) that have been caught in a weir.

Wetlands—An areas of low-lying land, inundated permanently or periodically by fresh- or saltwater.

Wind forcing—Various aspects of the wind field that produce effects in the ocean.

Year class—That part of a population that was produced during one year.

Zoogeographic affinity—A description of the geographical distribution of an animal.

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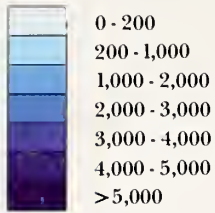
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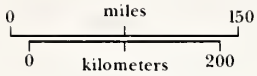
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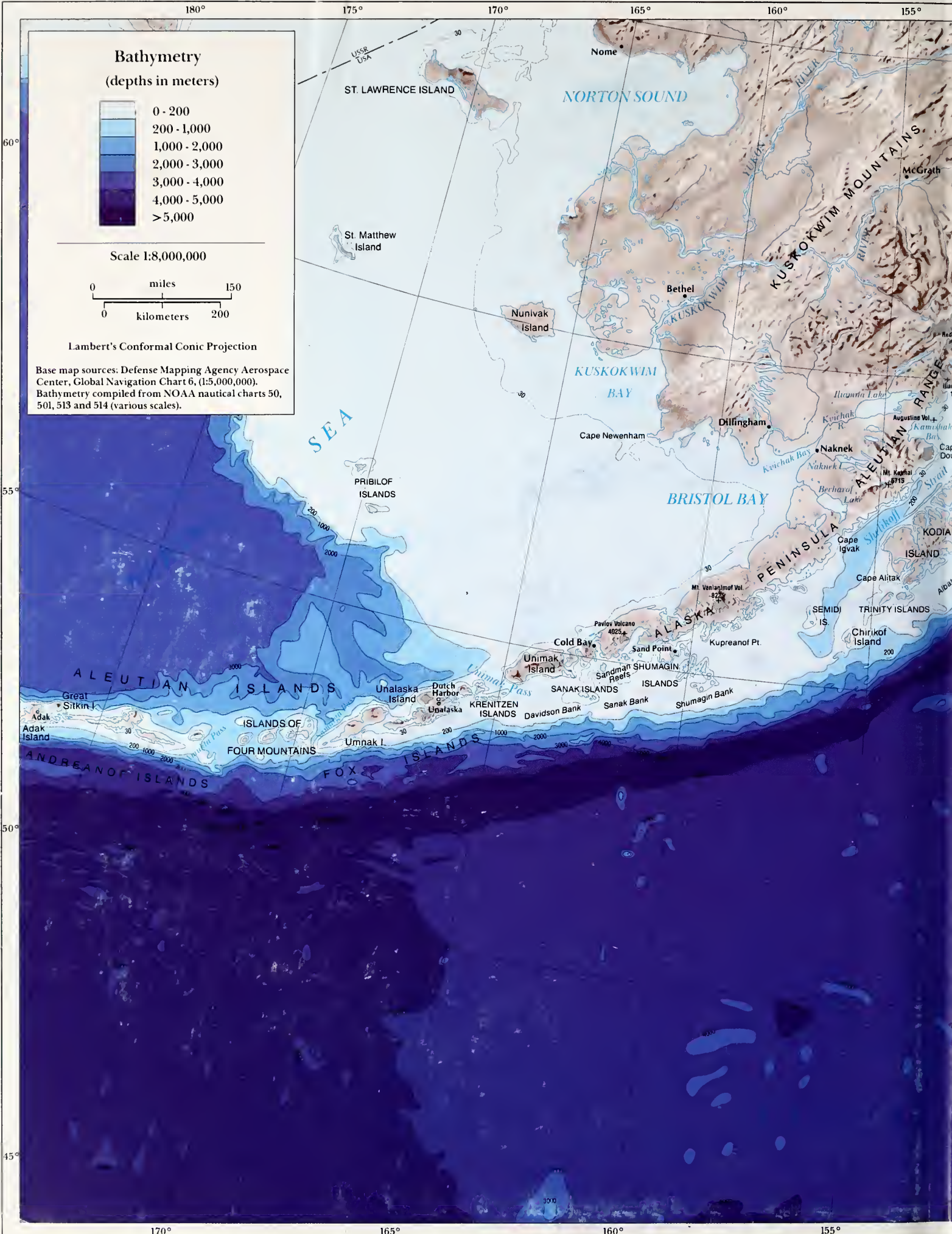


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