Environmental Assessment of the Alaskan Continental Shelf

Annual Reports of Principal Investigators for the year ending March 1977

Volume XVII. Hazards

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF INTERIOR
Bureau of Land Management

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Outer Continental Shelf Environmental Assessment Program

Boulder, Colorado

March 1977

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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VOLUME XVII

HAZARDS

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ANNUAL REPORT

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Marine environmental problems in the ice covered Beaufort Sea shelf and coastal regions

Principal Investigators:

Peter Barnes
Erk Reimnitz
David Drake

1 April 1977

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I. Summary of objectives, conclusions and implications with respect to OCS oil and gas development

Since 1970 we have been studying the marine geology and sedimentary processes of the arctic shelves of Alaska. The present investigation is an expansion and intensification of our earlier studies with emphasis on rates and processes. In particular we have concentrated on pehnomena involving ice and its unique influence on the shelf and inshore environment. The marine environment of the arctic shelf poses special problems to offshore development. Compared to processes related to cold temperatures and the predominant influence of sea ice-faulting, tectonic activity, and sea floor instability are environmentally of lower concern in the Beaufort Sea. Six years of study have provided a basic understanding of this unique marine geologic environment, however, many important aspects have yet to be addressed. For example the major processes involved in ice gouging of the sea floor are reasonably understood, including distribution, densities and gouge trends. Critical questions still remain as to rates of gouging, depths of reworking and the variability of gouge formation from season to season and year to year. It is now apparent that the interaction of the stamukhi with the continental margin plays an important part in the distribution and character of gouging, yet the time of formation and the year to year stability of the stamukhi zone is not presently known. Neither are its effect on oceanographic circulation, sediment disruption and dispersal, and the shelf profile understood.

Another area where we have poor understanding involves coastal zone processes. The spring (uliktuk) flooding of the sea ice with river water is reasonably well known as a phenomenon but the intensity of the associated processes of transport, scour and ice movement are not understood. Rates of coastal erosion are known to be significant, but the fate of these erosional products, their relationship to river input, and the growth and maintenance of the barrier islands needs to be assessed. Inside the 2 meter bench where ice rests on the bottom at the end of the winter, a unique sedimentary environment exists where tides and surges set up significant currents and cause vertical fluctuations in the ice cover. In addition, conductive heat transfer through the grounded ice makes this an area of differing permafrost character.

The second year of field work and subsequent laboratory and office work has resulted in the following tentative conclusions regarding the arctic nearshore environment.

Preliminary analysis of a series of 24 vibrocores taken in the nearshore area between the Sagvanirktok River and the Colville River show environments can be distinguished. Lagoonal and bay sediments are indistinctly laminated sandy silts and clays. Cores in the vicinity of the barrier islands are sands and gravels with an abundance of depositional sedimentary structures. Off the Colville delta layered sands, silts and peats are replaced seaward of about 5 m by disrupted or poorly laminated muds probably related to strudel and ice gouge reworking. Of significance to offshore development is the absence of gravels except in the immediate vicinity of the coastal bluffs and barrier islands.

Reexamination of two precisely controlled side-scan sonar survey lines first established in 1973 and subsequently resurveyed in 1975 and 1976 indicated that the inner shelf between 5 and 15 meters of water depth is reworked to depths averaging 30 cm in periods between 50 and 100 years.

Both the depth of gouge incision and width of gouges tends to increase offshore. Gouge trends appear to be consistent within any one year but show differences fron one year to another. Gouging is expected to be more intense further seaward within the stamukhi zone. Clearly the rates of gouge activity indicate these features will have to be considered for offshore installation, in particular pipelines, which will probably have to be protected from forces which can create gouges up to 2 meters on the inner shelf.

Detailed bathymetry in the vicinity of the new causeway and in the entrance channel to Prudhoe Bay show several significant changes. The Prudhoe Bay entrance channel is migrating shoreward at 1-2 meters per year and may be influenced by seasonal infilling and erosion resulting from channel restriction by ice growth. Coastal retreat in this area is also averaging 1-2 meters per year. It is apparent from this study that the construction of features like the new causeway will affect the patterns of erosion and deposition but to an unknown extent.

Surficial and cross-sectional observations of temperature, salinity and turbidity from several years of data indicate that central Harrison Bay may contain a slug of cold saline water related to the process of brine formation during the freezing of the two-meter seasonal ice cover. If this proves to be the case, then polutants entering this area may be entrained in an area of sluggish circulation and mixing.

Currents measured just west of the Sagavanirktok River in Stefansson Sound indicated a net drift of 3.75 cm/sec at 330° with a mean current speed of 12.78 cm/sec at 1 meter off the bottom. During the 53 day record in August and September of 1976, a warm brackish water mass was associated with easterly currents while colder more saline waters were found when westerly currents dominated the system.

A zone of grounded shear and pressure ridges - the stamukhi zone - develops each year between the moving polar pack ice and the stationary fast ice. The stamuhki zone, as mapped, essentially follows the 15-20 meter isobaths and is controlled by the coastal promontories and by offshore shoals. After the development of the innermost early winter stamukhi, additional stamukhi are formed seaward, generally in an accretionary manner. The existence of grounded ridges in a stamukhi zone acts to shield the inner shelf from ice forces. It is in these stamukhi that the energy of the winter Arctic Ocean is expended on the continents rather than in the swash zone of lower latitude shelves. The early winter zone of ice ridging will probably be the seaward limit of offshore development in the near future due to technological limitations of working in zones of intensive sea-ice ridging.

Sonographs obtained in the eastern Chukchi Sea reveal a character of ice gouged microrelief that is similar to the Beaufort Sea shelf. Ice gouging is extensive at least as far south as Cape Prince of Whales shoal and into water depths of at least 60 m, but is unevenly distributed. Highest densities of gouging (greater than 100 per km of track) occur in water depths between 21 and 40 meters. The maximum depth of gouge incision observed was 4.5 m. Repeated capture and holding of grounded ice masses on topographic highs, and sand wave fields, believed to be in equilibrium with existing current regimes, suggests that much of the ice gouged relief observed are contemporary features. Due to generally higher current velocities in the Chukchi Sea, development may prove more difficult here than it will be in the Beaufort Sea.

Examinations of shelled benthic organisms from the eastern Chukchi Sea has provided a base knowledge against which future changes can be assessed. The major controlling factors of species distribution are water depths and substrate texture. It is also apparent that ice gouging causes major disruptions in the benthic communities, and it is suggested that in areas of high ice gouge densities the faunas may be completely eliminated periodically.

Studies of suspended particulate matter during both the winter and summer show significant differences between the two seasons. In winter (March) low, oceanic, suspensate values contain less than 25% mineral matter, even in very shallow water. During summer(August, September), inner-shelf values of suspended matter are not especailly reflective of stream discharge, except in the vacinity of the Colville River, which apparently dominates the suspended particulate transport regime. By September it is difficult to observe any influence of rivers other than the Colville between the Canning River and Cape Halkett. The concentrations in summer are an order of magnitude higher(or more)than in winter, confiming that this is the season of maximum particulate transport.

Salinity measurements of sediment intersitial water indicates that either the sea bottom should be frozen to 7m depth in winter or that only those area shallower than 2m would be close to freezing, depending on the equation used. Thermoprobe temperature measurements did not confirm either of these equations, but show greatest seasonal fluctuations nearshore and a slight decrease in average bottom temperatures in an offshore direction.

A study of the bathymetry, geology, water characteristics of the Kogru River, a large elongate embayment of the coast, indicates that the origin of this admittedly lake-like feature may have been oversimplified in the past. For one, it is too deep and a morphologic misfit in comparison to the adjacent tundra. It does appear that the Kogru River area is near a significant facies change in the Pleistocene Gubic formation, and may mark the boundry between the redily available gravel to the east and a paucity to the west.

Diving observations of areas of sonograph anomalies called "funny bottom" led to some surprises. The marine encrusted boulder patch inside Karluk Island in Stefansson Sound is apparently a lag deposit from the Gubic formation which may correlate with the Flaxman boulders. Abundant marine growth and a lack of Sagavanirktok River sediments in this area is puzzeling. In another area of the lagoon, a dense field of polycheate worm tubes was responsible for "funny bottom" on the sonograph records. Observations in the channel east of Flaxman Island indicate a closed 10.5m actively deepening scour depression. A source for the strong currents at this depth and for observed ice gouges in the bottom of the depression is puzzeling.

II. Introduction

A. General nature and scope of study

Investigation of the marine geology and sedimentary processes of the continental shelf and shores of the Chukchi and Beaufort Seas in northern Alaska were initiated in 1970. Many aspects have been cooperative efforts with federal and state agencies and universities. The primary goal of the program has been to understand the processes that are unique to Arctic shelves and their sedimentary environment, where sea ice plays an important role. Our general objectives included: 1) a definition of the character of the bottom materials, including permafrost; 2) a study of the present sediment transport and depositional mechanisms; and 3) studies of the Holocene and Pleistocene geologic record.

B. Specific objectives

Many questions have been raised on the basis of our past investigations, and apparently hold the key to an understanding of the seasonal cycle in the marine environment. It is these tasks that we address in our current research.

1) Processes of ice gouging - in particular the repetitive rates of gouging and the extent to which it occurs outside the area of our past investigations. Repetitive side-scan sonar surveys with precise navigational control and direct diving observations will be used. For the outer shelf studies a manned submersible must be chartered.

2) Shelf sediment transport regime - including ice rafting, river effluents and reworking and resuspension of bottom materials by ice and benthos.

3) The fast-ice zone, and its influence on nearshore current circulation, bedforms, sediment transport, permafrost, and on river discharge.

4) The stamukhi between the coastal ice and the offshore pack ice, and its influence and/or relationship to a) bathymetry, b) thermal effects on the sea floor, c) ice gouging, d) winter current regime, e) tides, and f) sediment transport.

5) An estimation of coastal erosion and its relationship to the formation of offshore islands and the stability of the coastal marine environment.

6) Inner shelf oceanography, and its relationship to the sedimentary environment. This includes upwelling in the coastal zone, the dispersal of highly saline (60 ^{o}/oo) and cold (-5^{o}C) water generated in shallow embayments, lagoons, and river mouths during the winter, and possibility of anchor ice formation as a factor in the sedimentary environment.

7) A study of the apparent lack of deltaic sedimentation near river mouths in the Arctic, and the unique marine aspects of arctic rivers in general.

8) Outlining the Pleistocene stratigraphy and geologic history of the shelf from a combined analysis of available sediment and seismic data, drill hole data, and 2-m long vibrocorer samples.

9) Delineation of offshore sand and gravel resources on the inner shelf from a correlation of available seismic reflection records with permafrost drill hole data.

C. Relevance to problems of petroleum development

The character of the arctic continental shelf and coastal area, with its year round and seasonal sea ice and with its permafrost, faces the developer with many special problems. The interaction of the arctic shelf with the artic pack ice takes the form of ice gouging and the formation of a large stamukhi zone each winter.

Oil drilling and production during the next several years will probably not extend into the stamukhi zone seaward of the seasonal fast-ice zone. Of critical concern are the ice gouge and strudel scour effects on structures and pipelines. A similar emphasis has been taken by the Canadian Beaufort Sea Project in their more advanced state of knowledge and readiness to lease their outer continental shelf lands (Milne and Smiley, 1976). Any structure which is to be mated with the ocean floor requires data concerning the strength and character of the ocean floor. Furthermore, foundation materials in the form of gravels will be needed for work pads offshore. In addition, the offshore drilling operation may encounter permafrost which could be substantially altered during the process of pumping hot oil up to the sea floor or along the sea floor in gathering and transportation pipelines.

III. Current state of knowledge

The current state of general knowledge has been excellently summarized in the Arctic Institute of North America's 1974 publication: The Coast and Shelf of the Beaufort Sea. The bulk of background geologic material for the Alaskan Beaufort shelf have been summarized in articles by Reimnitz and Barnes, Naidu, Short, Walker and others, in this same volume. References to more recent material may be found in the Results and Discussion sections below and in the appended reports. The interested reader is directed to the comprehensive series of reports resulting from the Canadian Beaufort Sea Project.

Briefly, results to date have clearly established drifting ice as a major factor in the marine geologic and sedimentologic environment of arctic shelves (best summarized in Reimnitz and Barnes, 1974; Barnes and Reimnitz, 1974; and the 1976 Annual Report).

Major boundaries exist which are related to inner shelf sea ice zonation (Figs. 1a & b). Inside the two meter contour ice rests on the bottom at the end of the seasonal growth, and generally remains stable and undisturbed through the winter. Seaward from this bottom fast ice, a zone of relatively undisturbed ice up to 2 meters in thickness of floating fast ice extends offshore to where it meets the moving ice of the polar pack. At this juncture, shear and pressure ridges develop which become grounded forming the stamukhi zone. Each of these zones apparently has distinctive sedimentologic, permafrost, morphologic and ice gouge character.

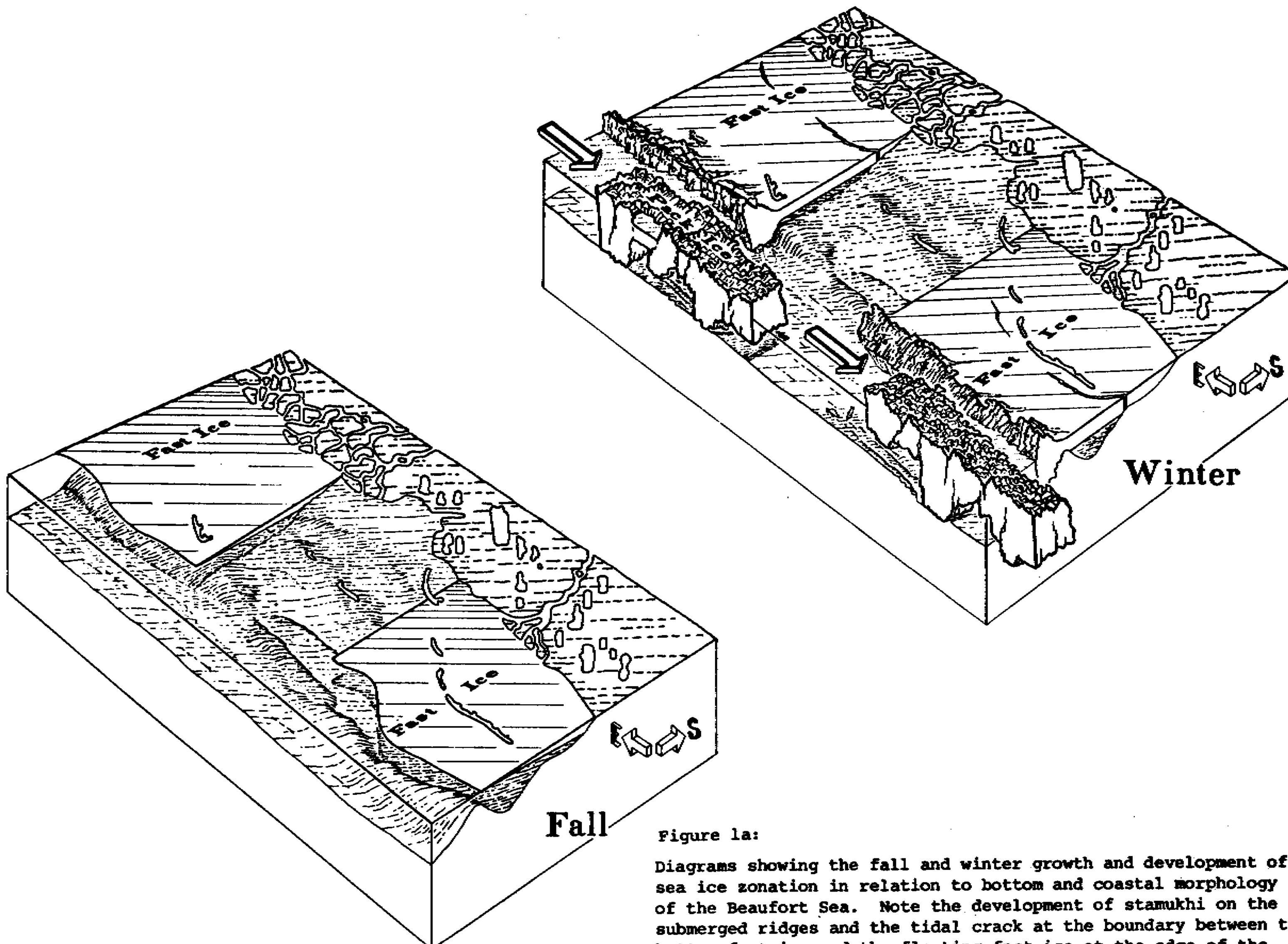

Figure 1a:

Diagrams showing the fall and winter growth and development of sea ice zonation in relation to bottom and coastal morphology of the Beaufort Sea. Note the development of stamukhi on the submerged ridges and the tidal crack at the boundary between the bottom fast ice and the floating fast ice at the edge of the 2 m bench. Drawings by Tau Rho Alpha.

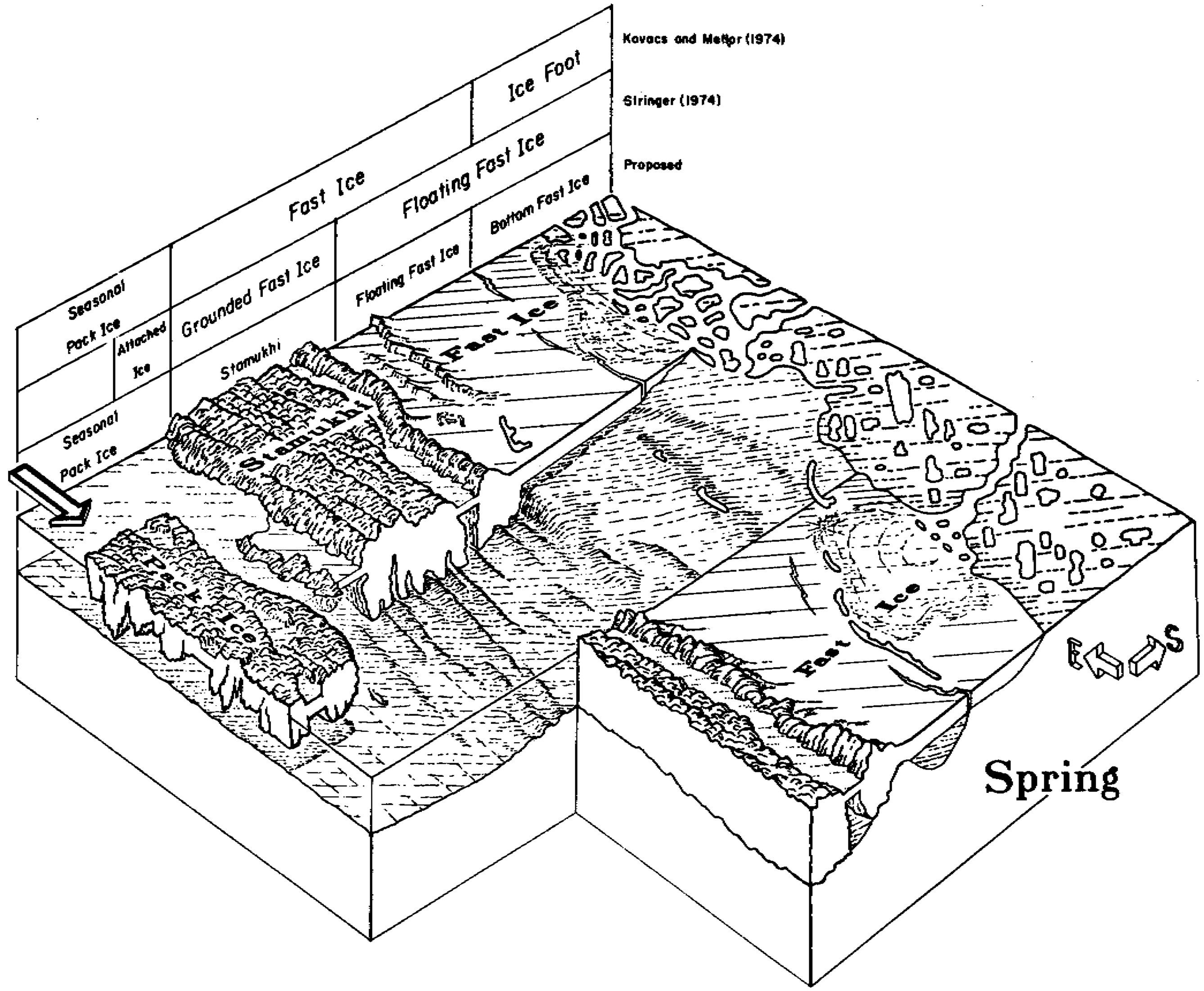

Figure 1b: Diagram of an idealized cross-section of the fully developed ice zonation along the Alaskan Beaufort Sea coast at the time of maximum ice growth in Spring. Drawings by Tau Rho Alpha.

A rudimentary framework for the processes and related sedimentologic record over the entire shelf width has been established. Utilizing this framework a conceptual model has been developed which relates the relative importance of ice and water as dynamic agents to depth and distance from the coast (Fig. 2). It is believed that the two areas of most intense sedimentologic activity occur along the coast and in the stamukhi zone between the coastal and ice and the artic pack ice. Ice deforms and stirs bottom sediments, permits conductive thermal transfer between the atmosphere and the seafloor where gounded, inhibits free discharge of river water during spring, resuspends sediments and transports sediments by bulldozing and rafting.

Processes related to the fast-ice flooding by rivers (uliktuk) during the spring river flood, have a strong influence on the inner shelf sedimentary environment of the Beaufort Sea shelf. It is during this event that winter accumulations of pollutants would be remobilized, transported, and redistributed. Drainage through strudel and subsequent underflow, scour and reshape the bottom in the region off arctic deltas. However, little sediment is initially carried in the uliktuk and conditions for ice rafting sediments great distances on the inner shelf are unfavorable. Seismic studies have shown only a thin layer of Holocene sediments manteling the entire width of the continental shelf, thus the scarcity of modern deltaic sediments near arctic river mouths remains an enigma. These same studies show that the Holocene sedimentary section is reworked by ice currents, and strudel scour obliterating most of the bedding features.

IV. Study Area

The primary study area includes the Beaufort Sea shelf between Barter Island on the east and Point Barrow on the west, with emphasis on an inshore segment between Flaxman Island and Cape Halkett. The width of the shelf in this area is variable, ranging from 55 km in the east to 110 km in the west. The adjacent land is a broad, flat coastal plain composed mainly of Quaternary deposits of silts, sands and gravels. In much of the area, the coast is being eroded by the sea at a rapid rate, forming coastal bluffs up to 6 m high. The line of bluffs is interrupted by low prograding mudflats at the mouths of major rivers. Much of the coast is marked by barrier islands at varying distances from the shore. Most of the islands are less than 3 m in elevation, narrow, and comprised of sand and gravel. Others are capped by tundra and are erosional remnants of the inundated coastal plain. Coast parallel shoals are also a feature of the inner shelf off many of the islands.

The shelf generally is rather flat and remains shallow for a considerable distance from shore. Off the Colville River the 2 m isobath is up to 12 km from shore. The shelf break lies at depths of 50 to 70 m. The shallowness of the shelf break and the presence of elevated Pleistocene beach lines suggests a broad regional uplift. The Holocene marine sediments on the inner shelf are generally 5 to 10 m thick on the inner shelf, although 'windows' of older sediment are exposed on the central and outer shelf and near river mouths.

Since oil drilling and production during the next several years probably will not extend seaward beyond the seasonal fast-ice zone, and since existing data in this area are sparse, our summer operations will focus on the shelf region from the stamukhi zone (10-30 m) shoreward to the coast.

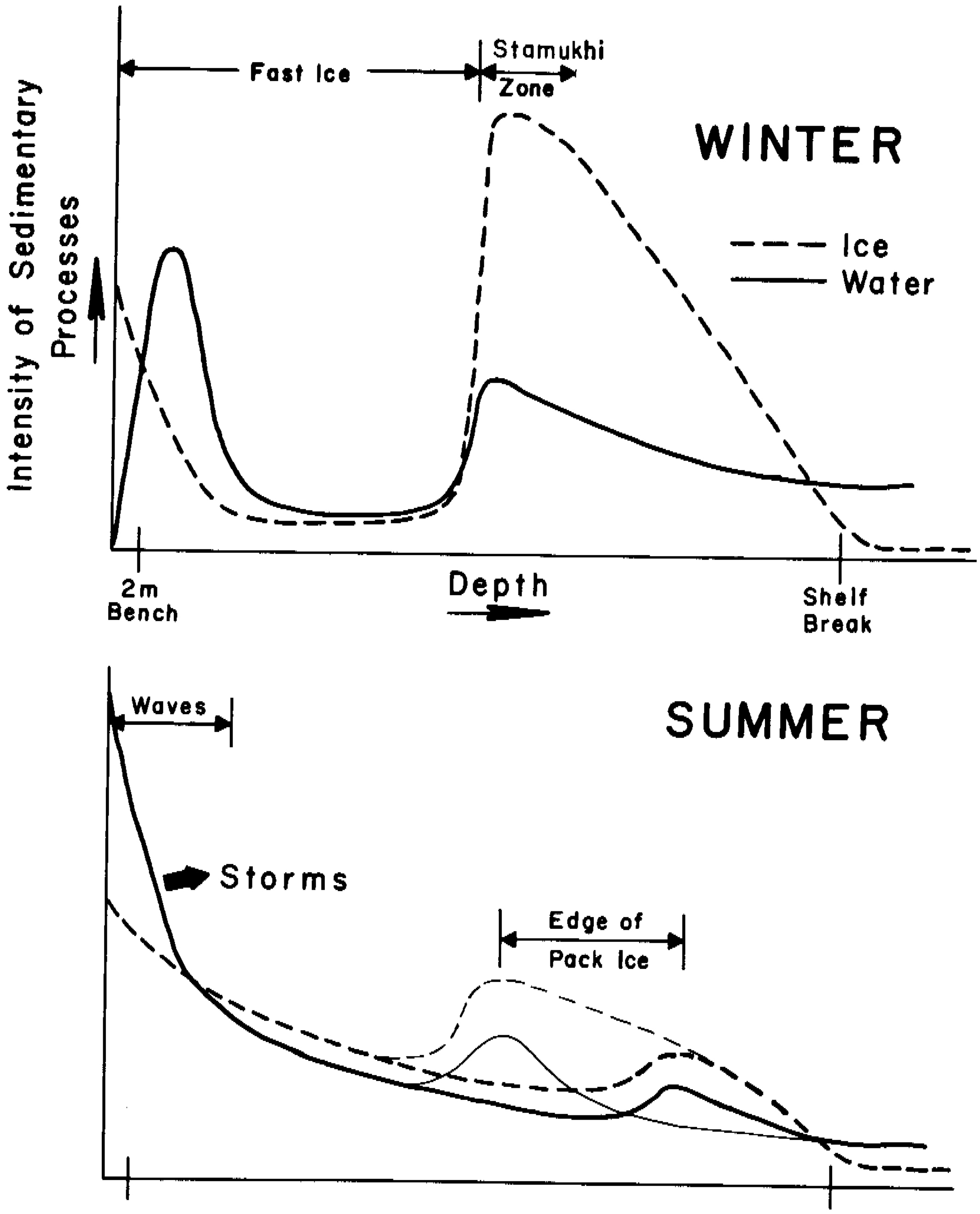

Figure 2: Conceptual model of the relative importance of ice and water as process agents on the bottom sediments of the arctic shelf off northern Alaska.

V. Sources, methods and rationale of data collection

Equipment operated routinely from the R/V KARLUK includes bottom sampling and coring gear, water salinity, -temperature, and -turbidity sensors, fathometers, a high and medium resolution seismic system, and a side-scan sonar. Precision navigation is maintained to 3 m accuracy with range-range system. Near Prudhoe Bay, a seismic refraction system has and will be used (in cooperation with the Institute of Geophysics of the University of Alaska) to search for high-velocity layers that may be related to permafrost.

Topical problems listed earlier will be investigated using current meters implanted on the inner shelf near Prudhoe and just off the Colville River. Special techniques include (a) repetitive sonar and fathometer surveys of ice gouges, (b) diving observations and bottom photography, (c) measurements of sediment thicknesses within ice gouges by combined use of narrow beam echo sounder, and (d) a near-bottom tow package incorporating sub-bottom profiler and television, (e) near surface stratigraphic studies using a vibrocorer capable of obtaining two meter long cores and (f) detailed surveys of bathymetry in river and lagoonal channels and in the vicinity of manmade structures. River delta sediments will also be examined with cores and sediment profiler. Coastal observations are planned of rates of bluff erosion and the distribution and elevation of storm surge strand lines.

The past and present status of data and product submission to NOAA-BLM-OCSEAP is given in the table on the following page.

VI,VII,VIII, Results, Discussion and Conclusions - (As attachments to report)

A. Salinity of intersititial water, sea floor temperature, and freezing points on the Beaufort Sea shelf, by Reimnitz, Barnes and Maurer.
B. Some coastal oceanographic observations, Beaufort Sea, Alaska, by Barnes, Reimnitz and Smith.
C. Current meter and water level observations in Stefansson Sound, summer, 1976, by Barnes, Reimnitz and McDowell.
D. Preliminary results of Kogru River studies, by Reimnitz, Maurer and Barnes.
E. Suspended matter in nearshore waters of the Beaufort Sea, by Drake.
F. Bathymetric and shoreline changes, northwestern Prudhoe Bay, Alaska, by Barnes, Reimnitz, Smith and Melchior.
G. Rates of ice gouging, 1975 to 1976, Beaufort Sea, Alaska, by Barnes, McDowell and Reimnitz.
H. Characteristics of ice gouging in the eastern Chukchi Sea, by Toimil.
I. Distribution of shelled benthic critters in the eastern Chukchi Sea by Mann.
J. Funny bottom diving observations, summer, 1976, by Reimnitz and Toimil.

IX Needs for further study -

The interdiciplinary meeting held in Barrow during February outlined the present needs for additional information. See Hopkins, 1977 and Aagaard, 1977.

R.U. 205 Barnes, Reimnitz, and Drake

Product Submission Status

X = data or information submitted
0-0-0 = work in progress or planned for this period

REPORTS TO NOAA-BLM

	Sept.1976	Dec.1975	Apr.1976	June 1976	Sept.1976	Dec.1976	Feb.1977	Apr.1977	June 1977	Sept.1977	Other Sources of Data
Data Products											
Non Digital											
- core descriptions									0-0-	0-0	
- acoustic profiles w/nav.			x		x			x	0-0-	0-0	(8)
Digital											
- water temperature/sal.				x	x			x			
- current meter			x					x			(2) submitted tapes to PMEL
- nephelometer				Lost	Equipment			x	0-0-	0-0	
Summary Products											
1. Ice gouge maps							x				(4,6)
2. Evaluation of ice hazards	x	x	x		x		x	x	0-0-	0-0	(5,6,7,10,11,12)
3. Offshore gravel resources					x		x		0-0-	0-0	(1)
4. Holocene Marine sediments		x				x	x	x	0-0-	0-0	(1,6,7)
5. Bottom currents and processes	x	x	x	x		x	x	x	0-0-	0-0	(1,4,7)
6. Sediment transport regime	x						x	x	0-0-	0-0	(1)
7. Interpretation of stamukhi							x				(6,10,11)
8. Coastal erosion and delta progradation			x	x	x		x	x	0-0-	0-0	(3,9)
Additional Information - submitted or available gratis from us											
1. Sediment distribution and character			x				x	x			(1)
2. Charts			x	x							
3. Oceanographic studies			x					x	0-0-	0-0	(2)
4. Engineering properties						x		x	0-0-	0-0	(1)
5. Chukchi Sea studies						x		x	0-0-	0-0	(13)
6. Fresh water resources			x								(3,12)

Note: Numbers under 'other' refer to reports listed on the following page.

REFERENCES

(1) Barnes, P. W., and Reimnitz, Erk, 1974, Sedimentary processes on arctic shelves off the northern coast of Alaska, in Reed and Sater, eds.: The Coast and Shelf of the Beaufort Sea, The Arctic Inst. of N. Am., Arlington, Va., p. 439-576.

(2) Barnes, P. W., and Garlow, R., 1975, Surface Current Observations-Beaufort Sea, 1972, U.S. Geological Survey Open-File Report-75-691 3 p. and map.

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(7) Grantz, Arthur, Barnes, P. W., Eittreim, S. L., Reimnitz, Erk, Scott, E. W., Smith, R. A., Stewart, George, and Toimil, L. J., 1977, Summary of the sediments, structural framework, petroleum potential, environmental conditions, and operational considerations of the United States Beaufort Sea, Alaska area: U.S. Geological Survey Open File Report 76-830, 32 p., 3 figs., 1 table.

(8) Reimnitz, 1977, High resolution seismic profiles, Beaufort Sea, 1975: U.S. Geological Survey Open File Report 76-747, 3 plates.

(9) Barnes, P. W., Reimnitz, Erk, Smith, Greg, Melchior, John, 1977; Bathymetric and shoreline changes, northwestern Prudhoe Bay, Alaska, U.S. Geol. Survey Open File, 8 p. and 4 figs, (in press).

(10) Reimnitz, Erk, Toimil, L. J., and Barnes, P. W., Arctic Continental Shelf Processes and Morphology Related to Sea Ice Zonation, Beaufort Sea, Alaska: AIDJEX Bull. (Arctic Ice Dynamics Joint Experiment, University of Washington) 36 p. and 20 illus. (in press).

(11) Reimnitz, Erk, Toimil, L. J., and Barnes, P. W., Stamukhi Zone Processes: Implications for developing the arctic offshore area; Offshore Tech. Conf., Houston, Texas, May 2-5, 1977 (OTC Proceedings Volume) (in press).

(12) Harden, Deborah, Barnes, P. W., and Reimnitz, Erk, 1977, Distribution and Character of Naleds in Northeastern Alaska: Arctic Bulletin U.S. Geol. Survey Open File Report 77-91, 20 p., 7 figs.

(13) Toimil, L. J. and Grantz, Arthur (1977), Origin of a Bergfield at Hanna Shoal, Northeastern Chukchi Sea, and its Influence on the Sedimentary Environment, AIDJEX Bull. No. 34, p. 1-42.

X. Summary of 4th Quarter Operations

A. Ship or Laboratory Activities

1. Ship or field trip schedule - Peter Barnes attended the Beaufort Sea synthesis meeting at Barrow on 7-11 February, 1977.

2. Personnel involved in project:

Peter Barnes	Project Chief - Geologist	U.S. Geological Survey, Office of Marine Geology
Erk Reimnitz	Principal Investigator-Geologist	" "
David Drake	" " "	" "
Larry Toimil	Co-Investigator-Geologist	" "
Doug Maurer	Physical Science Technician	" "
Dennis Mann	" " "	" "
David McDowell	" " "	" "

3. Methods

Because oil drilling and production in the next several years will likely not extend seaward of the seasonal fast-ice zone, nor be very far removed from existing north slope development, and because existing data is sparse, summer operations aboard the U.S.G.S. R/V KARLUK have been concentrated on the shelf shoreward of the winter shearzone (10-30 m water depths) between Cape Halkett and Flaxman Island. Data collected and systems routinely run during the summer included: bottom sediment samples obtained using a van Veen grab, underway sampler and an electrically powered vibrating corer; suspended sediment samples of surface waters; water salinity, temperature and turbidity measurements; bathymetry using both 30 and 200 kHz fathometers; sub-bottom profiles using 7 kHz and high resolution seismic reflection systems; underwater television observations; and side-scan sonar recording of seabed morphology. A range-range precision navigation system was utilized in detailed bathymetric and repetitive side-scan sonar surveys. Direct observations of the sea floor at a number of selected sites were carried out by divers using Scuba. The temporal and spatial scheme of samples obtained was often dictated by day-to-day changes in ice conditions, while others were selected on the basis of side-scan sonar, seismic profiles and underwater television observations.

4. Sample localities and tracklines:

Locations of data collections pertinent to this reporting period are given in the attachments to this annual report. That way they are near to the discussion!

5. Data collected or analyzed:

DATA TYPE	Km of record or number of samples analyzed
Side-scan sonar	60 km
Bathymetric profiles	80 km
High resolution seismic profiles	40 km
Bottom photographs	20
Current meter records	1

DATE TYPE Contd.

Temperature, salinity, turbidity, suspended sediment samples and observations	250
Samples of benthic fauna	9.0×10^3
Core radiographs	43

B. Summary of funds expended: (during last quarter)

NOAA-BLM-OCSEAP- $13,331

USGS funds- $ 5,279

TOTAL $18,610

XI. BIBLIOGRAPHY OF PERTINANT REPORTS PRODUCED SINCE 1976 ANNUL REPORT & REFERENCES.

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ATTACHMENT A

Salinity of interstitial water, seafloor temperatures, and freezing points on the Beaufort Sea shelf

E. Reimnitz, P. Barnes, and D. Maurer

A variety of data pertinent to offshore permafrost problems has been gathered by our Beaufort Sea project over the years. During the 1976 summer field season on the R/V Karluk we made a special effort to obtain reliable data on the salinity of interstitial waters in surficial sediments on the inner shelf. In this short report we are presenting the data so that others may use them.

Our main objectives in this study are to gain an understanding of the sedimentary environment on the arctic shelf. The shelf surface is affected and modified by waves, currents, strudel scour, ice gouging, small critters, and many other factors. Our thinking about bottom processes has been based on the assumption that the sediment surface is unfrozen (Reimnitz and Barnes, 1974). There is some justification for this assumption, at least for summer conditions. In our sampling, driving of thermoprobes, diving, and boat anchoring, etc., we apparently have never encountered ice bonded sediments, (except perhaps at several vibrocoring stations in very shallow water near the Colville River, as reported in our last quarterly report). Even during the driving of a thermoprobe in bottom-fast ice off the Kuparuk River, when some of the data reported on here was obtained, penetration was not prevented or retarded by ice bonding within the sediment, as far as we can determine.

If the surficial sediments did become ice bonded in certain environments during the peak of the winter, this would be very important for our studies of bottom processes, for biological studies of bottom dwelling organisms, and for offshore construction projects. Thus, our current observations indicate flow velocities high enough to activate certain bedforms, yet the bedforms may not form as the substrate is actually frozen. An example of potential environmental impact may be envisioned when contemplating the influence of a cold pipe line carrying natural gas buried on the shelf. If the shelf sediments are close to the freezing point, the cooling effect of such a pipe line may result in the freezing of overburden. Bedload transport of sediment might be affected such that individual grains in transit, temporarily contacting the bottom, may become adfrozen. This in turn could result in the formation of a sediment dike along the pipeline corridor.

In this report we planned to present the data without interpretation, but found it difficult to restrain our temptation to speculate a little on the data.

Interstitial salinities were determined from sediment samples obtained in 1972 and 1976. In 1972, deep water samples were obtained by gravity corers on the outer shelf (Table I, stations 1 -5). From these cores 10 cm sub-samples were taken, squeezed, and processed on board by diluting 40 ml of interstitial water to 200 ml, on which the conductivity was measured. The 1976 values (Table I, stations 6 - 21) were obtained from samples collected in plastic tubes by divers, stored at $0^{\circ}C$ until processing. Since these inner shelf samples were quite variable in composition, different methods had to be used for water extraction and salinity determination. Some of the samples were centrifuged for 15 minutes at 15,000 rpm. 20 µl of interstitial water were titrated against a Copenhagen Standard seawater of known chlorinity, using a London Co. Automatic Chloride Titrator. Values obtained by this method are given in Table I. The remainder of the samples required a dilution method to obtain an adequate volume for titration. A portion of the subsample was oven-dried at 110°C to determine moisture content. The remainder was diluted with 2 ml of distilled water, shaken on a wrist action shaker for 20 minutes, and centrifuged for 15 minutes at 2,000 rpm. Again, 20 µl were titrated using the automatic titrator. The values obtained by this technique are identified in Table I by asterisks (*). Chlorinities were converted to salinities using the relation

$$\text{Salinity } (^{o}/oo) = 0.03 + 1.805 \times \text{Chlorinity } (^{o}/oo).$$

Using the salinity values of interstitial water, we calculated the hypothetical freezing temperatures of the sediment from two different relationships:

1) Molochushkin and Gavuliev (1970) show that:

$$T_f = 28.4 \times (e^{0.022 \times S/W} - 1) - 5e^{-35 \times (W - 0.035)}$$

where T_f is the freezing temperature in degrees Centigrade, S is the salinity of pore water in parts per hundred, and W is the moisture content in "relative units" (from our translation). For the simple-minded geologist this relation has only one minor problem: it gives positive freezing temperatures. Changing the term

$$e^{0.022 \times S/W} \text{ to } e^{-0.022 \times S/W}$$

we obtain what appear to be reasonable values for freezing temperatures, and therefore assume a printing error was made. The equation now reads:

$$T_f = 28.4 \times (e^{-0.022 \times S/W} - 1) - 5e^{-35 \times (W - 0.035)}.$$

Only for the samples processed by the dilution method did we obtain values for moisture content (Table 1). In our calculations of freezing temperature we assumed a moisture content of 50% for the remaining samples. These appeared somewhat more moist than the former, which averaged between 35 and 40% in moisture content. Possible deviation of ± 20% in moisture content from the assumed 50% value would result in freezing point errors of ± 1.5°C for the most saline samples to ± 1.0°C for the least saline samples.

2) Osterkamp and Harrison (1976), working on offshore permafrost problems in the Prudhoe Bay area, in calculating the freezing point termperature of sediments, have used an equation that applies to seawater alone (Doherty and Kester, 1974), and disregards the fact that the deposit is a mixture of water and sediment:

$$T_f = -1.37 \times 10^{-2} - 5.199 \times 10^{-2} S - 7.225 \times 10^{-5} S^2.$$

For the soil samples they obtained, the error in this procedure was estimated to be less than 20%. Here S is salinity in parts per thousand.

A two-meter long thermoprobe, with thermistors, coupled to a Wheatstone Bridge, was used in two different field operations to measure sea-floor temperatures. Nine measuring stations occupied by the R/V LOON during the middle of September in 1971 are shown in Figure 1 (inset, black dots). The values obtained at these stations, shown in Figure 2, represent seafloor conditions close to the end of the open water period, probably slightly past the time when the sea floor is the warmest. The measurements around the mouth of the Kuparuk River were made in late May, 1972, using the sea ice as a base of operations. These values represent temperature conditions just prior to river flooding of the sea ice, shortly after the temperature-low of the winter. Thus, the temperature data shown in Figure 2 does not represent the extremes encountered from winter's low to summer's peak. These values are plotted with the respective station locations in Figure 1. The sediment surface temperatures were extrapolated and the results are shown in Table II.

Speculating on the implications of the presented data we sketched Figure 3, even though data scarcity and skepticism should have prevented this. We reasoned that the average annual temperature and environmental conditions for the thermoprobe stations off the Kuparuk River are rather similar to those in the Prudhoe Bay vicinity, occupied at a different time of the year. We therefore sketched a hypothetical cross section extending from near the coast across a shallow lagoon or bay, a sill with a depth less than the maximum fast ice thickness (approx. 2 m), and to the open ocean (Fig. 3). On this figure winter and summer bottom temperatures measured in the very shallow lagoon, in the deepest part of the lagoon, at the shallow sill, and at several water depths offshore are shown. Note that no values are available for the shallow sill during winter conditions. In the deep part of Prudhoe Bay and near the sill the summer temperatures show a considerable range of values, and these are shown as vertical bars in Figure 3. Also shown in Figure 3 are the calculated freezing temperatures for the seabed calculated from our data on salinity of interstitial waters and moisture content, using the two different equations.

Using the equation for the freezing point of seawater (Osterkamp and Harrison, 1976) we find that the seabed from shore to a water depth of about 7 m should become ice-bonded during the winter. This equation therefore probably should not be used. The equation from Molochushkin and Gavuliev (1970) shows that only those areas shallower than 2 m of water depth are close to the freezing point during the winter.

Plans are being made to obtain more of this type of data during the coming field season.

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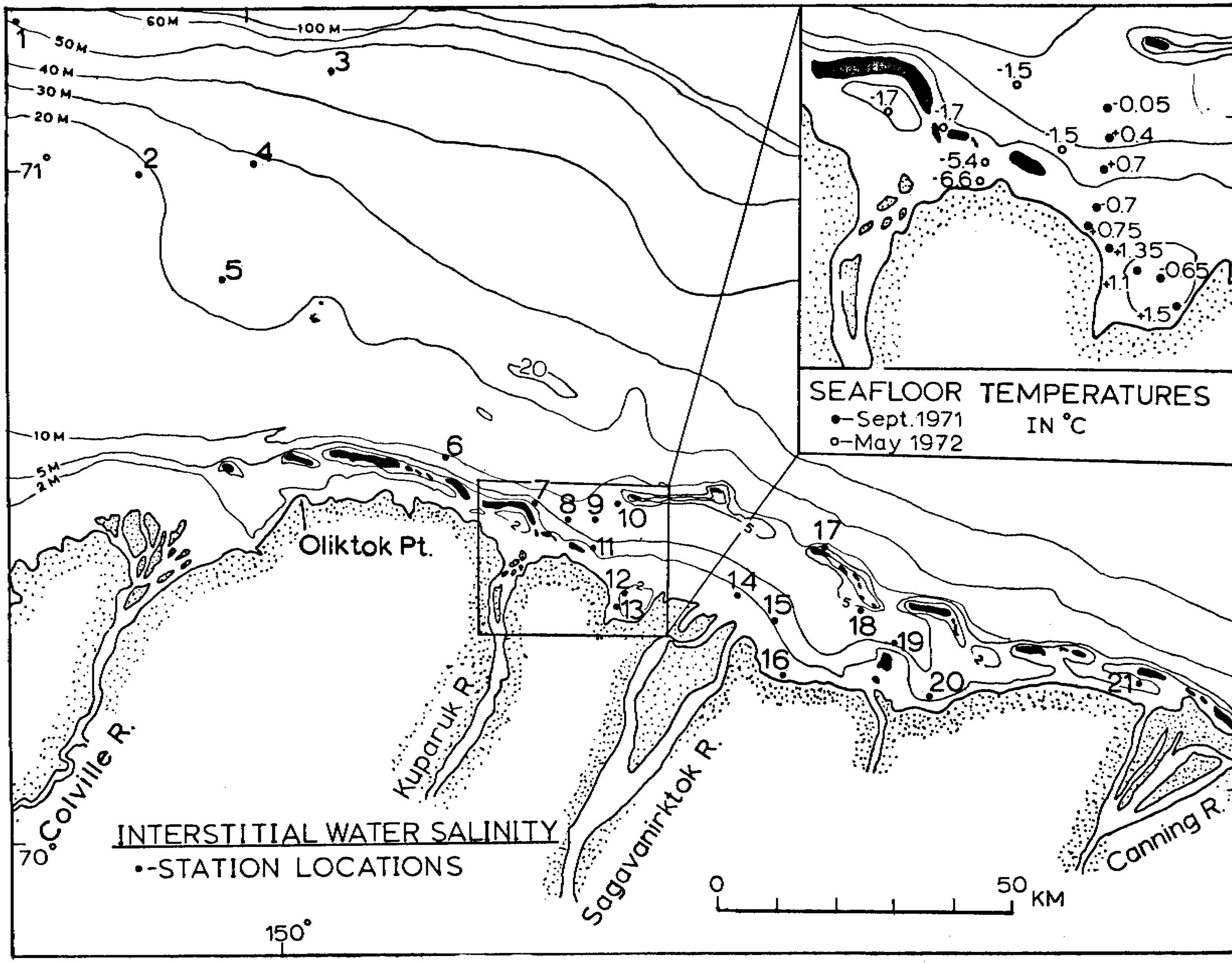

Figure 1. Location map for stations at which the salinity of interstitial waters in bottom sediments were determined, and extrapolated seabed temperatures at the thermoprobe stations (Inset).

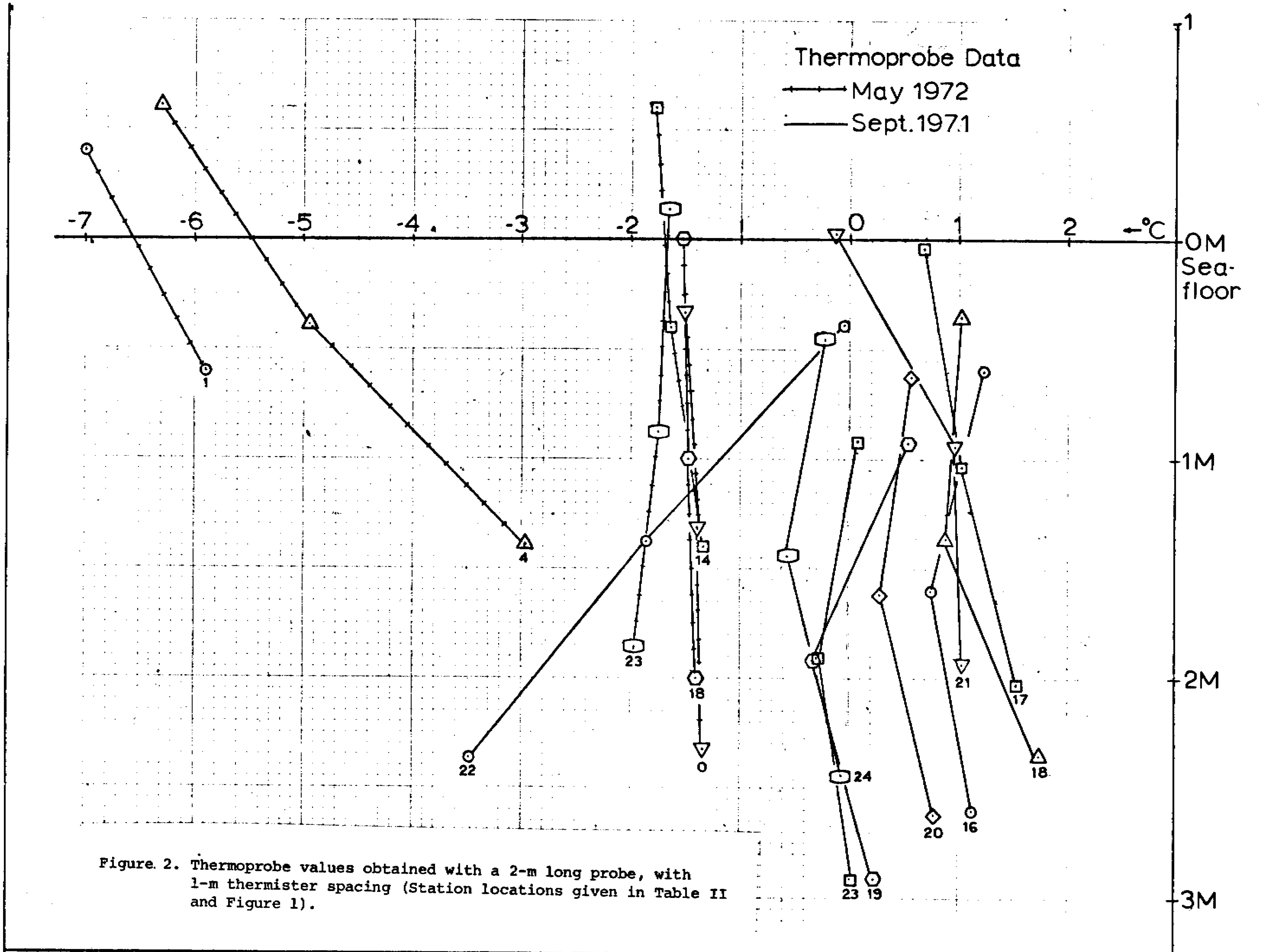

Figure. 2. Thermoprobe values obtained with a 2-m long probe, with 1-m thermister spacing (Station locations given in Table II and Figure 1).

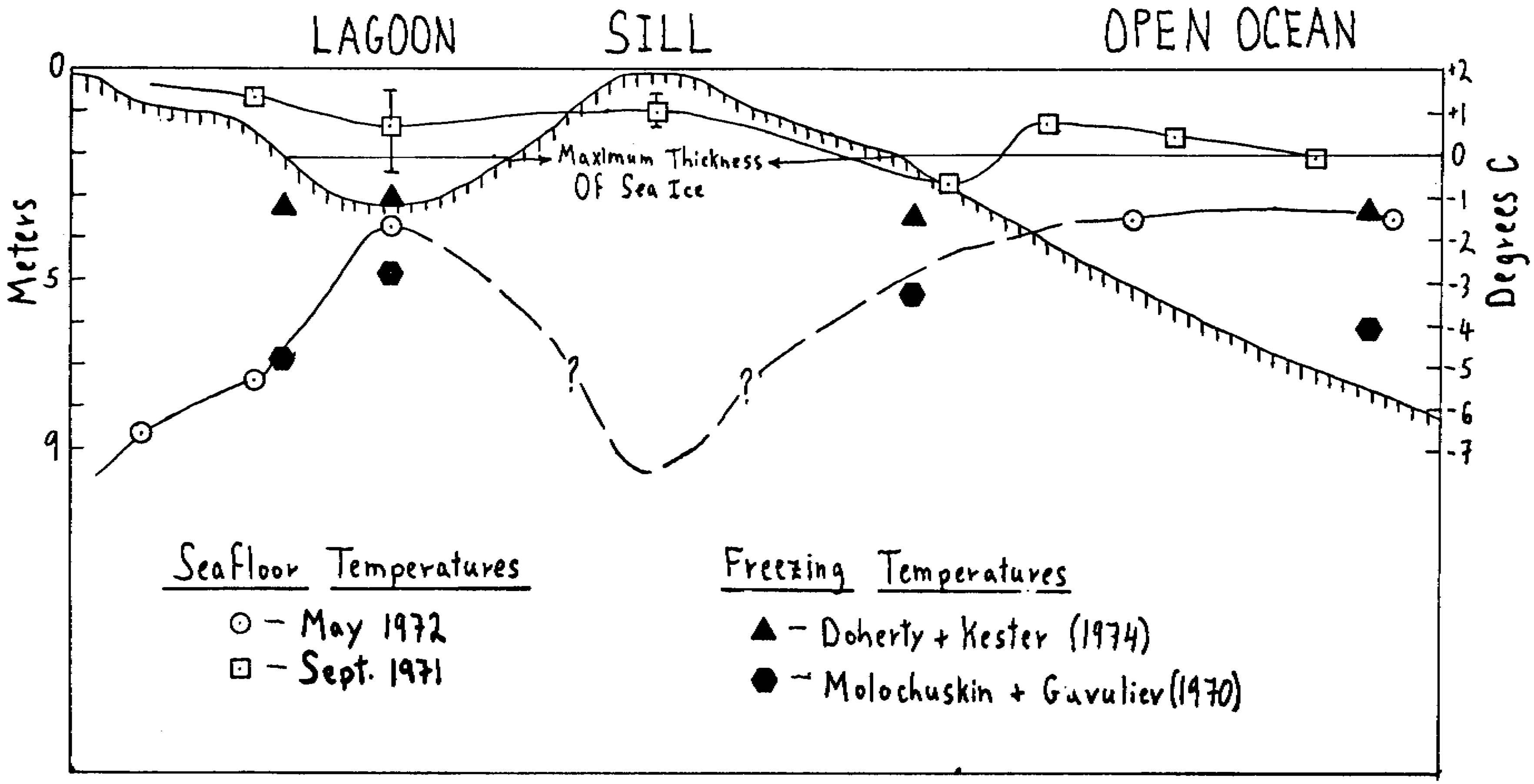

Figure 3. Hypothetical seafloor profile extending from beach through a lagoon or bay, across a shallow sill to the open ocean. Representative extrapolated bottom temperature values during summer and winter conditions and calculated seabed freezing temperatures from two different equations.

TABLE I

FREEZING TEMPERATURE OF BOTTOM SEDIMENTS

' - Conductivity Method
* - Dilution Method
" - Centrifuge Method

1. Molochushin & Gauvliev (1970)
2. Doherty & Kester (1974)
#-Assumed Moisture Content = 50% dry weight.

Station #	Location	Water Depth (M)	Depth of Sample below Sediment Surface (CM)	Interstitial Salinity (0/00)	Water Content 0/0	T_F^1 (°C)	T_F^2 (°C)	Sediment Description
1	151°00.0'W 71°12.2'N	53	2.5 - 12.5	38.0'		#-4.37	-2.09	Sandy Mud
			12.5 - 22.5	37.7'		#-4.34	-2.07	
			22.5 - 32.5	33.4'		#-3.88	-1.95	
			32.5 - 42.5	32.9'		#-3.83	-1.79	
			42.5 - 52.5	33.6'		#-3.90	-1.84	
			72.5 - 82.5	32.8'		#-3.82	-1.80	
2	150°58.0'W 70°58.8'N	19	12.5 - 22.5	24.4'		#-2.89	-1.32	Stiff clay with Sand Pockets
3	149°37.1'W 71°07.8'N	46	0 - 10	33.8'		#-3.92	-1.85	Mud with Fine Sand Patches - Scattered pebbles
			10 - 20	39.9'		#-4.57	-2.21	
			20 - 30	32.5'		#-3.78	-1.78	
4	150°00.0'W 71°00.0'N	28	0 - 10	25.9'		#-3.06	-1.41	Oozey mud
			10 - 20	33.0'		#-3.84	-1.81	Very stiff - fine-grained sandy mud
			20 - 30	33.3'		#-3.87	-1.82	
5	150°00.0'W 71°52.5'N	24	0 - 10	33.1'		#-3.85	-1.81	Fine mud grading into very sticky mud with very fine to fine clean dark sand at bottom
			10 - 20	33.3'		-3.87	-1.82	
			20 - 30	33.3'		-3.87	-1.82	
6	149°11.0'W 70°33.2'N	11.5	15	26.5*	21.99	-6.61	-1.44	Very clean medium grained sand
7	148°47.2'W 70°28.4'N	4.5	10	20.8*	26.35	-4.50	-1.11	Muddy, gravelly sand with sub-rounded granules
8	148°37.5'W 70°26.9'N	6.4	5	21.3*	74.83	-1.68	-1.13	Grey Mud
			15	26.8*	36.93	-4.19	-1.46	Stiff, very fine sandy mud
			-	24.3*	36.89	-3.83	-1.32	Dark grey mud
9	148°30.5'W 70°26.9'N	8.5	6.5	24.7*	35.27	-4.06	-1.34	Fine grained muddy sand
10	148°24.0'W 70°28.1'N	8.5	-	22.1*	40.59	-3.21	-1.20	Fine-grained muddy sand with wood fragments
11	148°31.5'W 70°24.2'N	3.0	15	27.9		#-3.28	-1.52	Fine-grained muddy sand
12	148°22.5'W 70°20.2'N	2.0	-	24.0"		#-2.80	-1.30	Very fine-grained muddy sand
			-	18.9*	40.79	-2.85	-1.05	Light grey very fine muddy sand
13	148°25.3'W 70°19.0'N	2.0	-	34.7*	41.71	-4.75	-1.91	Light grey very fine muddy sand
			-	24.4*	74.45	-1.98	-1.28	Grey m[illegible]d
14	147°51.5'W 70°19.5'N	2.5	14	18.9*	24.36	-4.46	-1.[illegible]3	Clean fine sand
15	147°42.8'W 70°17.2'N	3.0	16	25.5"		#-3.01	-1.39	Medium grained Muddy Sand with shell fragments
16	147°41.0'W 70°12.8'N	1.6	5	18.8"		#-2.25	-1.02	Muddy fine grained sand
			20	27.3"		#-3.21	-1.43	Muddy very fine-grained sand
17	147°28.7'W 70°23.8'N	1.5	10	22.3"		#-2.65	-1.21	Clean medium-grained sand
18	147°18.7'W 70°18.2'N	6.0	14	30.2"		#-3.53	-1.65	Grey mud
19	147°10.5'W 70°14.7'N	2.5	5	24.9*	25.66	-5.46	-1.35	Fine-grained muddy sand
20	147°01.0'W 70°10.3'N	4.5	17	29.4"		#-3.45	-1.60	Dark grey fine sandy mud
21	146°03.4'W 70°10.8'N	2.5	14	23.7"		#-2.81	-1.29	Medium to coarse-grained muddy sand

TABLE II

Thermoprobe Stations:

*May, 1972

'Sept., 1971

Station	Location	(M)Water Depth	(°C)Sea Floor Temperature
0*	70°25.0'N 148°30.8'W	5.5	-1.5
1*	70°23.8'N 148°41.0'W	1.0	-6.6
4*	70°24.4'N 148°40.5'W	1.4	-5.4
14*	70°25.9'N 148°45.3'W	3.2	-1.7
18*	70°27.4'N 148°34.0'W	5.1	-1.5
23*	70°26.6'N 148°50.2'W	1.8	-1.7
16'	70°18.2'N 148°19.0'W	3.2	+1.5
17'	70°19.2'N 148°20.5'W	3.2	-0.65
18'	70°19.9'N 148°23.0'W	2.7	+1.1
19'	70°20.6'N 148°26.0'W	1.5	+1.35
20'	70°21.6'N 148°28.5'W	1.7	+0.75
21'	70°22.4'N 148°27.6'W	2.6	-0.7
22'	70°24.7'N 148°26.0'W	4.1	+0.7
23'	70°25.0'N 148°25.1'W	5.5	+0.4
24'	70°26.1'N 148°25.1'W	6.8	-0.05

ATTACHMENT B

Some Coastal Oceanographic Observations -- Beaufort Sea, Alaska

Peter Barnes, Erk Reimnitz, Greg Smith, U.S. Geological Survey, Menlo Park.

INTRODUCTION

The coastal oceanography of the Beaufort Sea (Fig. 1) is poorly known. Earlier studies have either been very local or of short time span (Kinney, et al., 1972; Wisemann and others, 1973; Walker, 1974). Others have focused on the outer portion of the continental shelf (Hufford, 1974; Mountain, 1974). The studies of the outer shelf and Canada Basin have documented a generally westward movement of water on the outer shelf during the open water season (Coachman and Aagaard, 1974; Mountain, 1974). But this westerly drift is often complicated by an easterly intrusion of Bering Sea water in the upper 50 m along the shelf break (Mountain, 1974; Hufford, 1973).

Inshore studies indicate that the open water circulation is closely correlated with wind speed and direction (Dygas, 1974; Wisemann and others, 1973) but is generally westerly under a dominance of easterly winds. Coastal and river sediment plumes on Landsat imagery show a dominance of westerly displacements for all of the north coast of Alaska (Barnes & Reimnitz, 1974). Winter circulation is virtually unknown for the inner shelf, although limited data from late spring and early summer show a weak sub-ice westerly drift parallel to the coast (USGS unpublished data).

The seasonal formation of about two meters of ice occuring from September through May, has a profound effect on the inshore temperature and salinity structure. During freezing approximately 80-85% of the solutes are excluded, thereby increasing the salinity and density of the subjacent waters. This effect is most noticeable in shallow waters, especially in isolated and semi-isolated bays and lagoons, where winter salinities are usually above 35 ‰

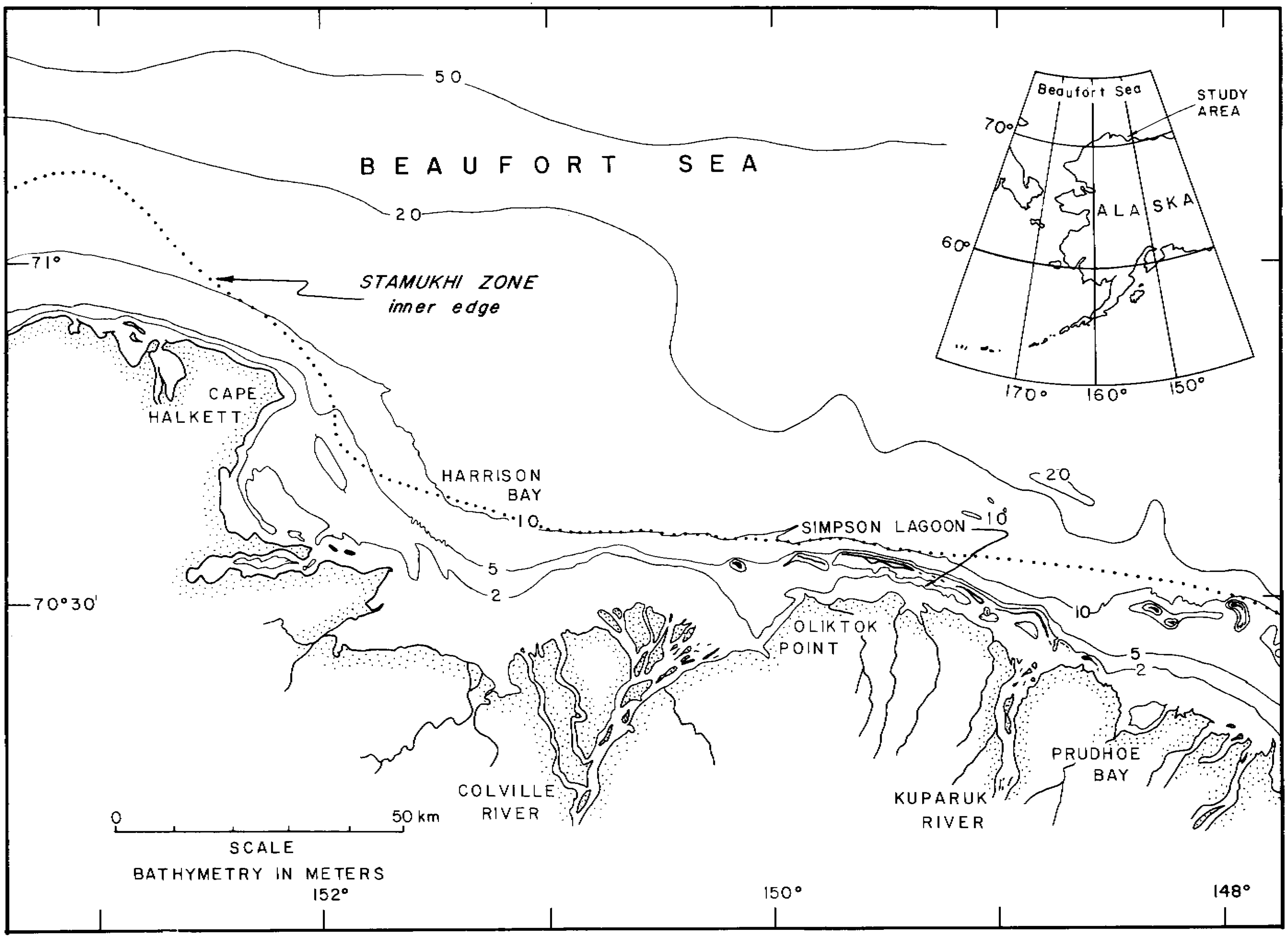

Figure 1. Location map showing areas discussed in the text. In Harrison Bay bottom fast ice extends out to the two meter isobath, floating fast ice extends from the two meter isobath to the first set of grounded ice ridges which mark the inner edge of the stamukhi zone.

and can commonly rise above 50 ‰ (Schell, 1974). The low tidal range of 10-15 cm allows for only minimal volume changes for flushing and mixing the hypersaline waters with the open ocean.

The ice zonation and character on the inner shelf area has been described in detail by Reimnitz and others (1976). Briefly, inshore of the 2 m isobath ice rests on the bottom at the end of the season of ice growth (Fig. 1). Seaward from this bottom-fast ice zone is a zone of floating fast ice up to two meters thick with inclusions of remnants of older ice. Between the 10 and 20 m isobath, interaction of the moving polar pack and the fast ice form the highly deformed ridges of the stamukhi zone. Many ice keels in this zone are in contact with the bottom and may form a partial barrier to the onshore--offshore circulation of water.

In spring, river flow is initiated before the melting and breakup of the fast ice. This fresh water flows over a bottom-fast ice and drains through strudel in the floating fast ice, forming a fresh water layer (Walker, 1974, Reimnitz and others, 1974). As melting proceeds along delta fronts much of the fresh water influx is impounded on the surface by the receding ice front. The bulk of the fresh water input from rivers occurs during this time, prior to the period of open water mixing conditions later in the summer season.

During our geological studies of the inner Beaufort Sea shelf, we have routinely observed temperature, salinity, water turbidity and occasional surface currents. Coverage in two climatically different years, 1972 and 1975, was sufficient in the Harrison Bay area to allow a comparison study. Herein we report the results of these data and speculate on the factors controlling the seasonal and yearly differences in the hydrologic regime of an ice-covered shelf.

Water Characteristics

Three primary sources of surface water on the shelf of the Beaufort Sea during the open water season from mid-July to mid-September can be identified by their temperature, salinity, and turbidity characteristics: river water, sea-ice melt water and oceanic shelf water (Barnes & Reimnitz, 1973; Hufford and Bowman, 1974).

From June to early September river water is distinguishable as warmer water (1-11°C) of low to brackish salinity (0-10‰) with significant quantities of suspended sediment and lower transmissivity values (<15α light attenuation coefficient). The initial river floods supply the bulk of the annual water and sediment discharge (Arnborg & Walker, 1962). This occurs in late May and early June, prior to the melting and breakup of the sea ice. The ultimate fate of the water and sediments supplied to the shelf at this time are presently unknown. In part, the initial flood mixes with the highly saline brine remaining from sea ice freezing in the coastal lagoons and lower sections of the deltas (Schell, 1974; Walker, 1974). Subsequent river flow also mixes in part with the sea ice melt waters immediately adjacent to the delta front and in part with the sub-ice shelf waters.

As the sea ice recedes, a second identifiable water type develops from ice melt offshore. This water is of moderate salinity (5-15‰) cold (0-2°C), has little suspended material, and therefore is characterized by the high light transmissivities (Barnes, 1974; Hufford et al., 1974). The melt water abundance and dispersion . is strongly dependent on seasonal ice distribution and wind regime. Winds act to destroy the density stratification in the surface waters, obliterating the characteristics of this water type. In 1975 an abundance of ice close inshore, aided by restricted wind mixing, resulted in greater amounts of surficial ice melt water than in 1972.

Hufford and others (1974) report mixing processes form a summer surface layer which is stable due to higher surface temperatures and lower salinity thereby decreasing the water density. This stable layer tends to be maintained due to the low wind velocities rarely over 20 knots) which characterize the open water season.

The third water type, Arctic Surface Water (Hufford and others, 1974), acts as the background influence on the other local water types. Arctic Surface Water of the inner shelf is cold (-1 to 3°C) with salinities of 27-30 ‰, depending on the degree of mixing with river effluent and ice melt waters.

Below the summer surface layer a cold (-1.1 to -1.5°C), saline (30.1-32.2 ‰) layer 5 - 10 m thick is commonly found at depths of 15 to 40 m, east of Prudhoe Bay (Hufford and others, 1974). As winter cooling and convection is more intense than summer heating and mixing, this cold water is presumed to be the remnant of the winter convective processes. A body of water with similar temperature and salinity characteristics occurs in shallow (< 10 m) water of Harrison Bay (this Report).

Methods

Surface temperature and salinity observations were made with a conductivity cell modified for negative temperatures encountered in Arctic use. Measurements of water clarity were obtained routinely from a 10 cm pathlength transmissometer during underway geophysical studies in 1971, 1972, 1973 and 1975. Temperatures are believed to be accurate to ±0.5°C salinities to ±0.5‰, and transmissivities to ±2%. Early data were obtained from the R/V LOON and R/V NATCHIK, the 1975 data from the R/V KARLUK. Repetitive coverage of the inner shelf in the vicinity of Oliktok Point during 1972 and 1975 by these three vessels was sufficiently dense for us to make a multiyear comparison of the water structure in this area. Landsat imagery is used to correlate our water data with surface water character elsewhere on the inner shelf during the open water period of 1972.

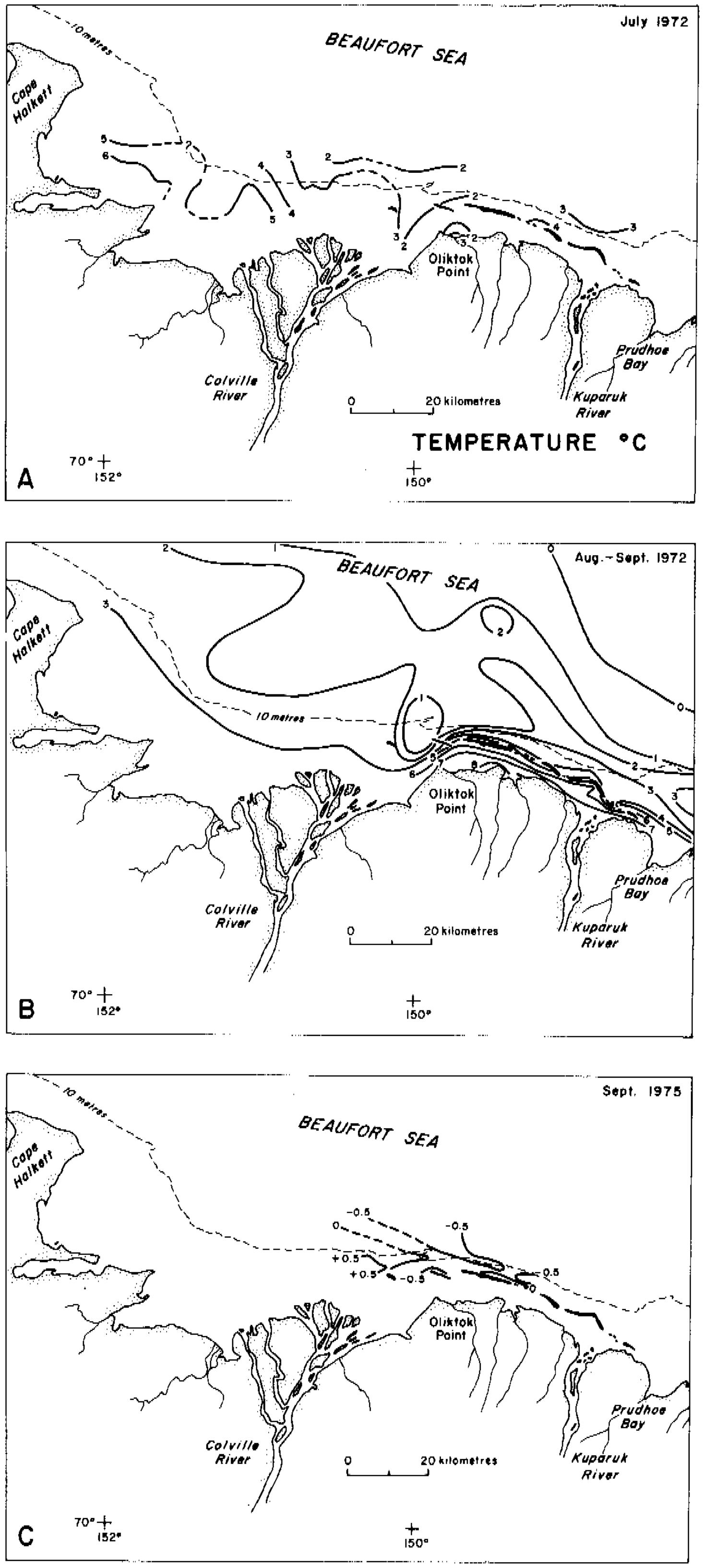

Figure 2. Distribution of surface temperature values during early summer, 1972(A); late summer, 1972 (B); and late summer, 1975(C). Contour interval; 1972-1°C; 1975-0.5°C.

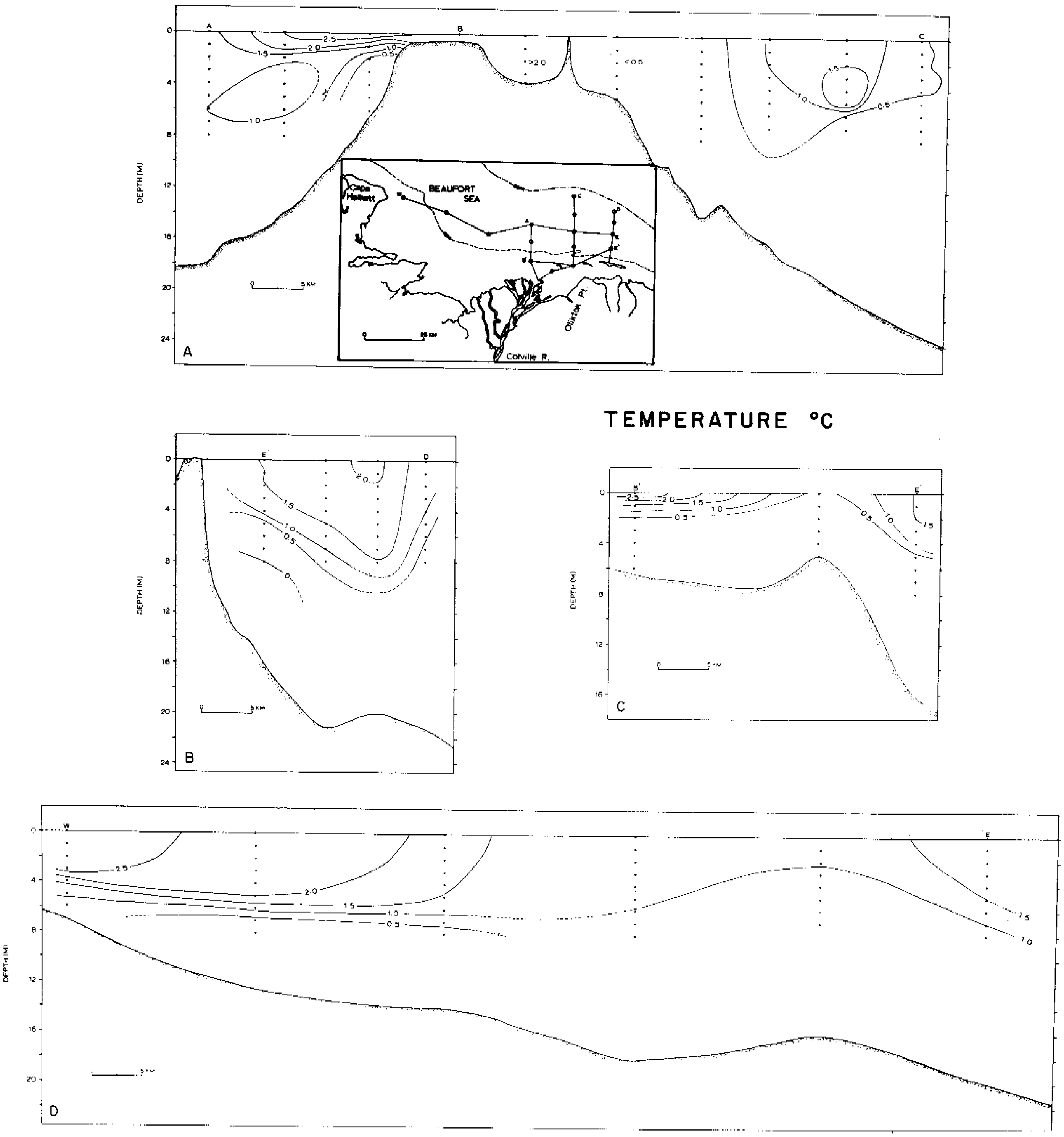

Figure 3. Vertical distribution of temperature in the Harrison bay area in late August and early September, 1972. Location of the four profiles is shown in the inset (A). Contoured at 0.5°C interval. Surface values are contoured in Figure 2B.

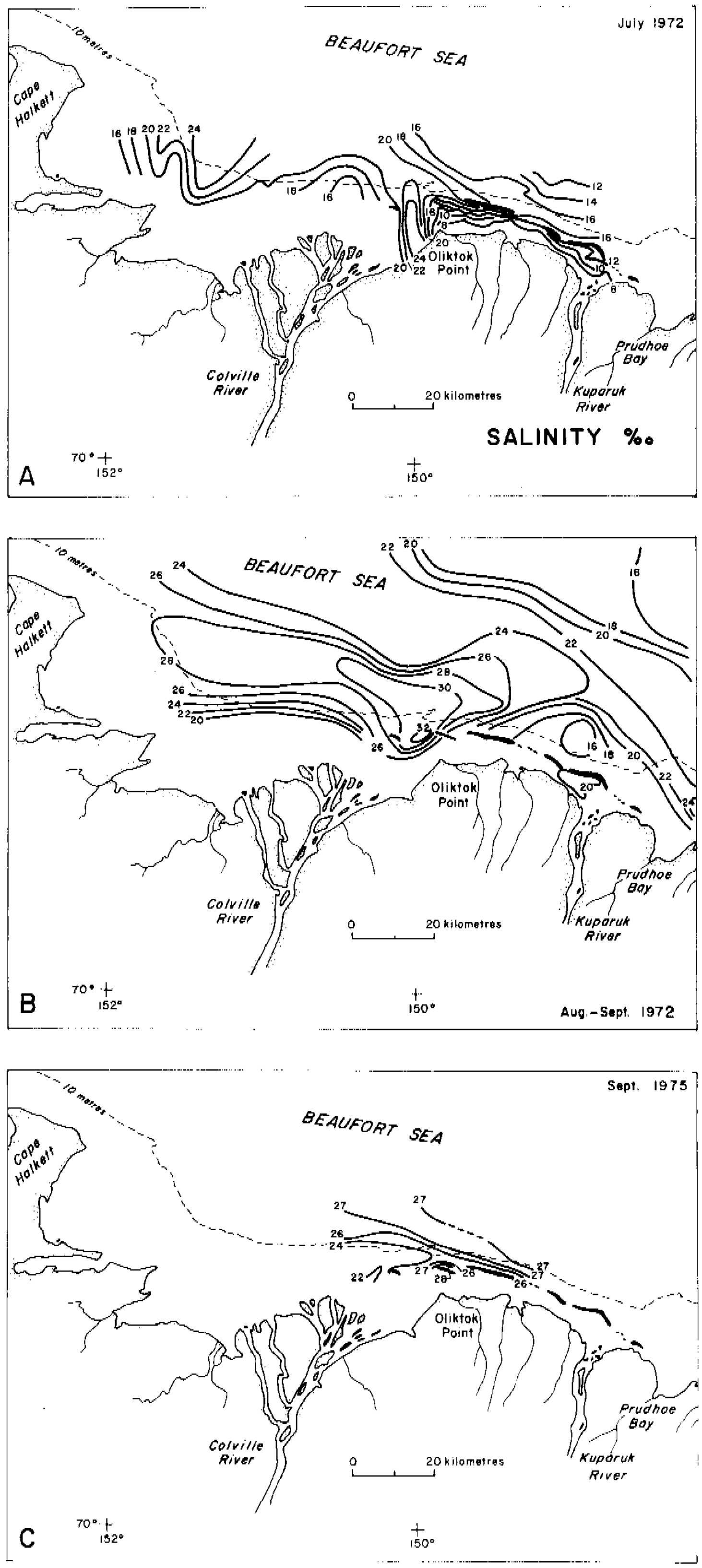

Figure 4. Surface distribution of salinity values during early summer, 1972(A); late summer, 1972(B), and late summer, 1975(C). Contour interval 2^{o}/oo. Note the occurence of high salinity surface water off Oliktok during all three surveys - 24^{o}/oo water in July, 1972; 32^{o}/oo water in August and September, 1972; and 28^{o}/oo water in September, 1975.

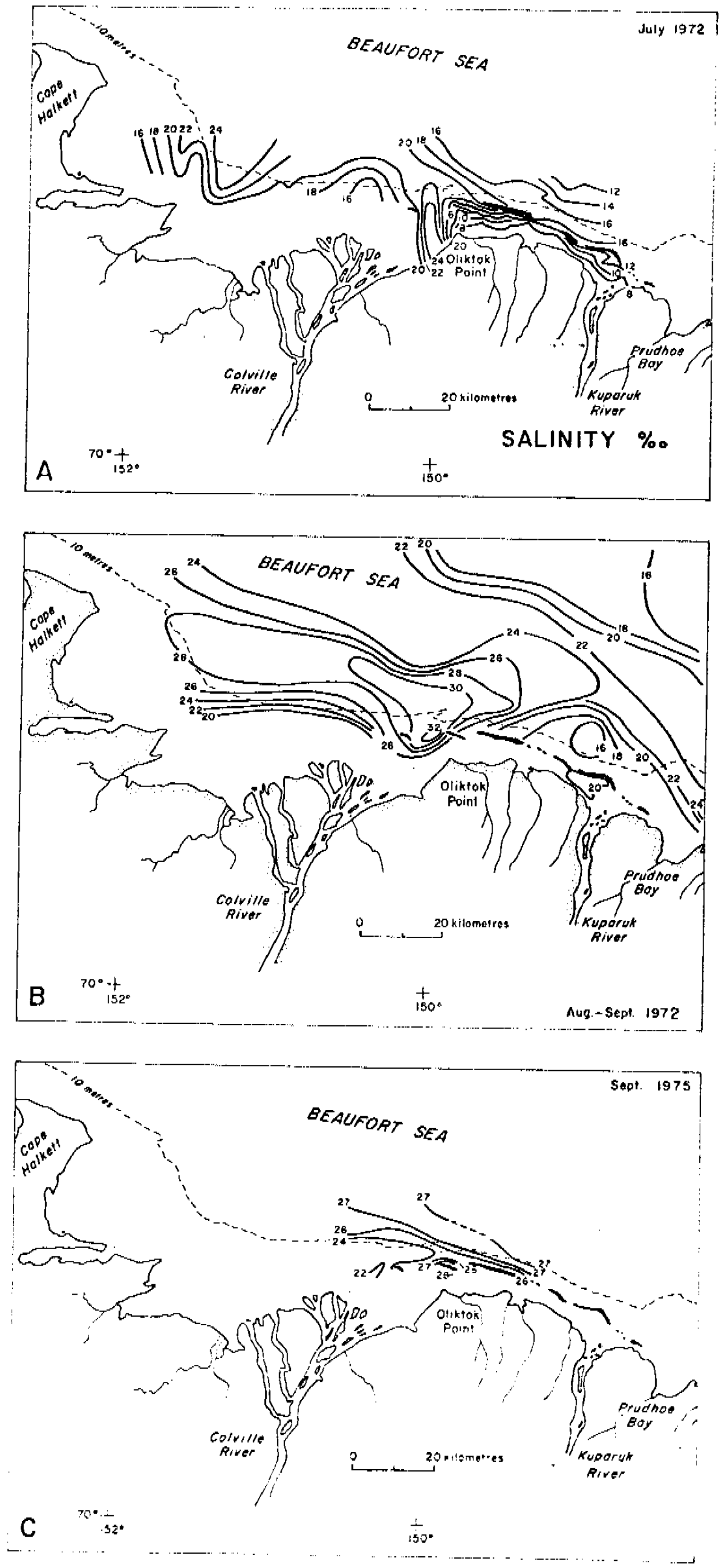

Figure 4. Surface distribution of salinity values during early summer, 1972(A); late summer, 1972(B), and late summer, 1975(C). Contour interval 2^{o}/oo. Note the occurence of high salinity surface water off Oliktok during all three surveys - 24^{o}/oo water in July, 1972; 32^{o}/oo water in August and September, 1972; and 28^{o}/oo water in September, 1975.

salinities (greater than 32 $^{o}/oo$) were observed off Oliktok Point. In 1975 the area of high salinity is displaced eastward along the outside of the islands by the fresher waters of Harrison Bay (Fig. 4C) when compared to either of the 1972 data sets (Figs. 4 A&B). During this year the surface salinity gradient is less pronounced than in earlier surveys.

Vertical profiles of salinity which complement the August -September 1972 surface distribution (Fig. 4B) show a thin (2-m surface layer of low salinity water off the central Volville Delta (Figs. 5 A & C). Elsewhere the salinity surface layer is thicker (4-6 m). The underlying layer of high salinity water is best developed in central Harrison Bay (Fig. 5 D) west of its surface expression off Oliktok Point (Fig. 4 B). It appears to be less developed offshore (Figs. 5 A & B) and to the east (Fig. 5 D).

Transmissivity

Patterns of water clarity measured as light transmission (transmissivity) show a gradual seaward decrease in surface water turbidity (Fig.6). In July, 1972, (Fig.6A) coastal waters were most turbid in Simpson Lagoon and off the Kuparuk River. A zone of clearer water extended from the coast near Oliktok Point to the northwest. A Landsat 1 image taken on 25 July, 1972, during the period of shipboard observations, also shows this area of less turbid water (Fig.7). A band of turbid water can be traced close inshore along the mainland coast from the Kuparuk River to Oliktok Point and across the front of the Colville Delta to Cape Halkett. Darker, less turbid offshore waters extend to the coast just south of Oliktok Point. Winds during this period were from the east-northeast.

Later in the same year there is a similar seaward decrease in turbidity, but the gradient is much less pronounced (Fig.6B). Furthermore, the surface waters are generally more turbid than during the July observations with the comparable transmissivity contours located further offshore. The tongue of clear water extending landward to Oliktok observed in the July surface data

Figure 7. LANDSAT image of Harrison Bay area, Beaufort Sea. Image taken 25, July, 1972, during the period of observations which are shown in Figures 2A, 4A, and 6A. Note the displacement of Colville River plume to the west toward Cape Halkett and the tongue of clear water extending almost to the coast at Oliktok Point.

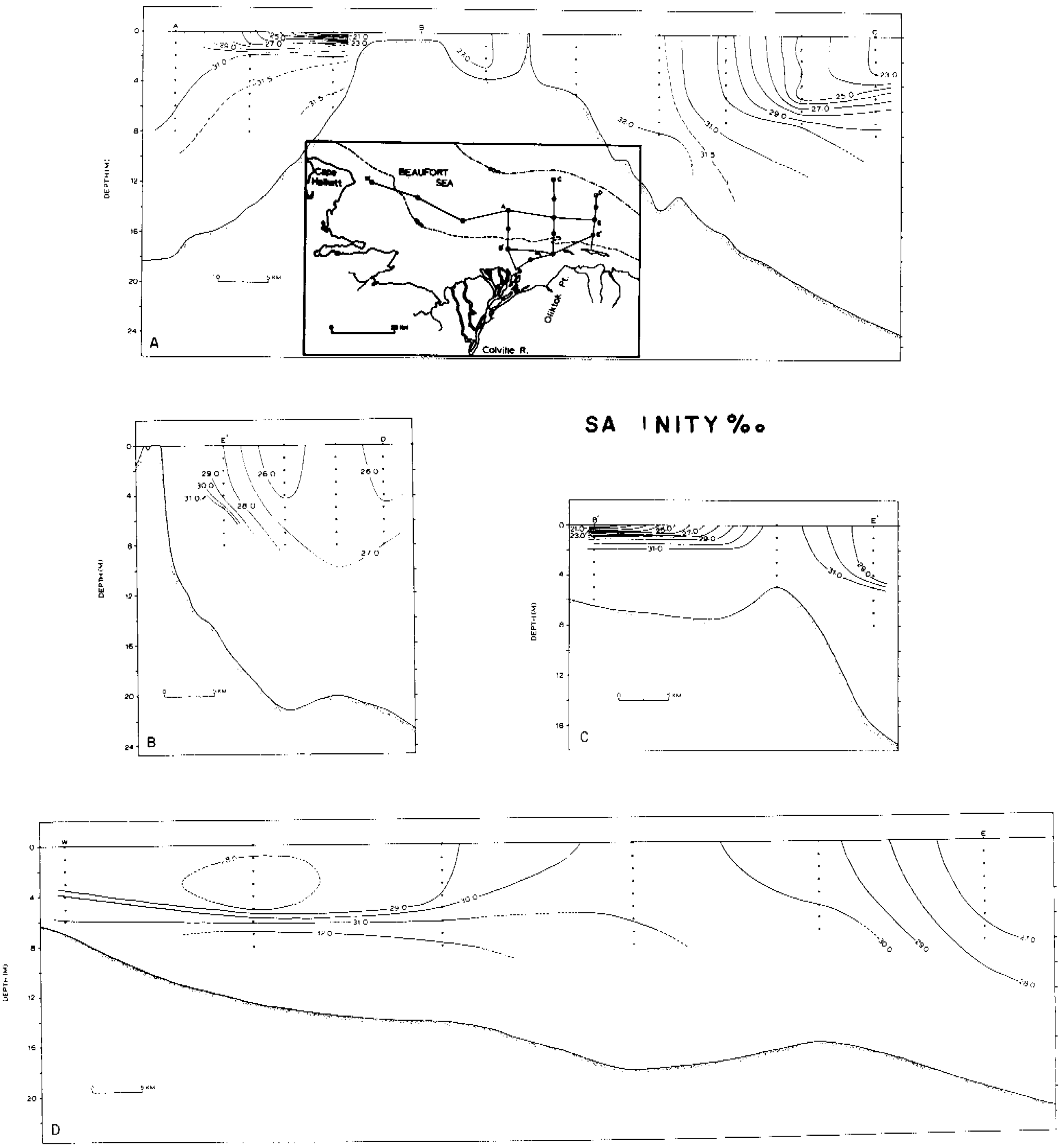

Figure 5. Vertical distribution of salinity in Harrison Bay during late August and early September, 1972. Location of the four profiles is shown in the inset (A). Contour interval $1^{o}/oo$. Surface values are shown in Figure 4B.

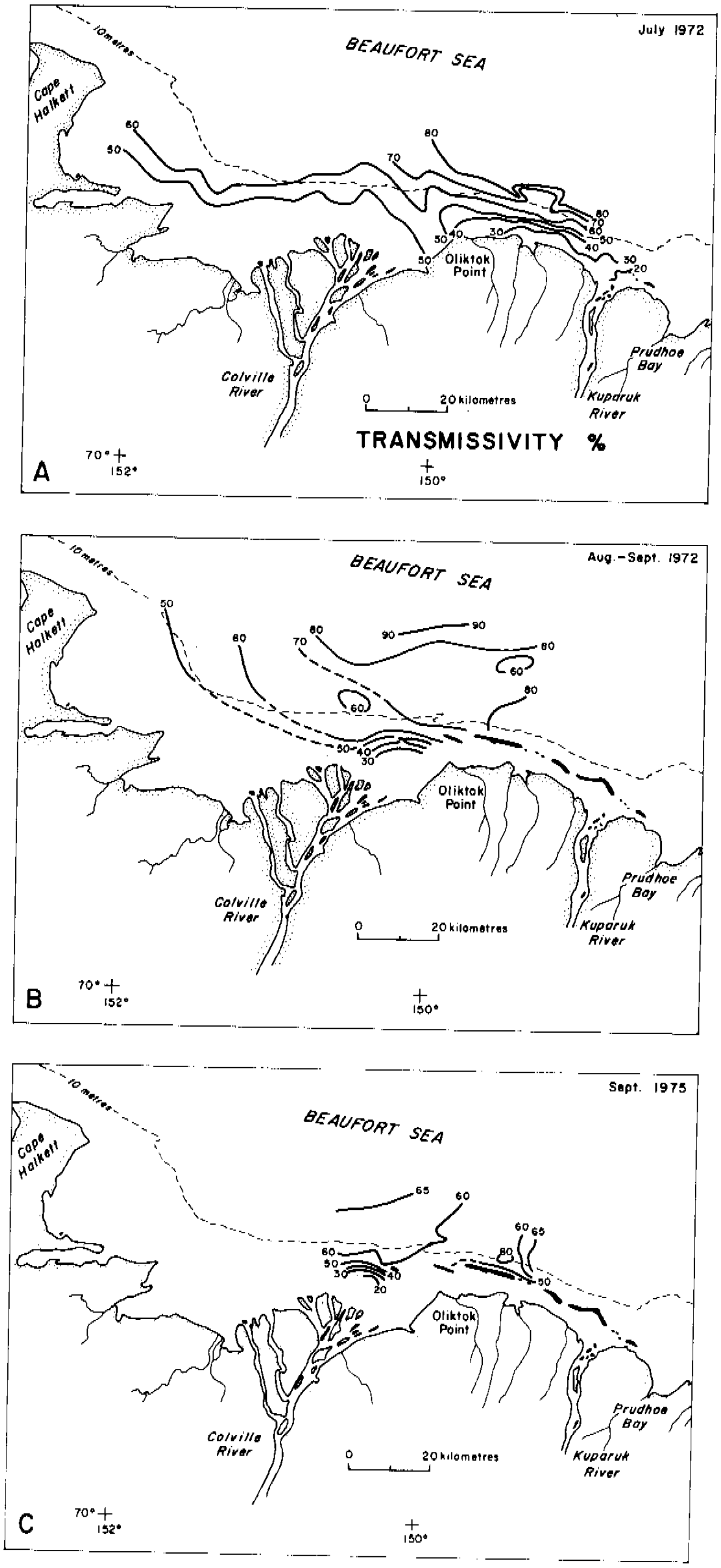

Figure 6. Surface distribution of water clarity expressed as percent transmissivity. Early summer, 1972, (A); late summer 1972 (B); and late summer, 1975 (C). Contour interval 10%.

(Fig. 6A and satellite image Fig. 7) is not present. On the contrary, the waters are most turbid in this area. Winds during late August and early September were generally strong from the east and during the first week in September a storm occurred with strong northeasterly wind and an unusually large 8-10 sec swell. Aerial observations during this storm indicated considerable resuspended material was present inside of about the 5 m contour. This storm is probably the major cause of the turbidity pattern of Figure 6.

During September of 1975, inshore waters were generally more turbid than in either period of observation in 1972 (Fig. 6C). In addition to the coastal and river-supplied turbid waters there appears to be a zone of turbid water extending northeastward from Oliktok Point. Winds during the 1975 study were dominated by westerlies.

DISCUSSION AND CONCLUSIONS

A comparison of surface water characteristics indicates that the three periods of observation were distinctly different. Yet more saline, colder water was consistently present northwest of Oliktok Point throughout all of the periods of observation.

The July 1972 (Figs. 2A, 4A and 6A) data with lowest salinities and generally low turbidities appears to reflect the influence of fresh, warm and turbid Colville River water from the melting of the fast ice. These data also show a decrease in surface salinities toward the pack ice edge, a source of melt water.

The August-September 1972 (Figs. 2B, 4B and 6B) distribution of variables is apparently dominated by oceanic influences. The river flow is lower at this time of the summer and pack ice melting is reduced due to lower temperatures The summertime coastal salinities are therefore at their highest as mixing processes have had an extensive period in which to act.

During both 1972 observation periods the flow of surface water appears to be westerly, with the less saline, turbid plumes of the Colville displaced to the west of the delta front. This conclusion is supported by Landsat imagery (Fig. 7) and by the dominance of easterly winds during the 1972 open water season, which kept the pack-ice well offshore in this area during much of the summer (Hufford, 1974) and encouraged westerly surface drift.

In 1975 the dominance of westerly winds kept sea ice close onshore and apparently resulted in easterly surface flow for the coastal water off Oliktok (Figs. 2C, 4C and 6C). At the end of the open water season in the average year, oceanic mixing is well advanced. However, in 1975, large amounts of pack ice in shallow water may have restricted spreading of river waters resulting in low salinities observed in September.

The relation of wind to the distribution of surface water character has been noted by others. Hufford and Bowman (1974) in an aerial radiation thermometer survey of Harrison Bay in August, 1973, show a surface thermal pattern, which they relate to westerly wind during the time of their survey. Two significant findings were noted: the lack of a major river plume off the Colville and a cold water zone extending from northwest Harrison Bay toward the delta of the Colville. They relate the cold water intrusion (1-3°C), paralleling the 5 m depth contour, to surface waters. The boundary between warm inshore waters and colder offshore waters was also marked by a color change from brown to green. During the survey, the warmer waters were confined to inner Harrison Bay and to the vicinity of Oliktok Point by the westerly winds. Thus, it appears that the general distribution of summer surface water character in Harrison Bay is primarily wind controlled with ice as a secondary influence.

It is apparent from the above discussion that the surface patterns are derived primarily from the influence of river input, ice melt and mixing with shelf waters. However, the source of the recurring colder and relatively more saline waters in the vicinity of Oliktok Point in 1972 and 1975, and for the cold (saline?) water in 1973 (Hufford and Bowman 1974) is not obvious. For the year in which we have vertical profiles (1972), the data shows the water seen at the surface occurs as a bottom layer along the islands to the east and also in central Harrison Bay. Water of similar character (temperatures below 0.5^{o}C and salinities of about 32 $^{o}/oo$ can only be found 60-70 km seaward at 70 m depth beyond the shelf break (Hufford and others, 1974). At the time of our survey these two similar water types were not connected. Although we can not rule out the possibility of a slug of water being a remnant from an upwelling episode (Hufford, 1974), these cold saline waters may well represent a remnant slug of the previous winter's convective cooling.

The winter freezing of 2 m of ice, coupled with the exclusion of solutes under conditions of reduced winter circulation, has a significant effect on the inner shelf temperature and salinity regime. The winter convective cooling is more intense than the summer heating of the near surface waters. The chacteristics of winter water may be preserved throughout the summer (Zubov, 1943).

We attempted to test this hypothesis by calculating the salinity increase of the sub-ice water in Harrison Bay resulting from brine exclusion during the formation of ice (Neshyba and Badan-Dangon, 1974). Because of some unknowns, and in order to simplify the calculations we are assuming a closed system. Arbitratily we have chosen the area between a line due north from Cape Halkett and one north from Oliktok Point out to the 10-m and

20-m isobath for our calculations. Assuming no advection across the above boundaries, an 80% exclusion of solutes during 2 meters of ice growht (Schell, 1974) and initial fall surface salinities of 20 and 30 ‰, the waters within these boundaries would increase in salinity as follows:

Fall Surface salinity	Spring Salinity of sub-ice water between 2 and 10 m isobath	Spring salinity of sub-ice water between 2 and 20 m isobath
20 ‰	46.7 ‰	34.3 ‰
30 ‰	55.0 ‰	36.4 ‰

Clearly enough cold saline water is generated to account for the volume observed in 1972, and could have been a partial remnant of the previous winter's convective cooling and brine exclusion from the winter ice cover.

The stagnation of this water mass in Harrison Bay may be aided by the stamukhi zone ice boundary which forms generally along the 20 m isobath (Reimnitz and others in press) and undoubtedly forms a partial barrier to offshore advection during the winter. In some years the stamukhi ice barrier may remain in place for much of the summer season, further isolating the inshore waters.

With dominant easterly winds during the 1972 summer season, it is apparent that the surface water in Harrison Bay moved westward and was replaced by cold, high-salinity subsurface water remaining from the winter. This type of upwelling should be expected to occur rather commonly as the summer winds are commonly from the east.

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ATTACHMENT C

Current meter and water level observations in Stefansson Sound, Summer, 1976.

Peter Barnes, Erk Reimnitz, and David McDowell

Aspart of the program to determine the rate and direction of sediment movement, an Aanderaa RCM-4 Current meter and an Aanderaa water level guage were moored along with a Montadero nephelometer-transmissometer in 5.5 meters of water in central Stefansson Sound, northeast of Prudhoe Bay, Alaska in late July, 1976 (Fig. 1). The water level guage was resting on the bottom and the current meter sensors were located about 1 m above the sea floor. The instrument array, in excellent condition, was recovered in late September of the same year for a record length of 52 days. The current meter and tide guage data tapes were interpreted at both the NOAA Pacific Marine Environmental Laboratory in Seattle and at the Environmental Protection Agency Corvallis office. The nephelometer-transmissometer data tape has yet to be decoded.

OBSERVATIONS -

Just prior to mooring this meter, a Bendix Q-15 vector-averaging current meter measured currents of 60 cm/s (-085^{o}T) at 1.5 m below the surface. Bottom currents were 40 cm/s (110^{o}T) at 0.5 m off the sea floor. Initial Aanderaa current meter readings were 25 cm/s-(075^{o}T). The water character, similar to the current regime, is very different at the surface and near the bottom. Surface temperatures were about 5^{o}C and salinities about 11 ^{o}/oo, while the initial temperature values from the current meter near the bottom were 0.5^{o}C and 24^{o}/oo. Continuous surface weather observations from Deadhorse, Alaska (Prudhoe Bay) were used for barometric pressure, windspeed and direction data in interpreting the current and water level records.

SEA LEVEL -

Graphical methods were used to determine if a correlation exists between sea level and barometric pressure. Water pressure a_ measured by the guage includes both atmospheric pressure and water density. These factors have to be considered before true sea level differences can be compared. A non-tidal water pressure curve was obtained from the mid-points of the semi-diurnal tidal ranges. Water density was determined from temperature and salinity values measured by the current meter. These values were used to approximate the temperature and salinity character of the entire water column. As noted above there could be significant differences between the surface and near bottom waters. Sigma-t values were taken from Hydrographic Office Special Publication No. 68. The pressure factor of water density was omitted as it is insignificant at four meters. True sea level was then calculated using the following equation:

$$H = \frac{P(\text{guage}) - P(\text{atm})}{\rho g}$$

where H equals sea level in centimeters; P equals pressure in bars and ρ equals density in gms/cm^3 and g is the acceleration of gravity.

The observed density, and atmospheric pressure are compared to the computed sea level data in Figure 2. Density which is directly related to temperature and salinity, tends to increase from August (about 16 sigma-t unit) to September (about 23 sigma-t units). This is probably partly due to the decreasing air temperatures toward the end of summer, and partly to mixing processes which have masked the early summer fresh water input from river flooding and ice melt. There does not appear to be a strong relationship between density and sea level.

Atmospheric pressure and sea level show a very similar trend. The atmospheric highs and sea level highs correspond well between about 15 August and 22 September, although the sea level maxima occur one to several days after the atmospheric pressure peaks. The matching of sea level highs with high atmospheric pressures would seem to be the inverse of what one might expect to observe. Apparently wind forces associated with atmospheric pressure changes are more influential on sea level than pressure itself.

Currents

The progressive vector diagram for currents at this site (Fig. 3) shows an overall transport of water 200 plus km to the northwest, the direction of the western entrance to Stefansson Sound (Fig. 1). There are notable secondary excursions to the northeast. As one might expect most of the water motion at this location is essentially parallel to the coast, and to the bathymetric contours. Peak velocities on the order of 53 cm/s were recorded (sufficient to resuspend and transport coarse sand) and the mean velocity was about 13 cm/s. A correlation exists between the progressive vector diagram and sea level, or atmospheric pressure. When these latter two factors are rising it appears that the net water transport is to the east, while falling sea levels generally correspond to westerly transport (Figures 2 & 3). Comparing winds to atmospheric pressure, we find that in general westerly water transport can be correlated with northeasterly winds and lowered sea levels. Weak or westerly winds correspond to easterly water transport and higher water level. Of course any native familiar with the area can tell you this same story about currents, sea level and wind relationships but, here is the scientific proof.

The correspondence between temperature and salinity at the current meter site is straghtforward (Figure 4). Bottom water temperature values ranged from a minimum of -0.9°C to 7.5°C, averaging 1.73°C while salinities varied from a low of 12.8 $^{o}/oo$ to 30.6 $^{o}/oo$, averaging 24.4 $^{o}/oo$. Both the minima and maxima of salinity and temperature occurred at the start of the record in early August. Throughout the record there is good correlation between temperature and salinity with high values of salinity being associated with low temperatures and conversely, low salinities with warmer waters. The record suggests a general cooling of the bottom waters starting around the first of September.

DISCUSSION

An inter-relationship between the surface winds at the Deadhorse airport and the movement and character of water at the current meter is apparently complex. At first glance it would appear that prevailing northeasterly winds are associated with westerly currents (Figure 4), demonstrating the classical influence of Coriolis force and Eckman spiral. Upon close examination, this relationship does not always hold true. Furthermore, it is apparent that during periods of weak, variable, or westerly winds, the currents flow to the east. We interpret this to suggest that under such conditions near bottom currents were trying to flow eastward, perhaps under geostrophic pressures, but were periodically reversed due to the influence of surficial wind stress from the northeast. In any event it is apparent that the response of current to wind stress occurs very rapidly.

Temperature and salinity changes are also associated with the alterations in the flow regime. Easterly currents are usually associated with warmer less saline waters while westerly's are coupled with colder more saline water. This relationship can best be explained, in our opinion, by a model in which warm, fresh surface water overlies more saline and colder near-bottom water (Figure 5). When the water moves in a westerly direction the surface water spreads out offshore due to the influence of Coriolis forces, and the near-bottom sensors see upwelling of cold saline water that enters the sound through the passes in the island chain to the northeast. During periods of easterly flow the surface layer tends to be piled up against the coast and if it is sufficiently thickened the warmer less saline water is seen at the current meter sensors.

In summary the following conclusions can be drawn from the records taken in Stefansson Sound during the open water season of 1976:

1. Sea level parallels changes in barometric pressure, but lags slightly behind.

2. Rising sea levels are associated with easterly currents and lowering levels with westerly currents.

3. Currents are essentially parallel to the isobaths, with a slight offshore component and a net drift to the northwest in the summer of 1976.

4. Warmer and less saline waters occur in the bottom water during periods of easterly flow, which is accompanied by rising sea levels and weak, westerly or offshore winds.

5. Westerly flow is associated with strong northeasterly winds, lowered sea levels, low temperatures and high salinities.

6. Current velocities are commonly sufficient to erode and transport medium to fine sands.

7. Currents respond quickly to changes in the wind regime.

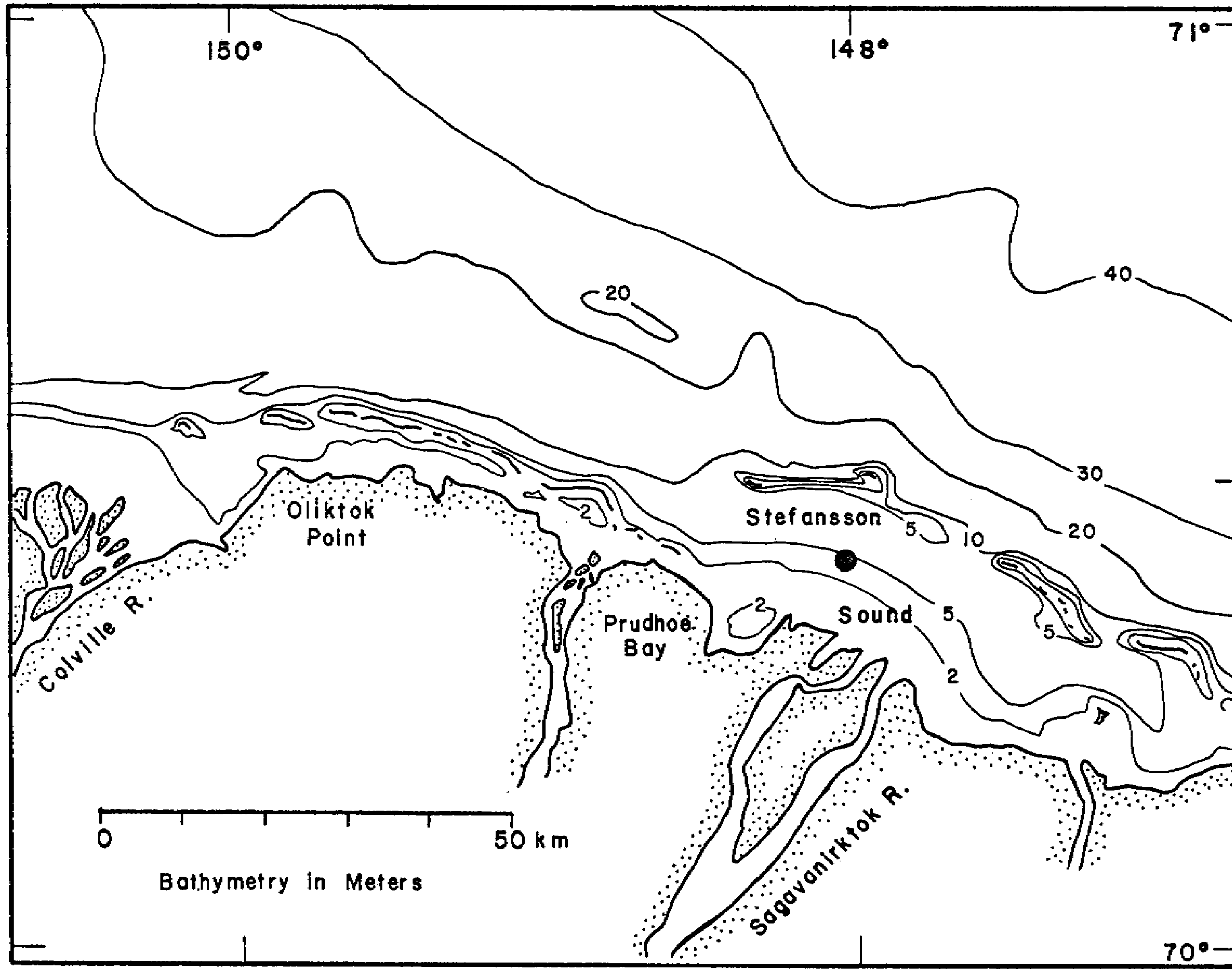

Figure 1. Map showing the location of the current meter mooring of August and September, 1976, in Stefansson Sound.

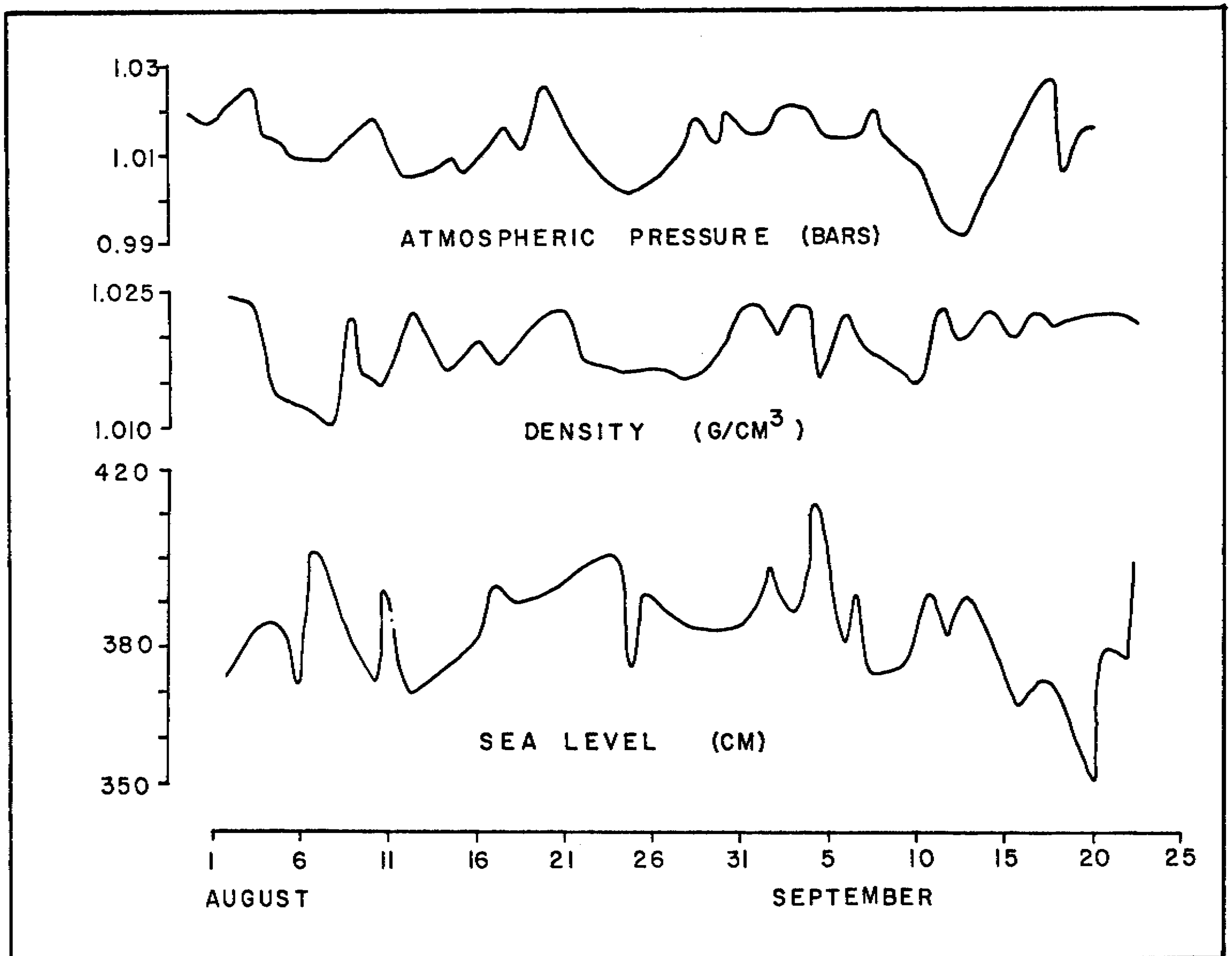

Figure 2. Relationships between atmospheric pressure(Deadhorse airport), water density(current meter sensors), and sea level. Note; Sigma - t =(density - 1)x10^{3}

STATION-STEFANSSON
PROJECT-USGS
LATITUDE-70 23.95 N
LONGITUDE-148 01.40W
DEPTH- 5.50 METERS

METER-17562
DEPTH-4.5 METERS
MEAN PRESSURE- 0.00 METERS
RECORD LENGTH- 52.58 DAYS
NET DRIFT- 3.75 CM/SEC, 330° T
MEAN SPEED- 12.78 CM/SEC
U-VARIANCE- 195.3
V-VARIANCE- 43.0

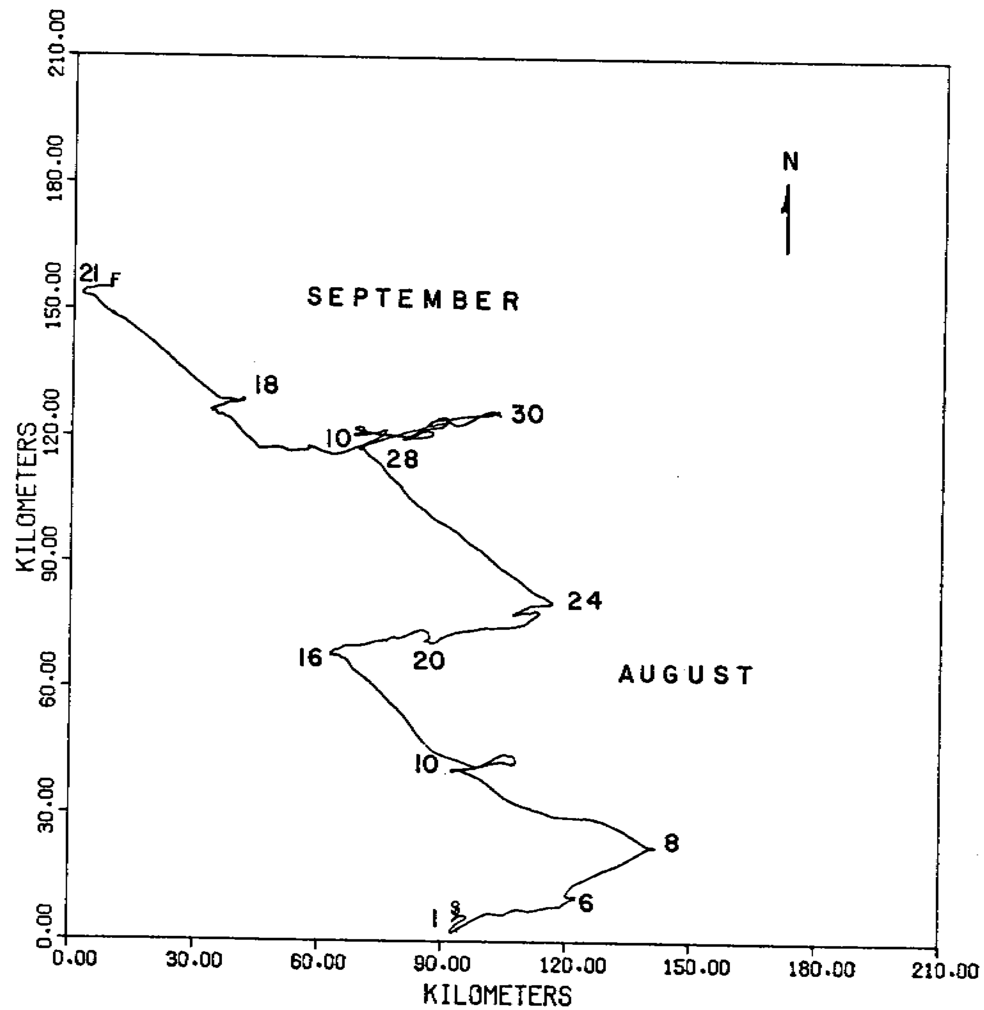

Figure 3. Summary characteristics and progressive vector diagram.

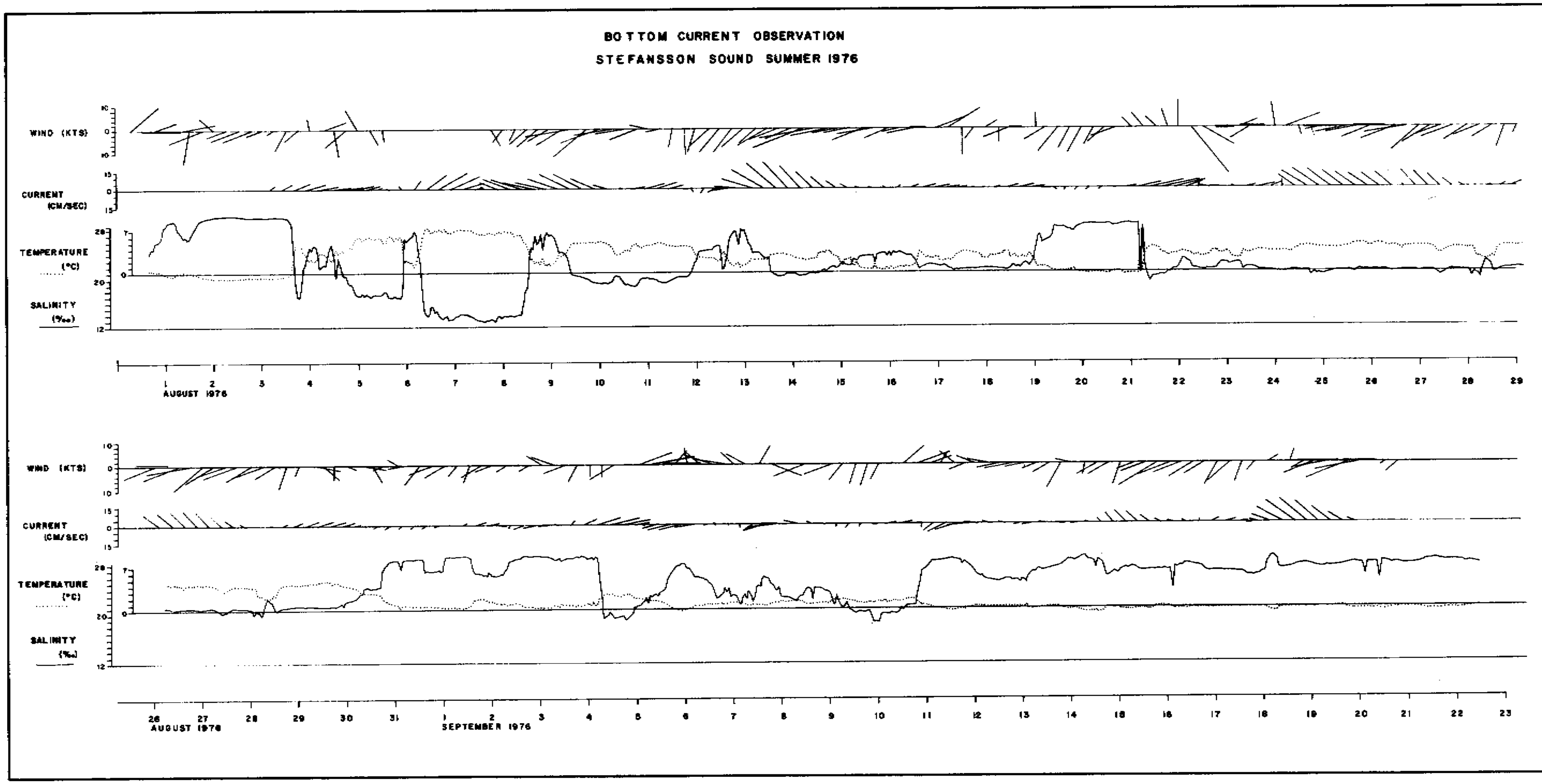

Figure 4. Plot of wind, current, temperature and salinity versus time at the current meter site.

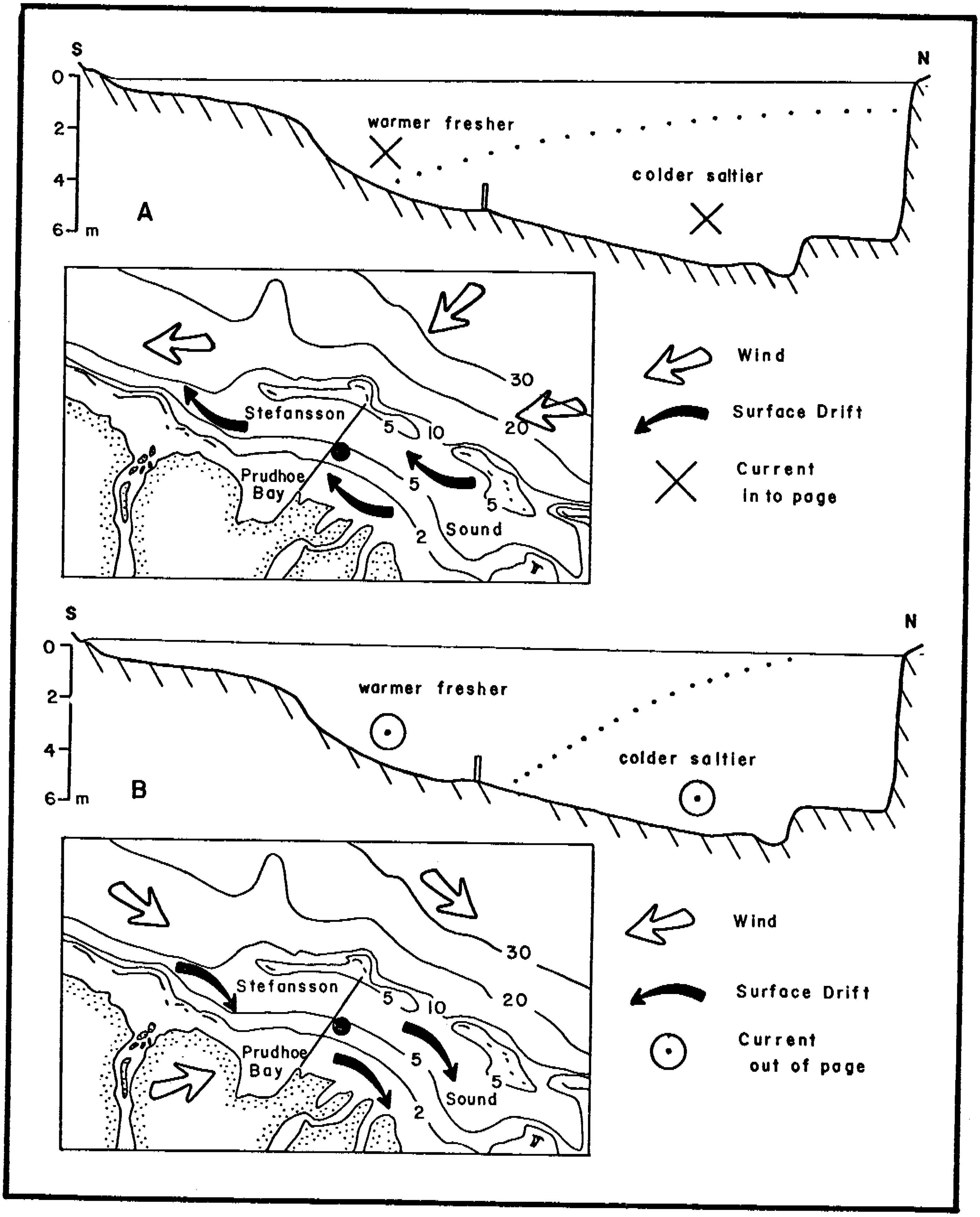

Figure 5. Wildly speculative model of wind, current and water regime in Stefansson Sound used to explain the variences in the record.

ATTACHMENT D

Preliminary results of Kogru River Studies

Erk Reimnitz, Douglas Maurer, and Peter Barnes

In our December 1976 quarterly report we discussed a reconnaissance survey of Kogru River, done during the 1976 field season. In that report we briefly discussed the bathymetry, water-salinity,-temperature, and turbidity, seismic reflection records, and the origin of the embayment. Here we will discuss further results from that study that may be of relevance to various aspects of the OCS program.

Seismic reflection records obtained during 1976 in southwestern Harrison Bay, and extending far up into the coastal palin along the Kogru River (Fig. 1), are very different from seismic records obtained with similar equipment on the arctic shelf in general. The records in this area exhibit strong, linear, and continuous reflectors down to a sub-bottom depth of about 70 m (Fig. 2). The inner shelf sub-bottom seen in high resolution seismic reflection records elsewhere in general is characterized by irregular, ill-defined, discontinuous reflectors (Reimnitz, 1976). This difference leads us to believe that a geologic boundary separates Quaternary Gubic deposits underlying the coastal plain from Barrow to Cape Halkett from those underlying the coastal plain and shelf to the east. It is important to know the nature and configuration of this boundary.

Line drawings prepared from two intersecting track lines in Kogru River are shown in Figure 2, along with a sketch of surrounding bluffs and the coastal plain. About 5 m of modern sediments, labeled Basin fill, covers the floor of this embayment. The rather flat-lying unit (about 10 m thick) below this rests on an unconformity, apparently an erosional surface, 15 to 20 m below the seafloor. The stratified section below this unconformity dips about 1.3° to 030°T. This uniformly dipping section can be traced about 10 km farther northward into Harrison Bay.

The unit above the unconformity is exposed in the bluffs along the north side of Kogru River, in the vicinity of the drained lake shown in Figure 2. A brief study of the exposures here revealed that the unit is composed of eolian, lacustrine, beach, and shallow marine sediments. We feel these exposures belong to the Barrow Unit of the Gubic Formation (Black, 1964). Distinct facies changes over short horizontal distances within this unit account for the somewhat irregular reflectors seen in the seismic profiles. These deposits of the Barrow unit, underlying the coastal plain and shallow shelf in western Harrison Bay indeed are very different from anything we have seen in coastal bluffs and seismic records to the east which lack easily identifiable units. If, and how far the Barrow unit in the Kogru River area extends to the south is unknown at this time.

Short and Wright (1974) show a pattern of primary and secondary "lineaments", as traced from map contour patterns and surficial geomorphic trends. One of their illustrations is reproduced here as Figure 3. These authors state that the lineaments have pronounced effect on the coastal configuration including alignment of barrier island chains, and that major offsets in the coast occur at intersections of lineaments. Our seismic profiles from the continental shelf in general, and around Cape Halkett and Kogru River in particular, provide no evidence for a geologic basis of the lineaments of Short and Wright (1974) (Fig. 3). Kogru River, in fact, lies along and parallel to a pronounced boundary separating distinct physiographic provinces of the coastal plain. This boundary is clearly visible on Landsat images, and runs oblique to the lineaments of Figure 3. The landform north of the boundary is dominated by large, elongated, oriented lakes trending north-northwest to south-southeast. The landform south of Kogru River is marked by a pattern of distinct lineation oriented parallel to Kogru River, essentially east-west. Sellman, et al. (1975) in their classification of lake types draw a boundary along and parallel to Kogru River. In their classification the lakes south of this boundary are the same as lakes to the east on the coastal plain from Oliktok to Prudhoe Bay.

Based on landform analysis some workers have proposed that the Kogru River boundary represents the limit for the last transgression during mid- to late-Wisconsin time (Sellman, et al., 1975). Furthermore, Black (1964) draws the boundary between the Barrow unit and the Meade River unit of the Gubic Formation along the Kogru River, but from the location of the sites he studied or described it appears that Black did not intend to position the boundary exactly along the Kogru River. Moreover he points out that the relation of one unit to the other is gradational or interfingering. Locally both units lie unconformably on the Skull Cliff unit of the Gubic Formation (Black, 1964). Based on available evidence we suggest that the surface of the Skull Cliff unit is the unconformity in the seismic reflection records of Kogru River (Fig. 2).

The nature of the Barrow unit in the seismic records of Kogru River does not change within the surveyed area, therefore the gradational boundary into the Meade River unit must lie slightly south of the River.

Thermal erosion plays a strong role in shaping the coastline of the Beaufort Sea. A better knowledge of how a) thermal erosion, b) a low-relief coastal plain underlain by frozen deposits, c) numerous ake basins ranging from very small to very large, and d) thaw settlement of the upper section of the coastal plain after inundation, interact, is important for the development of the arctic coastal region. The first thought which comes to mind when contemplating the effects of rapid coastal retreat into large lakes, their draining, filling with sea water, and subsequent thaw settlement, is to explain the large embayments of the North Coast as recently breached, coalesced thaw lakes. Prudhoe Bay may be a large breached lake, and a long core sample in the center of the bay would penetrate through marine sediments into lake sediments. Wiseman, et al., (1973) believe that even the lagoons backing the larger barrier chains originated through the erosion and coalescing of thaw lakes, as shown in Figure 4. We feel that this explanation is oversimplified, and acceptance of the hypothesis may prevent the search for the true answer. Some problems with this explanation are as follows:

In plain view, the lake pattern around Prudhoe Bay and around Kogru River is not coarse enough to permit the formation of another embayment similar in size by future breaching and coalescing. But more important, the surrounding lakes in these two areas are not deep enough. Most of them are about 2 m deep, for example, (Sellman, et al., 1975). In Figure 5 the cross-sectional profiles of several lakes adjacent to Kogru River and Prudhoe Bay are compared to the profiles of these two embayments. Also, the bluff along the north side of Kogru River exposes the peaty lake beds of a recently drained large lake, as sketched in Figure 2. The base of the modern fill in Kogru River, determined from seismic profiles, is shown inFigure 5. The base of the fill in Prudhoe Bay is sketched from Hopkins, et al. (1976). Comparing the elevation of the embayment fill with the elevation of lake bottoms we find a discrepancy of 6 to 7 m in both cases. Thaw settlement of originally frozen deposits below lakes after encroachment of the sea is not sufficient to account for the discrepancy (Sellman, et al., 1975). To form a deep embayment like Prudhoe Bay one would have to start from a deep lake, and such a lake would already be underlain by a thaw bulb. We must also rule out erosion as an agent to make a thaw lake into an embayment or lagoon. Prudhoe Bay contains 6 m of marine sediments (Hopkins, 1976).

From the data at hand, therefore, the origin of the long narrow embayment called Kogru River remains unknown. Teaschekpuk Lake, with the lake level 1.5 m above sea level, and a depth of up to 14 m (Chalres Sloan personal communication), if breached, would result in a large embayment. But this lake is not a thaw lake, but an anomaly in the general surface of the coastal plain that is due to other causes.

In our earlier report on the Kogru River survey we speculated that analysis of the high quality records may show the top of the ice bonded sediments as a recognizable reflector. The reasons were a) the geologic setting provides easily identifiable, dipping reflectors, which should allow us to trace a high velocity surface that is unrelated to geologic structure, b) the embayment was thought to consist of a series of recently breached lakes in which the narrow bottlenecks represent recently inundated terrain where the permafrost surface should rise, c) the seismic profiles in many places cross the 2 m depth contour which appears to be the place where the top of the ice-bonded section drops off rapidly toward deeper water. Careful analysis of the seismic records provides no clues for the distribution of ice bonded sediments.

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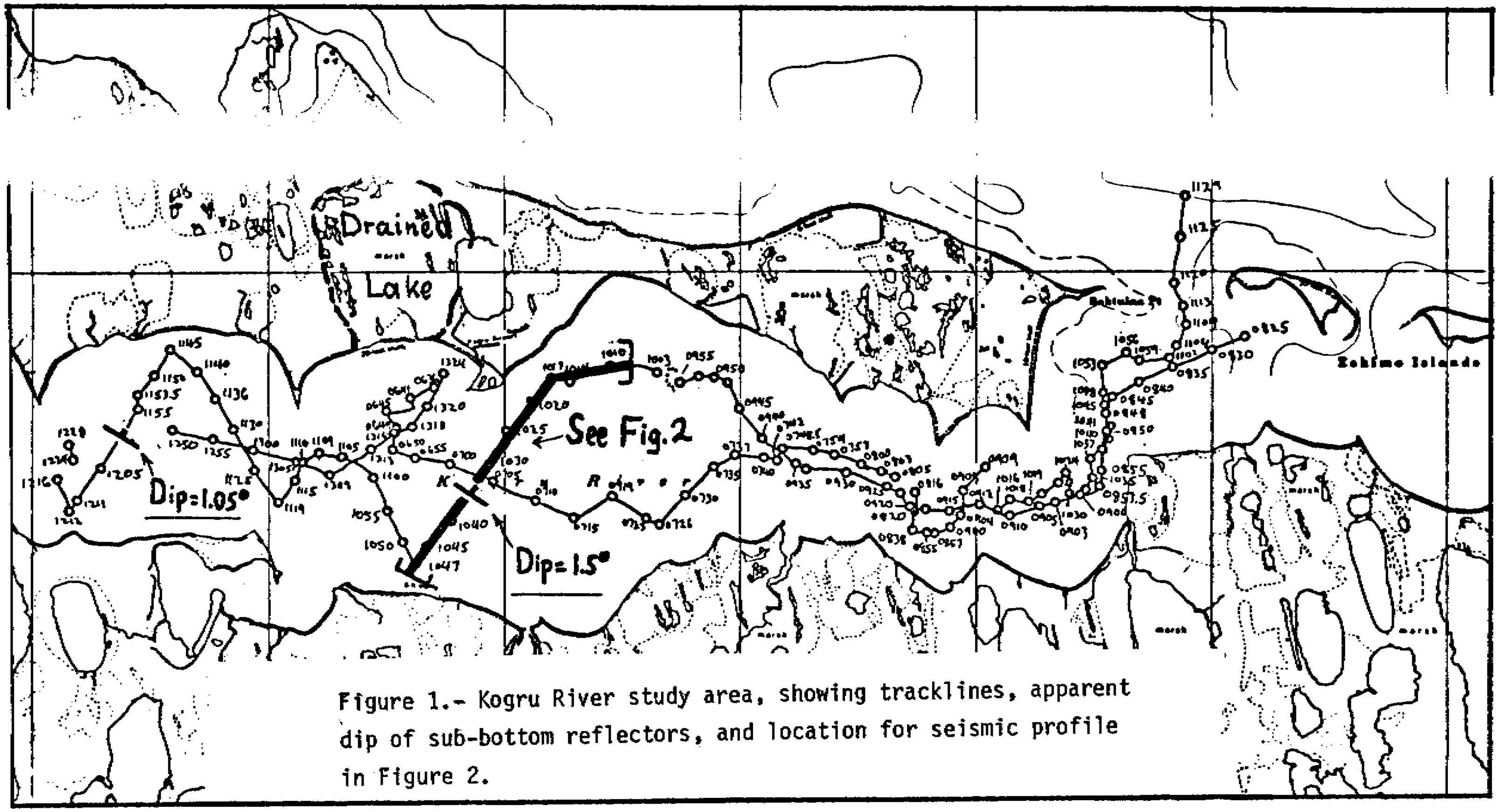

Figure 1.- Kogru River study area, showing tracklines, apparent dip of sub-bottom reflectors, and location for seismic profile in Figure 2.

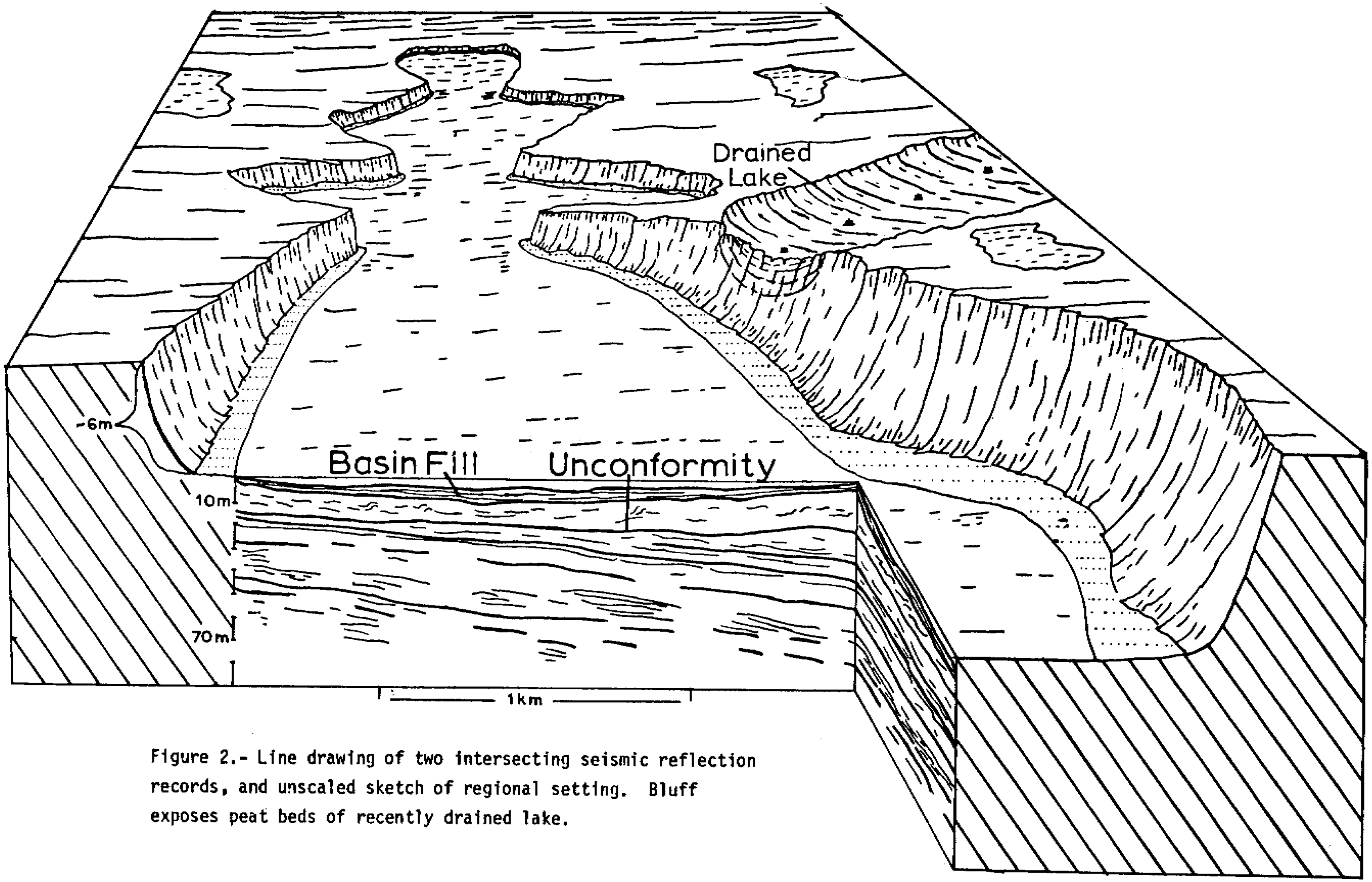

Figure 2.- Line drawing of two intersecting seismic reflection records, and unscaled sketch of regional setting. Bluff exposes peat beds of recently drained lake.

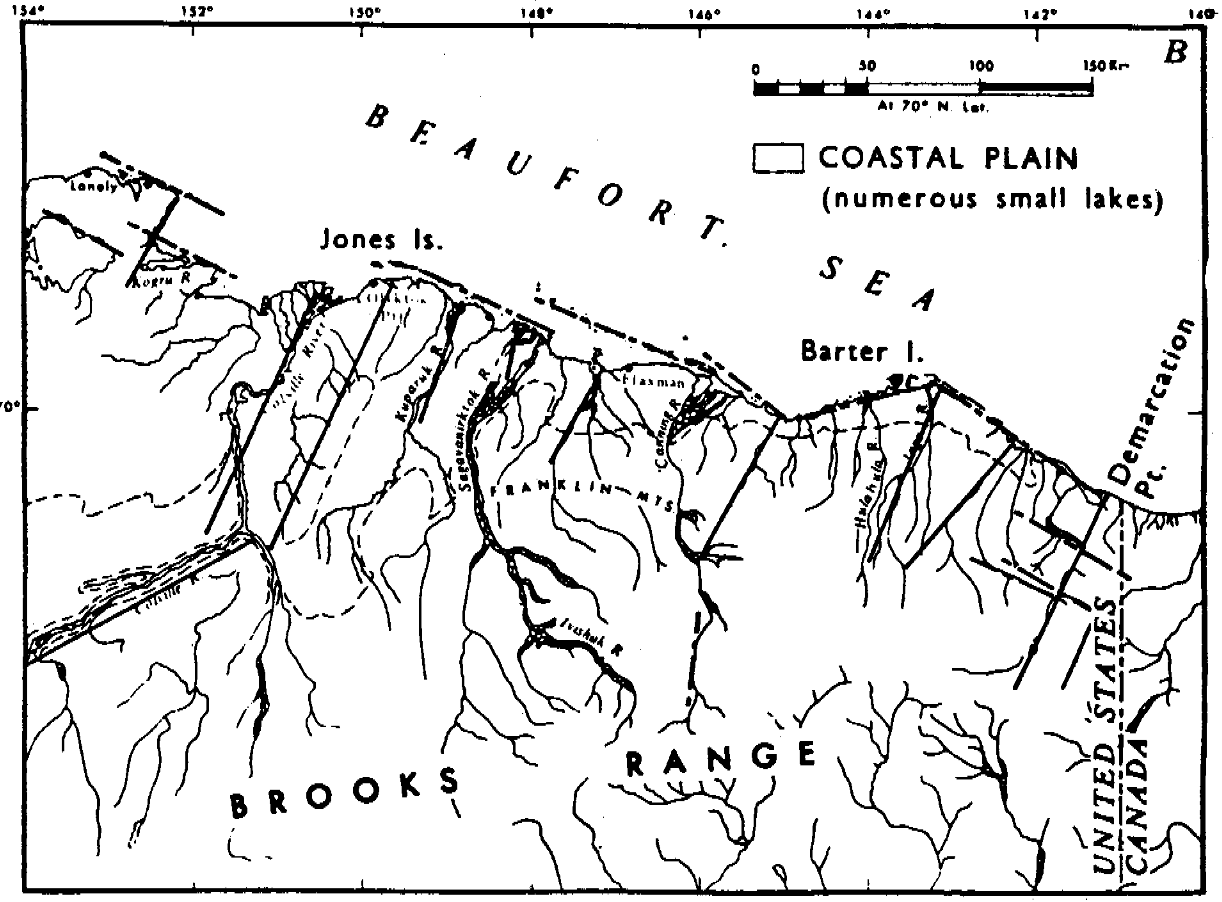

Figure 3.- Location of some of the most prominent and continuous lineaments on the North slope (From Short & Wright,1974).

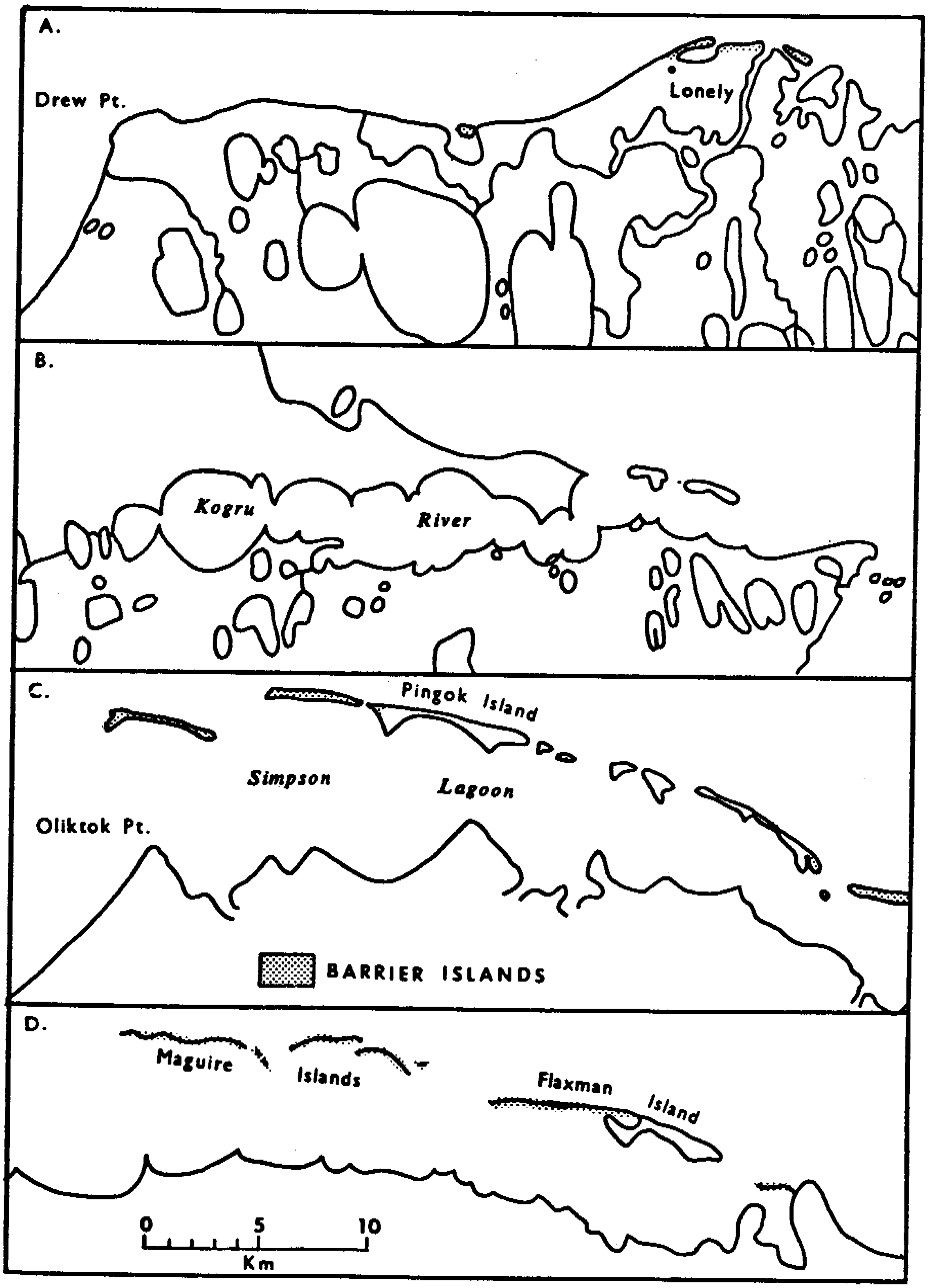

Figure 4. Sequence of lagoon formation and barrier island isolation by thaw-lake coalescence. A. Initial tapping, draining, and coalescing of lakes. B. Continued coalescing of lakes and thermal erosion of shoreline. C. Continuing thermal erosion and isolation of offshore tundra remnants. D. Erosion of tundra remnants and reworking of sand and gravel into offshore barriers.

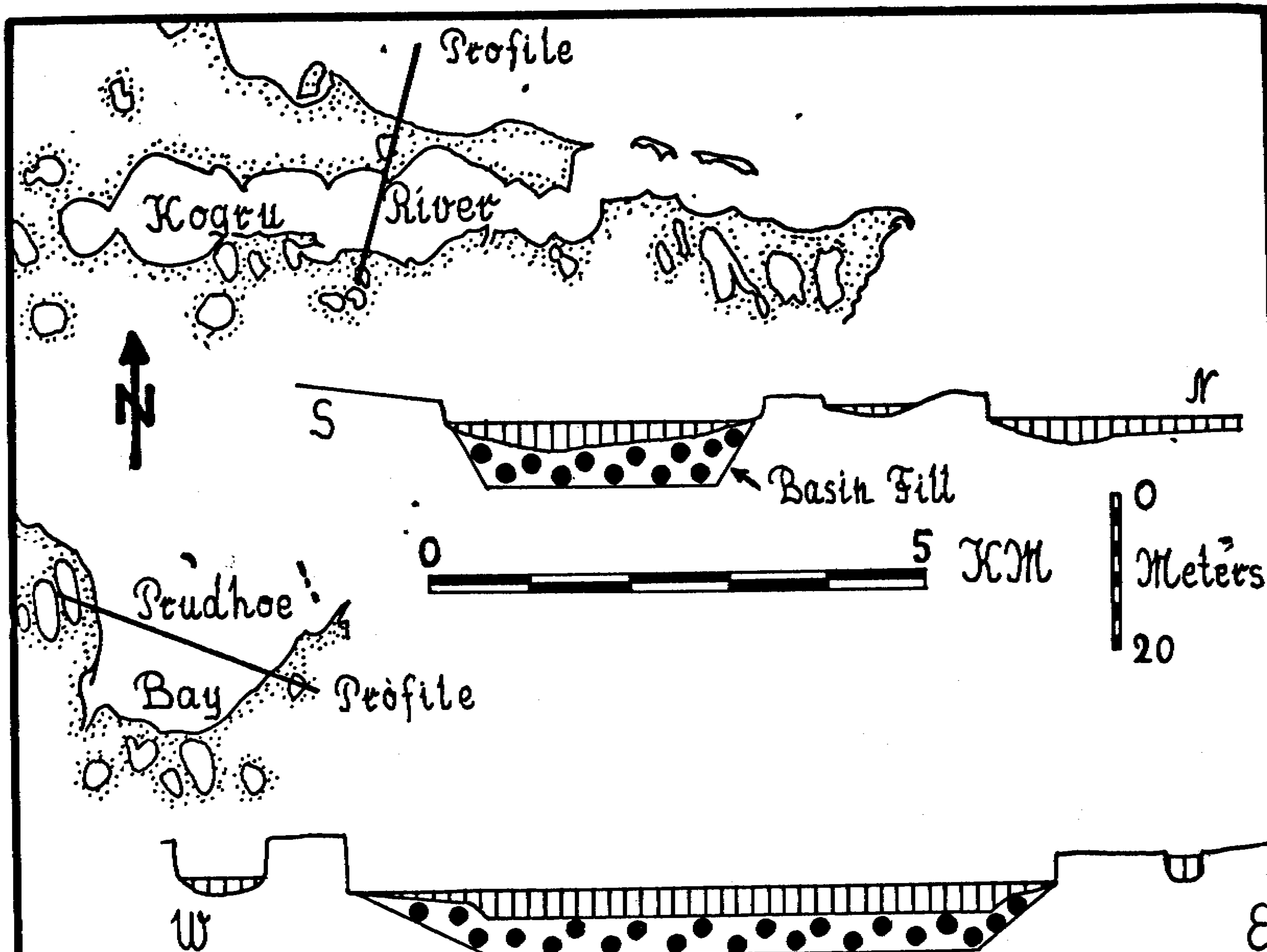

Figure 5.- Crossectional relationship of thaw lakes to Kogru River and Prudhoe Bay.

ATTACHMENT E

Suspended Matter in Nearshore Waters of the Beaufort Sea (R.U. 205)

David E. Drake, U.S. Geological Survey

I. Summary

The objectives that were emphasized during this year were:

1. determination of the concentrations and composition of suspended matter during the ice-covered winter season near Prudhoe Bay and the Colville Delta.
2. examination of the temporal variability in near bottom currents and sediment transport at selected nearshore sites.
3. determination of the distribution of suspended matter during the summer period (July - September) between the Canning River and Cape Halkett.

Useful results were obtained on objectives 1 and 3. Unfortunately, the rigors of the environment and equipment malfunctions combined to prevent us from accomplishing objective 2.

Suspended matter concentrations below the ice in March 1976 ranged from 130 μg/l to 1200 μg/l (mean value, 340) on two transects off Prudhoe Bay and the Colville Delta. The bulk of the sediment in suspension was of biological origin; inorganic clay-sized particles comprised <20% of all samples. These results combined with current measurements showing sluggish water flows during winter conditions suggest that the ice-cover effectively minimizes sediment transport. Surges and barotropic currents associated with storm passage undoubtedly increase sediment transport below the ice. However, we presently do not have data to evaluate these short, high-energy events.

The distribution and composition of suspended matter within 50 km of the coast during the summer suggest the following conclusions:

1. the sediment discharge of the Colville River far overshadows the discharges of the smaller north slope rivers. In fact, by late August and September suspended matter concentrations exceeding 5 mg/l are generally restricted to Harrison Bay and areas near the Colville Delta.
2. the great bulk of suspended matter transport in surface waters occurs within 10-15 km of the shore.
3. wind-driven transports (both direct flow of surface waters and indirectly-forced upwelling) appear to be the major mechanism controlling the fate of suspended clay and silt during the summer.
4. consequently, the movement of water and suspended matter is highly variable over the inner shelf. Nevertheless, data which bear on the pathways followed by surface suspended matter strongly suggest a net transport to the west within 20 km of the coast between Prudhoe Bay and Cape Halkett.

II. Introduction

Significant increases in concentrations of trace metals and hydrocarbons in the environment are a likely result of petroleum development. Both natural and artificial levels of these materials tend to be higher in fine-grained sediments. Therefore, it is important to understand the fate of fine-grained sediments which are introduced by rivers, coastal and sea floor erosion.

The problem involves two major aspects. First, the "fairweather" regime during both winter and summer seasons must be evaluated and, secondly, the transport rates which occur during storms must be determined. In particular, for the Beaufort Sea shelf influxes of new sediment occur during well-defined, short periods in June and July. Ice-free conditions prevail from July to September and one would expect that during this period the transport of suspended matter would be of relatively greatest importance. From September through June, ice cover over the inner shelf is essentially complete and this factor should substantially reduce the sediment transport rate (by preventing wave resuspension and wind-driven currents). However, the magnitude of this seasonal effect has never been directly investigated and this was one of the specific objectives of the first year of this research.

III. Current State of Knowledge

Principally through the efforts of Barnes and Reimnitz (1974) and Naidu and Mowatt (1974) the distribution of surficial sediments on the Beaufort Sea shelf between Cape Simpson and Barter Island is reasonably well known. Basically the distribution is characterized by nearshore and outer shelf bands of silty sand (and locally gravel) separated by a mid-shelf zone of mud (mean diameter, 0.016 mm). The distribution of clay minerals presented by Naidu and Mowatt (1974) bears on the fate of river-borne materials and will be discussed later in this report.

Research on the physical oceanography of the area has increased substantially in the past several years. However, the difficulties encountered in these investigations make additions to our understanding come slowly (Mountain, 1974). Pieces of information have been collected at various times and places but coordinated research programs which will eventually lead to a coherent synthesis are just beginning. Moored current meter measurements of suitable duration are critical to understanding any shallow water circulation system; this type of data is severely limited for the Beaufort Sea shelf (see other sections of R.U. report). The available data (Barnes and Reimnitz) show that inner shelf currents near the Sagovanirktok Delta respond quickly to the prevailing local winds. Easterly winds which tend to predominate during July and August (Mountain, 1974) drive surface waters westward and offshore inducing a near bottom onshore flow. Shifts to northwesterly winds rapidly reverse this system by piling surface water up on the coast and possibly causing downwelling in the subsurface.

Current measurements below winter ice cover (Barnes and Reimnitz, this report) reveal sluggish flow with very little net directionality. Removal of ice cover allows wind driven currents and a substantial increase in flow velocities.

Suspended matter samples were collected by P. Barnes in 1971 and 1972 aboard the USCGS GLACIER and NATCHIK (Barnes, 1974). This is the only sampling directed toward the suspended matter transport problem that has been attempted prior to the present research.

IV. Study Area

The area emphasized during the year extends from the Canning River to Cape Halkett. A description of the full study area for R.U. 205 is given in item IV above.

V. Data Collection

Water samples for suspended particulate matter determination were collected in March 1976 at eleven ice hole stations on two transects (figure 3). The samples were recovered using 5-l Van Dorn bottles lowered on a polypropylene line. Water was immediately transferred to plastic bottles and vacuum filtration using pre-weighed 0.4 μm Nuclepore filters was accomplished in the evening at the shore station in Deadhorse. In addition, a Martek beam transmissometer (1 m path) was used to obtain a profile of water clarity to the bottom at each station; the sensor included a thermistor for temperature determination. The sample filters were stored in plastic petri dishes and shipped to our California laboratory for analysis.

During the summer field season (1976) P. Barnes and E. Reimnitz collected 82 surface water samples (500 ml) between Canning River and Cape Halkett and to ~20 km offshore. Owing to the nature of the USGS KARLUK operations, it was not feasible to process the samples in the field. Therefore, all samples were kept cold and shipped to California for filtration. The water samples were stored in opaque plastic bottles to minimize biologic action. Nevertheless, some changes in the organic components undoubtedly took place but it is likely that the concentrations of noncombustible particles were not markedly changed.

Noncombustible and combustible fractions of the suspended matter were determined by ashing 1/2 of each sample filter for 6 hours at 550°C (Manheim et al., 1970). The remaining 1/2 of each filter was set aside for microscope investigation.

During March 1976 P. Barnes and the author attempted to deploy two bottom moorings for long-term current velocity and light transmission and scattering measurements. One mooring off the Colville Delta was successfully deployed but could not be found when recovery was attempted in July. The second mooring near Reindeer Island was damaged (the light transmissometer) and only one current meter was satisfactorily placed. Unfortunately, this mooring also could not be found during the following summer. Thus, our efforts to obtain time-series data which included optical sensing of water turbidity were unsuccessful.

VI. Results

The results of our winter and summer sampling programs illustrate the extreme seasonality of the suspended matter transport system (figures 1 & 3). Total suspended matter (TSM) concentrations in March ranged from 130 μg/l to 1200 μg/l* with a mean of ~340 μg/l. Most of this material was organic in origin and mineral particles represented <20% of the suspended matter. None of the samples contained grains larger than 16 μm in diameter. For comparison, concentrations of 100-300 μg/l TSM are generally present on the outer shelf and continental slope in mid-latitude regions (Meade et al., 1975; Drake, 1976).

The light transmission profiles (figures 5 & 6) show that the vertical distribution of suspended matter is simple during the ice-covered situation. Stratification is essentially lacking except for a slight but ubiquitous reduction in light transmission near the sea floor. This near-bottom layer implies that processes of fine particle resuspension from the bottom do not cease entirely in the winter.

*the value of 1200 μg/l may have been somehow contaminated because this particle concentration should result in a much lower light transmission than was measured at this site.

However, the particles in this layer were in all cases very fine silt or clay-sized (<8μm) and mostly low-density organic matter. These materials could be maintained in suspension by weak currents flowing over locally rough topography.

Following shorefast ice breakup in July, samples were collected seaward of the Sagavanirktok delta and in Harrison Bay (figures 1 and 2). These early summer surface water samples reveal the following:

1. samples immediately seaward of the Sag delta contained surprisingly low concentrations of noncombustible mineral particles (600 - 1040 μg/l);
2. similarly, TSM concentrations in Prudhoe Bay were less than 5 mg/l except within 1 to 2 km of the shore;
3. TSM concentrations and the content of terrigenous materials were significantly higher off the Colville River and in the central, nearshore section of Harrison Bay. These high concentrations (>10 mg/l) decreased dramatically at distances of 10-15 km offshore;
4. although the major distributary of the Colville River is on the northeast (Walker, 1974) the TSM values there and seaward of Oliktok Point were relatively low and also richer in plankton.

Following a crew exchange and completion of a vibracoring program, the KARLUK began a second regional sampling pattern (September 2-16). From September 2 to September 11 samples were collected east of 150°W and the samples in Harrison Bay were collected between September 11-16. Freeze-up was in progress by mid-September. Figures 3 and 4 show the results of this sampling. The following aspects of the suspended matter distribution are noteworthy:

1. with few exceptions (only the close inshore samples), TSM concentrations and ash residue values east of Oliktok Point were low and, in fact, not substantially greater than the values present in March 1976 below a continuous ice cover;
2. although the station coverage in Harrison Bay is not what one would like to have, it appears adequate to suggest that the highest concentrations of suspended matter were present in the western half of the bay;
3. in contrast to the general composition of the suspended sediment east of Oliktok, the material in Harrison Bay was clearly dominated by inorganic mineral grains of clay and silt (figure 4).

VII. Discussion

Mountain (1974), Wiseman et al. (1974), Hufford (1973; 1974), Short et al. (1974) and Barnes and Reimnitz (1974; and in this report) have presented evidence which suggests that the net movement of water on the inner shelf is westward during the summer. This transport occurs in response to the local wind field. An examination of ERTS-1 imagery for the summers of 1972 and 1973 (Barnes and Reimnitz, 1974) shows a general westward migration of coastal suspended matter plumes (figure 7).

The distributions of suspended matter in the surface waters during the July - August and September 1976 periods (figures 1 & 3) add further support to the westward flow model. In particular, Walker (1974) has shown that the bulk of the Colville River sediment discharge moves through the eastern distributary. His figure 22 also suggests that there is a westward drift of the underice fresh water wedge during the initial period of river flow (June). This interpretation, which is based on only one survey, implies that another factor may force westward nearshore flow in addition to the easterly wind stress following breakup of shorefast ice.

It is clear that during July and August suspended matter from the eastern distributary does not move toward Oliktok Point (figure 1). The distribution of TSM suggests that most of the surface suspended matter is transported westward within a relatively narrow coastal zone. In fact, the highest TSM concentrations (10-20 mg/l) in July were present in the central nearshore area of Harrison Bay about 40 km west of the delta. Late in the summer (September 15-16) the peak surface water concentrations were measured south of Cape Halkett in western Harrison Bay approximately 80 km from the eastern distributary of the Colville River (figure 3). Taken at face value, these data imply a net westward drift of 0.5 to 1 cm/s during the summer. This is admittedly a gross oversimplification of the actual transport system. However, a mean flow of this magnitude is physically reasonable and also agrees fairly well with the net drift measured over a 50-day period by Barnes and Reimnitz (see other sections of this project report).

Sediment discharge to the Beaufort shelf between Canning River and Cape Halkett is clearly dominated by the Colville River. The smaller rivers such as the Kuparuk, Sagavanirktok and Shaviovik appear to exert only a local and comparatively minor effect on suspended matter concentrations (figures 3 & 4). By September, flow from these small streams has little influence on nearshore TSM distributions (figure 3). In fact, the September TSM concentrations east of Oliktok Point are not substantially greater than those present below the winter ice in March (figure 3), although the late summer particulate matter contains more noncombustible grains (higher ash residues).

The low suspended matter concentrations below the ice in March 1976 combined with current meter data that reveals very sluggish sub-ice water flow (<1 cm/s; Barnes and Reimnitz, this report) show that the winter sediment transport regime is relatively insignificant. This conclusion is, of course, based on "fairweather" data. Meteorological tides associated with low pressure systems could produce important sediment transport during the winter. However, Mountain (1974) points out that the ice cover will tend to reduce the impact of storms. We need data with which to evaluate higher energy events (in both winter and summer), but at this point it appears that the great majority of sediment transport occurs in the summer.

Naidu and Mowatt (1974) presented mineralogical evidence which implies that mud deposits at water depths of 20-40 m northeast of Prudhoe Bay were supplied by the Colville River. The location of this material more than 100 km east of its suggested source contradicts the arguments for westward sediment transport discussed above. The problem is that this deposit is completely disconnected from materials of similar clay mineralogy in Harrison Bay. One would expect some evidence for a connection if the deposits were the result of a transport system operating at the present time. Nevertheless, we cannot present new data bearing on this anomalous sediment distribution and it represents an interesting possibility for research.

VIII. Conclusions

The first full year of research on suspended matter transport on the Beaufort Sea shelf leads to the following preliminary conclusions:

1. the transport of sediment during the winter season of ice cover is a small fraction of the transport which occurs in the summer (June - September).
2. the Colville River sediment discharge for overshadows the discharges of all the smaller rivers. By late summer the discharges from the small streams has a negligible impact on nearshore suspended matter concentrations.

3. there is no evidence for transport of Colville River suspended matter eastward around Oliktok Point. Easterly winds and possible upwelling near Oliktok appear to prevent eastward sediment transport.
4. westward migration of suspended matter occurs throughout the summer in the nearshore portion of Harrison Bay.

IX. Needs for further study

1. The mineralogy of the suspended matter should be investigated and this research will begin shortly on available samples.
2. Long-term current meter and transmissometer/nephelometer moorings along coast-normal transects are needed. This method of data collection is probably the only way to evaluate the influence of summer and winter storms.
3. A high priority should be placed on gauging the water and sediment discharge from the Colville River and one of the smaller rivers. Such data would allow a comparison of source level and the thickness of Holocene shelf sediments.

X. Fourth Quarter Activities

No field work was done. Laboratory analyses and interpretation of 1976 samples was accomplished during this quarter.

XI. References

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XII. Papers in preparation

Drake, D. E. and others, Seasonal changes in suspended matter in waters of the nearshore Beaufort Sea shelf, Alaska.

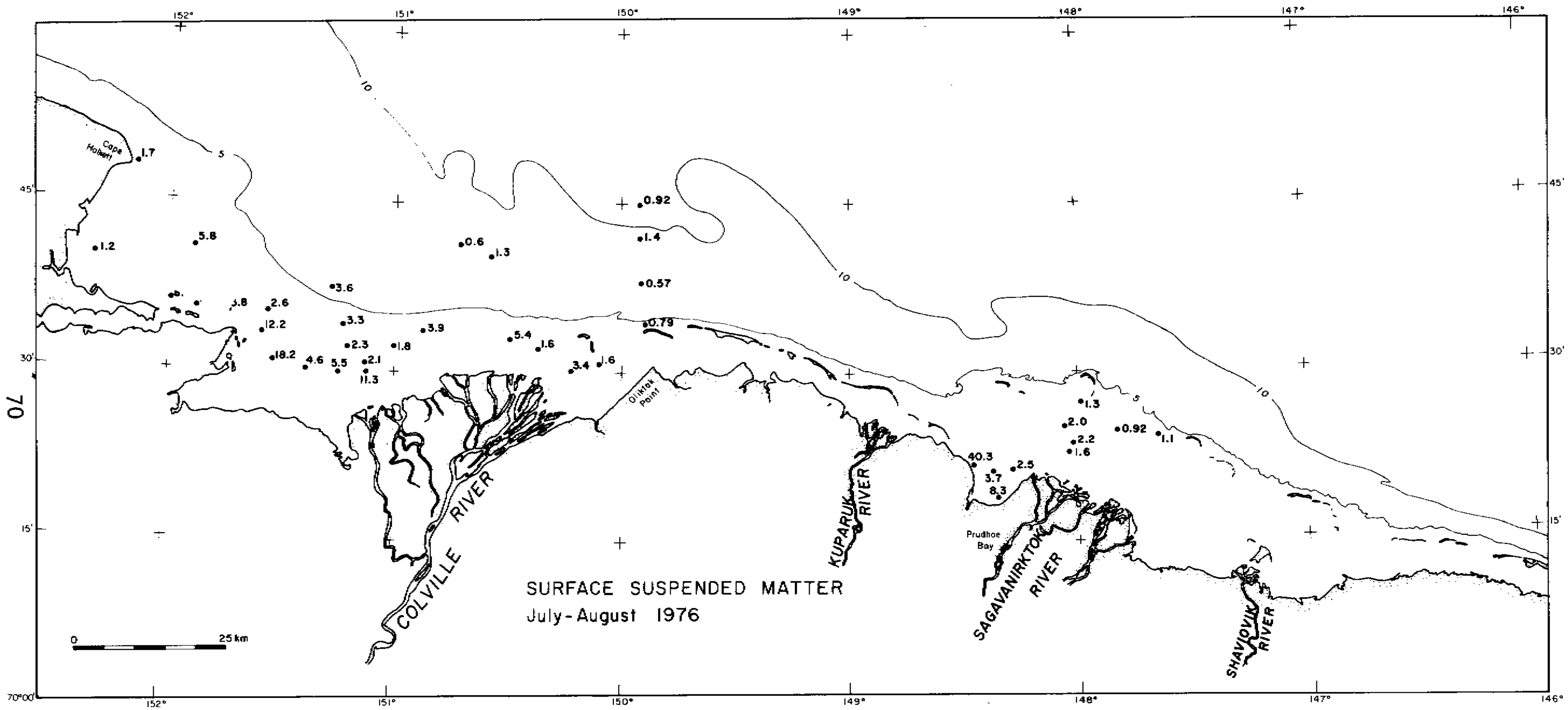

Figure 1. Total suspended matter (mg/l) in the surface waters during July and August 1976.

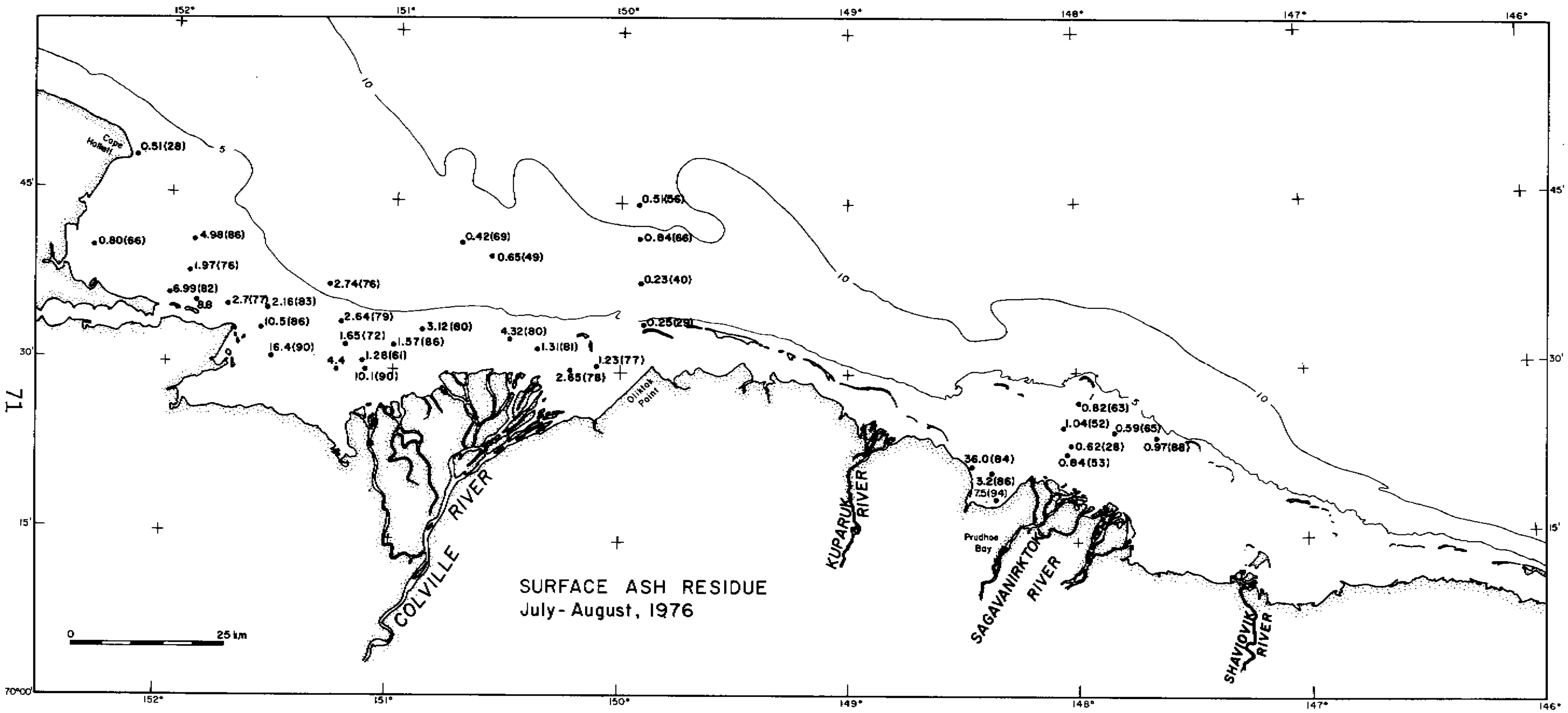

Figure 2. Noncombustible matter and ash residue percentages (shown in parenthesis) for surface water suspended matter, July - August 1976.

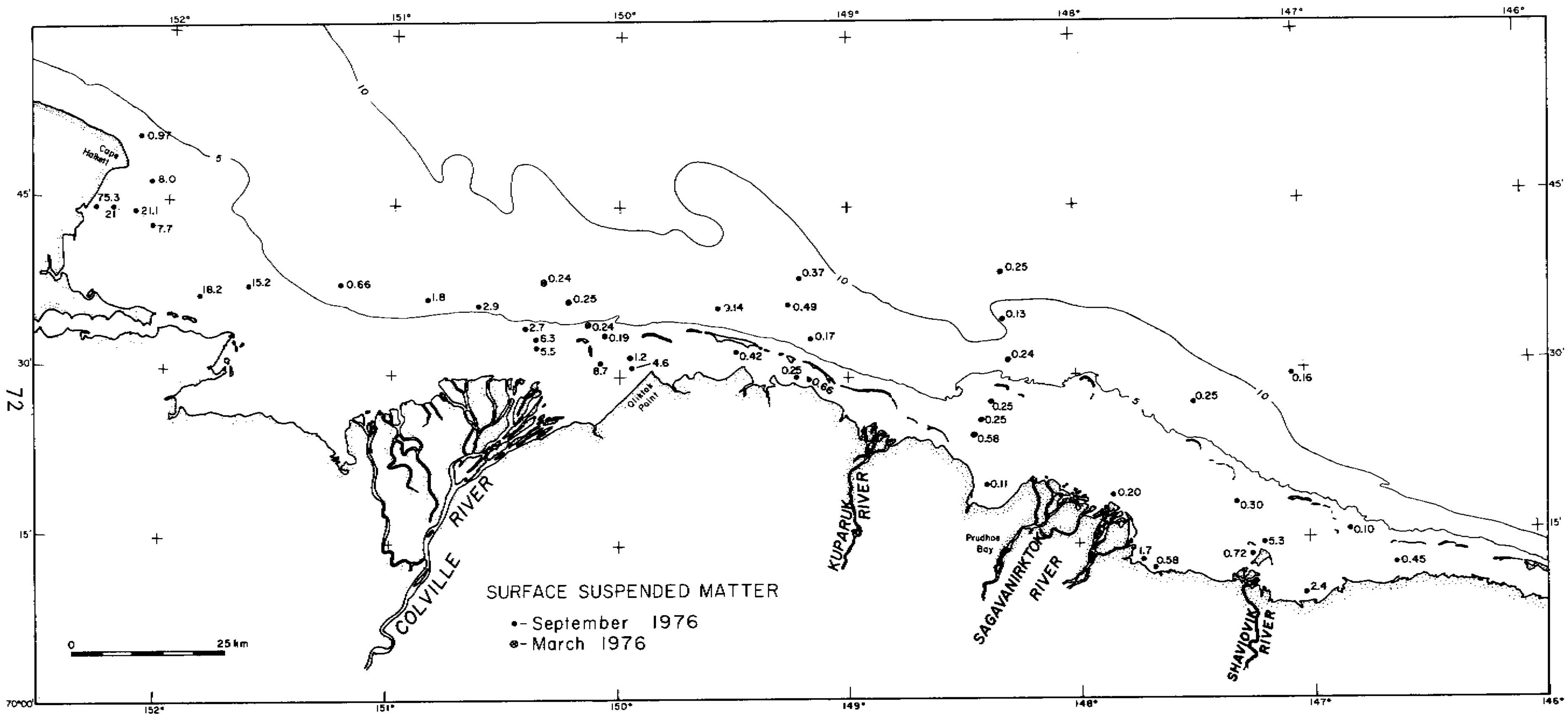

Figure 3. Total suspended matter (mg/l) in the surface waters during March 1976 (stations marked by X's) and September 1976.

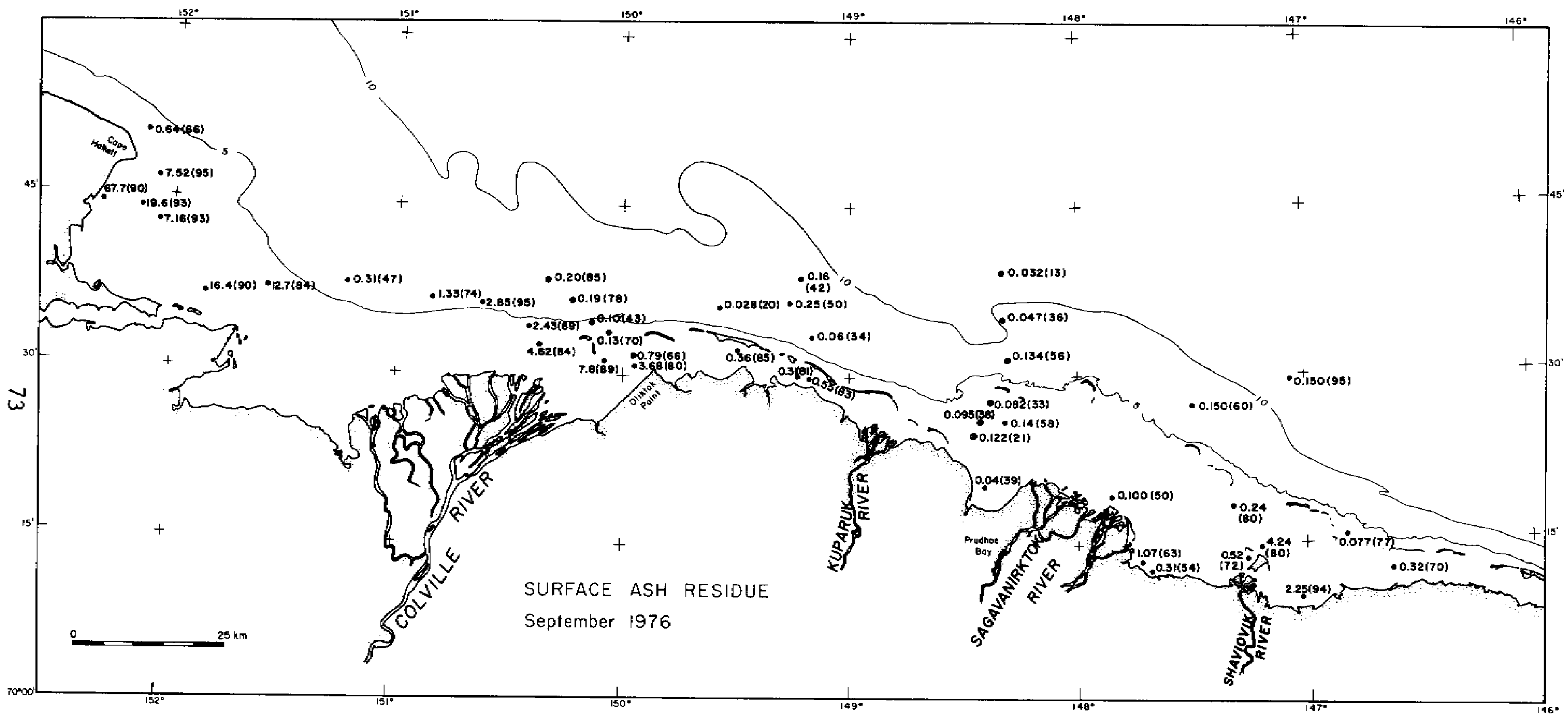

Figure 4. Noncombustible matter and ash residue percentages (shown in parenthesis) for surface water suspended matter in March 1976 (stations marked by X's) and September 1976.

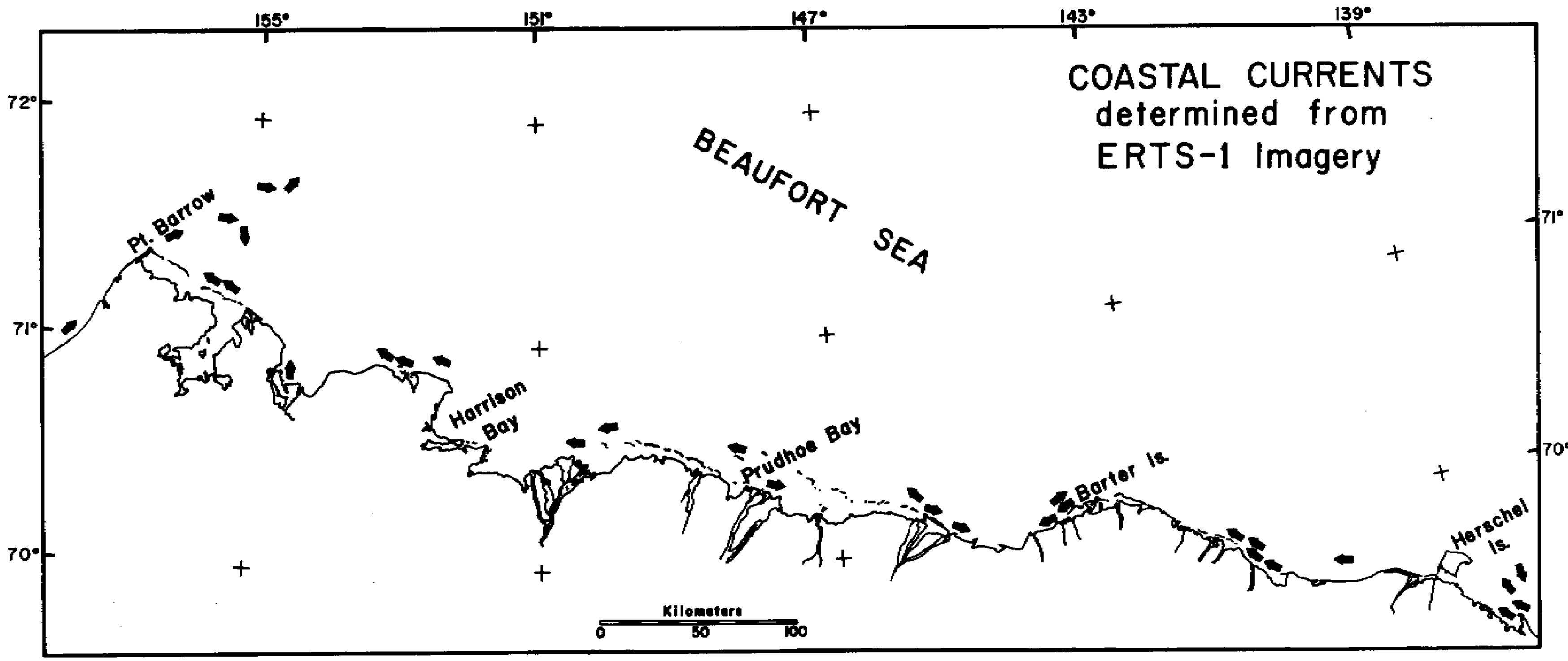

Figure 7. Nearshore transport based on analysis of ERTS-1 imagery for 1972 and 1973 (Barnes and Reimnitz, 1974).

ATTACHMENT F

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

BATHYMETRIC AND SHORELINE CHANGES NORTHWESTERN PRUDHOE BAY, ALASKA

By

Peter Barnes, Erk Reimnitz, Greg Smith, and John Melchior

OPEN-FILE REPORT 77-161
Menlo Park, California
March 1977

Bathymetric and Shoreline changes Northwestern
Prudhoe Bay, Alaska

By: Peter Barnes, Erk Reimnitz, Greg Smith, and John Melchior

INTRODUCTION

The coastal environment in the vicinity of Prudhoe Bay, Alaska (Fig. 1) is presently being vigrously utilized by petroleum activities. In particular, barges moving freight onshore over the past 8 years, have used the Prudhoe Bay entrance channel almost exclusively. To further facilitate the offloading of supply barges, Atlantic Richfield Company constructed a gravel fill causeway in 1975 between the Prudhoe Bay channel and Stump Island (Fig. 1). As initially constructed, the causeway extended 1.3 km perpendicular to the coast. Subsequently the causeway was extended 1.5 km in a northwesterly direction during the winter of 1975-76 to facilitate the offloading of barges stranded during the fall of 1975.

During July and August of 1976 the R/V KARLUK ran a series of sounding lines across the Prudhoe Bay entrance channel and in the vicinity of the new causeway west of the channel (Fig. 1). A skiff was also used to run lines between Stump Island and the causeway. This data compared with the detailed coastline and nearshore bathymetry from the U.S. Coast and Geodetic Survey smooth sheet (7857) and 1970 U.S. Geological Survey orthophotos, allow us to determine

qualitative changes in bathymetry and coastal configurations. Such a comparison provides a baseline to assess natural and man-related changes since 1950.

In addition to the long term variation of bathymetry, knowledge of whether bay and lagoon entrances in the arctic are blocked by fast ice during the course of the winter is of great importance for our attempts to evaluate the modern shallow water environments in the Beaufort Sea. Since the fast ice generally attains a thickness of about 2 meters (6 ft.), one might assume that shallow connections between the open ocean and bays or lagoons are sealed off sometime during the winter. Our studies in Gwydyr Bay and published reports (Schell, 1974), show that salinities below the ice can be twice as high as those in the open ocean. We have also found that the temperature of the high salinity water may be on the order of $-5^{o}C$. These facts would indicate that the shallow bodies of water indeed are isolated from the ocean. Before the isolation is completed, dense water may spill from the embayment of the lagoon, and flow seaward. The implications are important for the potential dispersal of pollutants, for example.

METHODS

U.S. Coast and Geodetic Survey smooth sheet 7857 was used to derive the 1950 bathymetry. The field data for this sheet was gathered in 1950 at 1:20,000 with trackline spacing of 300 m or less. Soundings were reported to the nearest foot below mean lower low water. As these early charts and our sounding instruments reported in English units, for ease and consistency, we have not interpolated to metric and will use English units for bathymetric measurements in this report (1 m = 3.28 ft).

During the 1976 survey, depths were measured to the nearest 0.1 foot, but were uncorrected for sound velocity, tidal or sea level differences. At the shallow depths (less than 10 ft) in this survey, sound velocity corrections are inconsequential. The tidal range is normally about 0.5 foot, with wind setup and setdowns of several feet during storms. Winds during this survey were not above 10 knots, and were from the northeast which causes a sea level set down. Line crossing from different times during the summer agreeed within 0.3 foot. Thus the 1976 data measured greater depths than the 1950 survey reported but the difference is less than one foot and probably less than 0.5 foot.

Line spacing for the 1950 survey was on the order of 300 m and during the 1976 work the spacing varied greatly (Fig. 1). Sallinger and others (1975) indicated the horizontal control for Coast and Geodetic Survey Charts of the scale used should be less than 50 m. Our navigational control was achieved using a range-range system giving a position accuracy of 20 m or better considering the system errors and the errors involved in locating the shore stations. Thus a detailed comparison of the absolute depth values of the 1976 survey with the 1950 survey is inappropriate, however, the changes in position and form are probably real.

Coastal configuration comparison was based on the 1950 smooth sheet coastline and the 1970, 1:20,000 U.S. Geological Survey Orthophoto maps of the area. The datum for the two surveys was based on mean lower low water and mean sea level respectively. Considering the small tidal range and the fact that the beaches are only a few meters wide, backed by 2 to 3 meter bluffs, and that the island foreshores are rather steep, the absolute difference between the two datums will amount to only a few meters or less.

Atlantic Richfield Company kindly permitted the use of data gathered for them on the thickness of the fast ice and the depth of the water beneath the ice in a reconnaissance study of the channel done in May and June of 1969. This data should closely represent conditions during the maximum thickness of the fast ice during the year. The report contains measurements of ice thickness and bottom depth along a track paralleling the axis of the channel (Fig. 1) and on cross-sections perpendicular to the axis. The initial survey of the axis and cross-sections was conducted in May using the top of the ice as the datum. The axial trackline was resurveyed in early June using the Prudhoe Bay benchmark as datum, which takes into account the irregular topography of the ice surface. When the correction for the datum level was made for the May data, the three sets (2 axis profiles and 1 cross-section profile) of ice thickness and depth curves agreed within .25 foot except for one point which seems to be in error.

RESULTS

Prudhoe Bay Channel

The most apparent bathymetric changes which have occurred in the 26-year interval between the 1950 and 1976 surveys, are the relative depth and location of the channel (Figs. 2 and 3). Within this time interval, the axis of the deepest part of the channel has shifted shoreward 50 to 175 m, the greatest onshore movement occurring near the midpoint of the channel. In addition to the onshore movement, the channel has been displaced seaward along with the shallows on either side of the channel, as evidenced by displacement to the northwest of the 1976 4-foot contour relative to its location in the 1950 contour.

Depth of the channel axis is 1 to 1.5 feet greater in 1976 than in the 1950 data. The 1976 fathograms also show local depressions up to 8 feet in depth. These deep holes may be related to seasonal changes in the maximum depth of the channel or to propellor wash from barge traffic. The 2-foot shoal in the central section of the channel has remained since the 1950 survey.

The study of the channel conducted in May and June of 1969 states that a general description of the channel would be approximately 4 feet of ice on top of 2 feet of water. This is significantly less ice than the normal 6-8 feet (2 m) seasonal ice growth found elsewhere. Using the data for the depth to the bottom and the ice thicknesses calculated from the drill hole logs, an isopach map of the thickness of water beneath the ice in the channel was constructed which showed water beneath the ice in all parts of the channel (Fig. 4). The assumption was made that the ice bottom was essentially flat along the length of the cross sections perpendicular to the channel axis.

The greatest water gap beneath the ice in the channel is three feet, and the least is 1.5 feet. This would indicate that water should have been able to flow in and out of Prudhoe Bay throughout the winter of 1968-1969 via this sub-ice channel although the pathway is much restricted compared to that of the open season.

Causeway and Vicinity

A comparison of the 1950 and 1976 bathymetry shows a number of marked changes in bathymetry in the vicinity of the causeway. The 6, 7, 8 and 9 foot contours on the east side of the causeway are displaced shoreward up to several hundred meters (Figs. 2 and 3). Southeast of the causeway, towards the entrance channel, the 4 and 5 foot contours are displaced offshore from the 1950 data.

Along the northeast side of the causeway extension our fathograms indicate a very irregular and disturbed bottom with depths of 3 to 15 feet. Field observations suggest that in part these features are due to dredging operations during causeway construction and completion. Furthermore, the aerial photographs show that the intense tug and barge activity in October, 1975 during freeze-up occurred along a corridor just to the northeast of the causeway extension. Propellor wash during this period could have created cut and fill structures.

Stump Island Area

Stump Island has undergone dramatic changes in shape and position during the twenty-year interval. The Island has moved onshore (southwest) 75-100 meters while both ends have extended in a northeasterly direction. In effect, this has changed the shape from lunate to almost linear. In addition, the area of the island has increased about 120,000 square meters between 1950 and 1970 (Figs. 2, 3, & 5).

The eastern tip of Stump Island has moved approximately 275 meters to the northeast of its 1950 location. The 1976 location from our studies and the 1970 location of the island terminus from U.S. Geological Survey orthophoto maps are essentially the same, indicating that the changes occurred prior to 1970 and that this end of the island has been essentially stationary since 1970. Our bathymetric survey crossed a shoal of less than 2 feet somewhere east of the present end of the island at a position which coincides with the 1950 location of Stump Island (Figs. 2 & 3).

Considering the earlier work on the movement of islands and spits on the Arctic Coast (Short, A.D., 1973; Barnes and others 1976) the onshore movement of Stump Island is to be expected. However, the earlier reports and our own data show that these islands typically migrate in a westerly direction as exhibited by the westward extension of Stump Island. The enlargement and offshore movement of the eastern spit is unique. Perhaps the funneling of water from occasional westerly storms down the coastal lagoon system, which extends some 50 km westward, has operated to maintain the eastern extremity of Stump Island.

Data from the 1950 survey did not cover much of the inshore area southwest of the causeway and across the eastern entrance to Gwydyr Bay, thus changes in this region cannot be evaluated. Our data shows a channel in excess of 5 feet deep along the mainland side of the channel between Stump Island and the coast. This channel shoals to the east and probably shoals to the west in Gwydyr Bay as we know this end of the bay is impassable to a vessel of 4-foot draft.

Coastal Erosion

A comparison of the 1950 and 1970 coastlines shows erosional changes on the mainland coast along with the marked change in the configuration of Stump Island (Fig. 5). The northeast-facing coasts east of Gwydyr Bay have been eroded up to 60 meters. The most pronounced erosion occurs a Point McIntyre. From here eastward the coast is uniformly eroded from 10 to 20 meters. Rates of erosion calculated for the 20-year interval range up to more than 3 meters per year, but average about 1 meter per year. Within Gwydyr Bay erosion has been restricted to the coastal promintory west of Point McIntyre. On this point maximum coastal retreat of 50 meters was measured.

The coastal retreat reflects the pattern of dominant winds and waves. On the exposed coast east of Point McIntyre, erosion is noted all along the coast while within the protected environment of Gwydyr Bay only the coastal promintory exposed to the considerable fetch of westerly waves has marked erosion. It is interesting to note erosion even in the region of coast somewhat protected by Gull Island shoal. Coastal retreat in the lee of the new causeway will probably decrease.

DISCUSSION

Prudhoe Bay Channel

The onshore movement of the channel axis is probably a result of the coastal retreat and the southwestward extension of the Gull Island shoal under the influence of the dominating northeasterly winds and waves. Apparently, however, the channel has moved more than the coastline has retreated. Furthermore, there is an apparent shoaling of the channel during the open water season. Personnel of the tug and barge operations report that the channel seems to become more difficult to traverse as the open water season progresses (July to September) due to shoaling. During the 1976 season with the KARLUK we noted that in late July and early August we could transit the channel easily with a draft of 4 feet, while in late September, even lightly loaded (3.5 foot draft), we had to grind along the bottom over much of the central portion of the channel.

One possible explanation for these changes is apparent when the entire yearly cycle of events is considered. During the fall and early winter when the sea ice canopy is growing in thickness, tidal and barometric changes in sea level must move in and out of Prudhoe Bay through smaller and smaller cross sections. Ultimately, when Gull Island shoal and the openings between Gull Island and Heald Point are sealed off by bottom fast ice, the only opening remaining for the flow of water in and out of the bay is the entrance channel. Data taken from channel cross sections by drilling through the ice in May and June, show that the channel may be hydraulically maintained all year below the ice (Fig. 4). The shallowest section of the channel in this survey was 5.5 feet. Thus each spring the channel could be scoured to a depth somewhat near the thickness of the seasonal ice cover (about 6 feet).

During the open-water season, the prevailing northeasterly winds and waves would tend to move sediments from the Gull Island shoal into the channel.

This would explain the shoaling noted by the tug and barge operators and the shallower depth of the August 1950 Survey of the Coast and Geodetic Survey. Our 1976 channel survey was accomplished in late July right after the ice had cleared and would explain why we observed a deeper channel. The southwesterly extension of the Gull Island shoal is further evidence that sediments are moving onshore. With the onset of freezeup, channel scour would be initiated with the newly infilled sediments being the most susceptible to erosion.

Coastal Erosion

The predominant winds and waves during the open water season on the arctic coast are from the northeast. Elsewhere along the coast this has resulted in longshore drift to the west as seen in the westward movement or extension of insular spits on many of the coastal islands (Short, A. D.,1973; Barnes and others, 1976) Furthermore, the eastern parts of these same islands show erosion. The rare late summer and fall storms usually are accompanied by westerly winds and a significant rise in sea level (up to 3 meters in 1970).

In the area of this study, longshore transport and accompanying erosion have been noted. At the dogleg in the causeway, sheet piling and weighted barrels are being used to retard and prevent erosion on the eastern side. Further inshore The Alaska Department of Fish and Game personnel experienced burial of their fish trap due to longshore transport of gravel (T. Bendock, pers. commun.).

Coastal erosion along the north coast of Alaska is a result of permafrost degradation of the low 1 to 3 meter high tundra bluffs. Rates of erosion are commonly around 1 meter per year with the greatest erosion occuring on headlands and the eastern ends of the offshore islands where rates of 10 to 40 meters per year have been reported (Short, A.D., 1973; Lewellen, R., 1970). The values we report here of up to 2.5 meters per year average for the 20-year interval between 1950 and 1970, are in keeping with the earlier observations. Furthermore, the northeast facing shores appear more susceptible to erosion from the prevailing northeasterly wind, even though these winds are not associated with the meteorological rise in sea level.

Conclusions:

1. The Prudhoe Bay channel is migrating shoreward at 1-2 meters per year and possibly experiences seasonal infilling and erosion which results in open season variations in channel depth.

2. Coastal retreat under the influence of the northeast winds averages 1-2 meters per year but may average more than 3 meters.

3. The construction of the causeway and the attendant ship traffic is affecting the bathymetry in the immediate vicinity, although it is too soon to see any established trends.

4. Stump Island has moved onshore and has undergone an apparently episodic change resulting in an increase in size and change in shape.

5. The nearshore environments in this area are influenced by long and short term changes in coastal configuration, bathymetry and island morphology which are and will continue to be influenced by man's activities.

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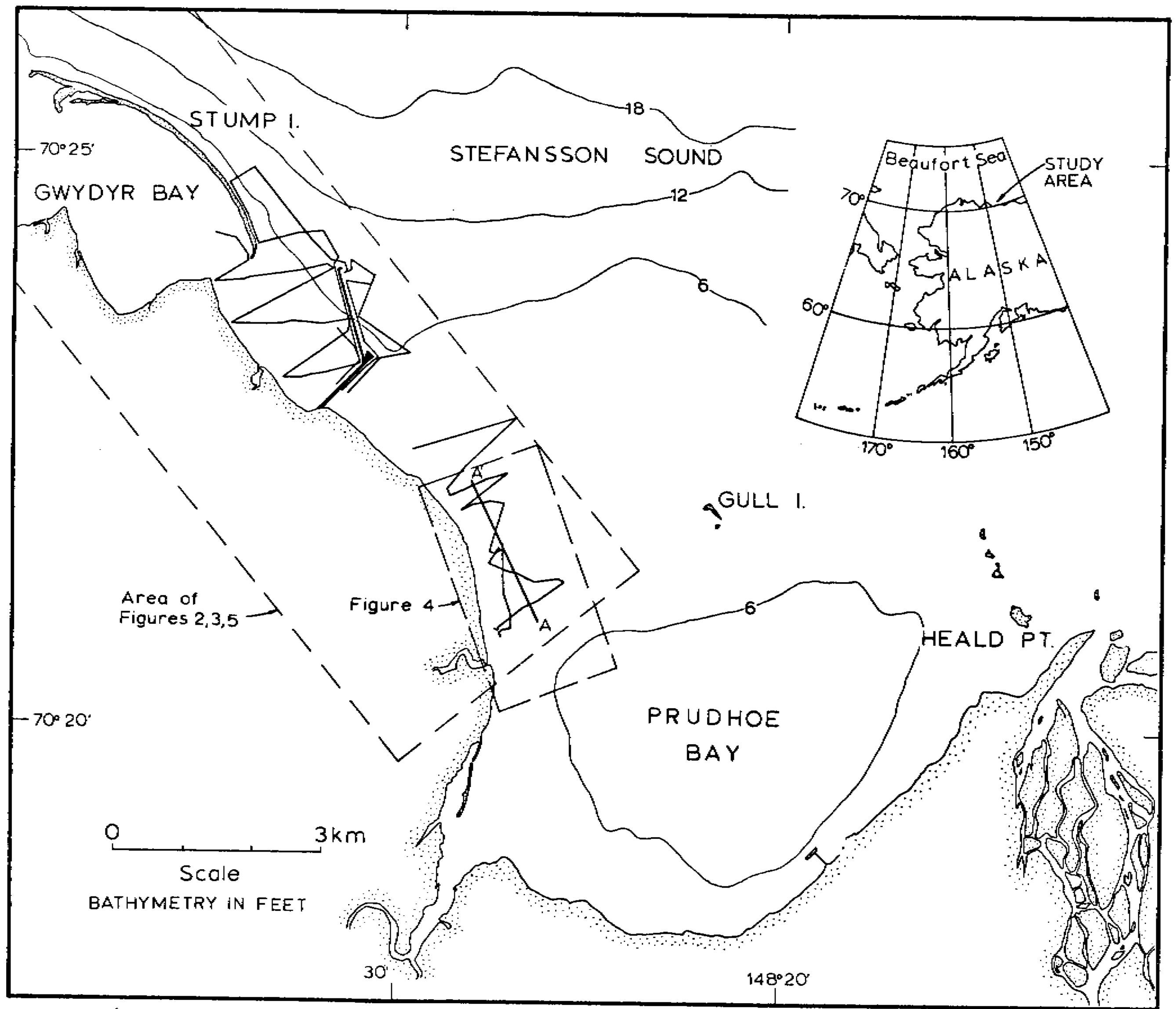

Figure 1. Location and trackline map showing the location of the study area of this report and the tracklines occupied in July and August, 1976. Section A-A' is the channel survey line occupied by the industry survey in 1969.

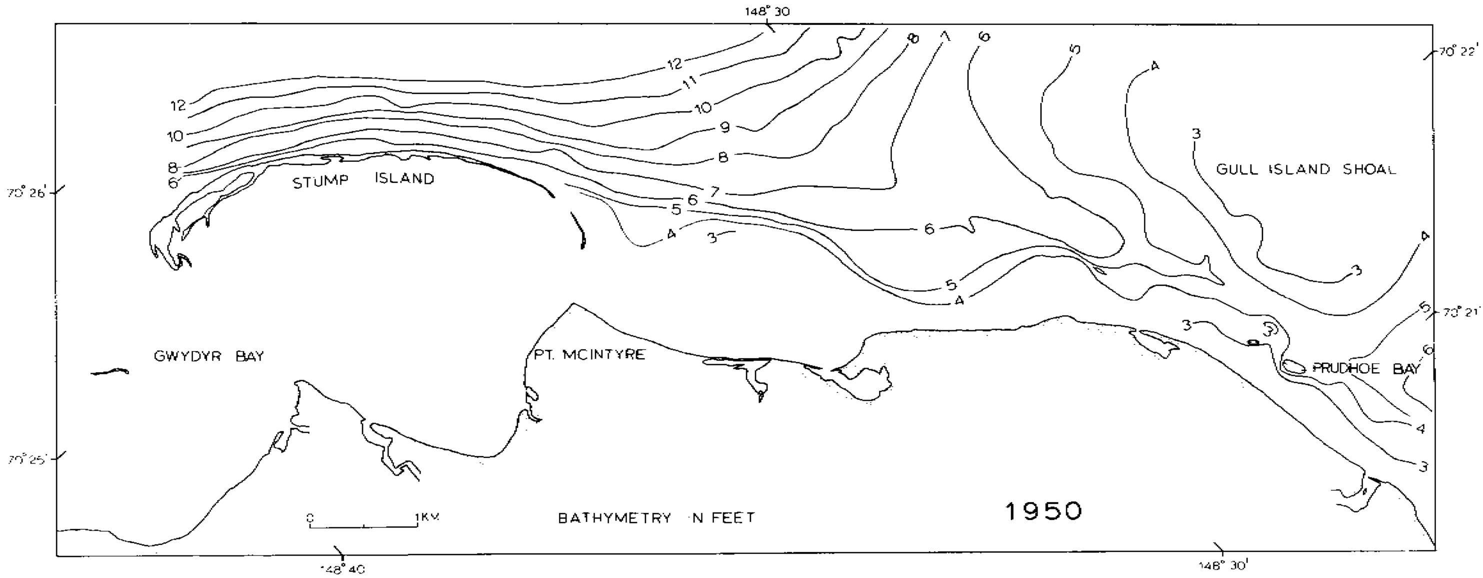

Figure 2. Bathymetric contours from the 1950 survey east of Stump Island, U.S. Coast and Geodetic Survey smooth sheet 7857. Contours at one foot increments.

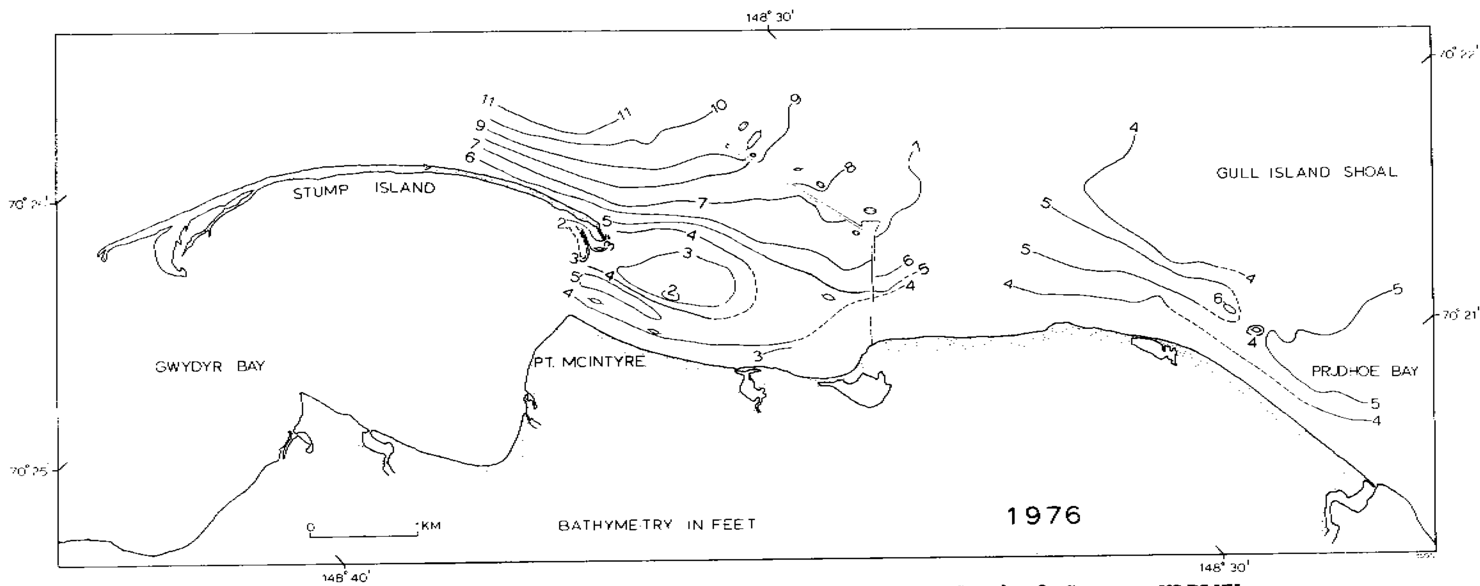

Figure 3. Bathymetric contours from the 1976 U.S. Geological Survey KARLUK data. The inner causeway segment was constructed in spring 1975 and the outer segment in the winter of 1975-76. Contours at one foot increments.

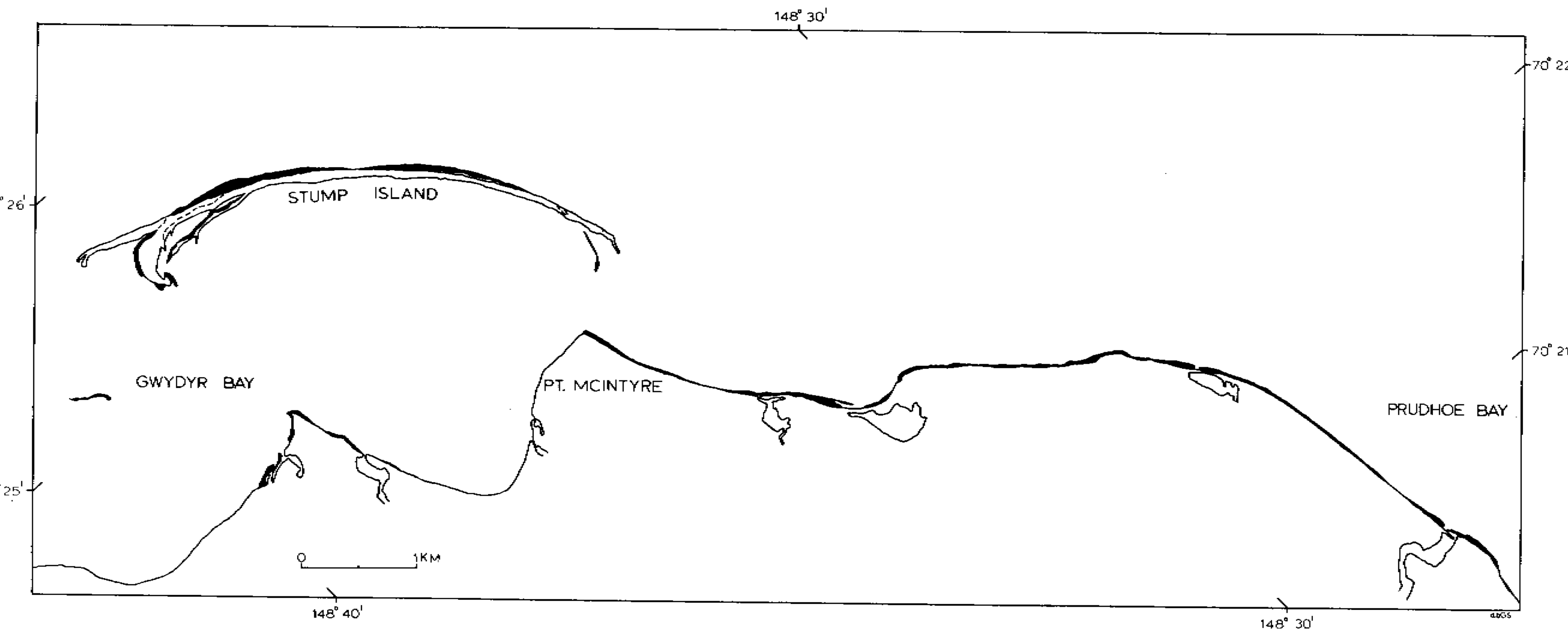

Figure 5. Coastal erosion and Stump Island re-configuration from 1970. 1950 data from U.S. Coast and Geodetic Survey smooth sheet 7857. 1970 data from U.S. Geological Survey Orthophoto map, Beechy Point B-4 NW, Scale 1:20,000. The coastal retreat and changes in island morphology from 1950 to 1970 are shown as solid black.

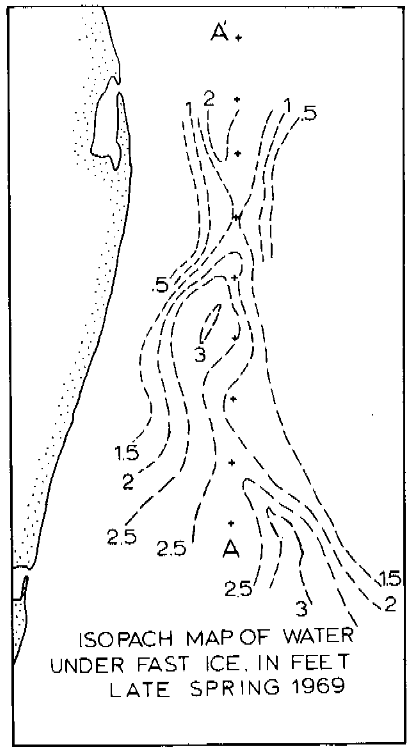

Figure 4. Isopach map in feet of the water beneath the ice in late May 1969. The + indicates the bore holes and center lines for the channel cross-sections from the industry report.

ATTACHMENT G

Rates of Ice Gouging, 1975 to 1976, Beaufort Sea, Alaska

P. Barnes, D. McDowell, E. Reimnitz

INTRODUCTION

Sea ice on the continental shelves of arctic Alaska impinges on the sea bottom at varying intervals of space and time. Knowledge of the recurrence interval at which ice is likely to interact with the sea floor, or the rate of ice gouging, is important from several standpoints. Using gouge recurrence and depths, the rates of sediment reworking can be estimated, and the effect on benthic communities evaluated. Furthermore it is of utmost importance in the planning and design of offshore installations, such as pipelines and subsea well heads, to know the rate and depth to which ice is likely to penetrate into the sea floor.

In the area of this study (Fig. 1) sea ice zonation falls into three general categories (Reimnitz and others, 1976): 1) a bottom fast ice zone inside the two meter isobath, where ice at the end of the season of ice growth rests on the sea floor; 2) the zone of floating fast ice, with varying quantities of thicker, older ice, seaward of the bottom fast ice; and 3) at the seaward edge of the floating fast ice, a zone of grounded ice ridges forming the stamukhi zone. The two fast ice zones remain essentially stable during the winter. The stamukhi zone, commonly occurring in 15-20 m depths, marks the boundary between the stable fast ice and the moving polar pack, and is an area of shear and pressure ridge formation and ridge grounding during the winter. During the summer open water season, drifting ice of various drafts is commonly present at all water depths on the inner shelf. Solidly grounded stamukhi may remain grounded throughout one or several seasons of melting.

The area of this study (Fig. 1) is located north of Oliktok Point in water depths of 6 to 12 m, the zone of floating fast ice (Reimnitz and others, 1976). In some years an early winter shear line crossing the test area (Fig. 1) develops in the vicinity of the 10 m isobath in Harrison Bay. The sea floor in the study area slopes steeply offshore from the islands to depths of about 7 m, then move gradually seaward. Test line 1 runs northwest from Thetis Island and test line 2 heads just about due north from Spy Island.

METHODS

In 1973, 1975 and 1976 a side-scan sonar and fathometer were used on carefully navigated test lines to repeatedly examine the same area of sea floor in each of the three years (Fig. 1). A comparison of gouging on testline 1 between 1973 and 1975 has already been reported on (Reimnitz and others, 1977). Sonographs from the side-scan sonar were the key data to define the presence of new gouge features from one year to the next. The 1973 and 1975 records cover a 125 m swath on both sides of the ship's track while the 1976 survey flubbed and covered only 100 m on either side. Depending on sea state, bottom reflectivity, and system tuning the sonographs produced by the side-scan can resolve features less than 10 cm high.

Navigation along the test lines was accomplished by ranging on landmarks onshore and by a precision range-range navigation system which reads to the nearest meter and is accurate to ± 3 m. With these techniques the test lines were re-surveyed within 50 m from year to year and obtained overlapping sonographs of the sea floor except in areas of detours to avoid ice. The fathometer used in this survey utilized an 8° cone in 1975 and a narrow beam 4° cone in 1976 and was capable of resolving bottom relief of less than 15 cm.

RESULTS AND DISCUSSION

The analysis of ice gouge character along the two test lines was divided into two parts. First the summary character of ice gouging of 1/2 km line segments were tablulated from the 1975 records. Secondly, the new gouge features formed between 1975 and 1976 were examined using both the 1975 and 1976 records. Only the data from test line 1 have been completely analyzed at this time.

An idealized gouge cross section is shown in Figure 2 as an aid in clarifying the terminology used in this report. Note that: a) "incision depth" is generally less than true relief; b) the final gouge depression may be narrower than the incision due to slumping; and c) the "extent of disruption" probably often reaches beyond the original incision.

Summary of ice gouge characteristics

The dominant gouge trend, depth profile, density, maximum incision depth, and maximum disruption was determined for 1/2 km segments of the test lines (Fig. 3). We have tried to standardize as many of the admittedly subjective observations (Hnatiuk and Brown, 1977) as noted below, in an effort to make them comparable from one area to another and from year to year.

Gouge trend: Most ice gouge features are linear. The gouge trend is the orientation of the major portion of the linear features within a given segment. As both the boat speed and paper speed are variable, the sonographs exhibit horizontal exaggeration. By removing the exaggeration and computing the true orientation relative to the ship's course, the gouge trends may be determined. A dominant trend was computed for each 1/2 km segment. Occasionally subordinant trends were evident, or the variability and non-linearity of orientation were so pronounced that it was not possible to plot a representative trend.

On test line 1 the dominant trend is clearly east-west, which is essentially parallel to the depth contours in this area (Fig. 1 & 3). The trend is uniform on both the inner and outer parts of the line. The dots circumscribed by circles (Fig. 3) denoting no dominant trend occur on the inner parts of test line 1. On test line 2, (not shown), the lack of preferred orientation was associated with the tops of submerged ridges.

Gouge density: To determine the density of gouges per square kilometer, every linear feature resulting from ice contact with the bottom was counted, including each individual scratch produced by multi-keeled ridges, as we wished to assess the effects of ice on the bottom. As more gouges would be seen when the ship's track is perpendicular to the trend of gouges over a given distance than when the track is parallel to the features, due to limited scan width of the sonar, gouge counts were normalized to represent the number of gouges that could be seen if all gouges were at right angles to the ship's track using the following equation:

$$N = \frac{i}{i \text{ Sin } \emptyset + R \text{ Cos } \emptyset}(N_{obs})$$

Where: N =corrected number of gouges in counting interval
N_{obs}= observed gouges in interval
R = recorded width of sonograph - meters
i = counting interval length in meters
$\emptyset$ = dominant trend angle of gouges relative to ship's track
(90^o = perpendicular to track).

For the 1975 records and a 500 m counting interval this formula reduces to:

$$N = \frac{500}{500 \text{ Sin } \emptyset + 250 \text{ Cos } \emptyset}(N_{obs}) \quad \text{or}$$

$$N = \frac{1}{\text{Sin } \emptyset + .5 \text{ Cos } \emptyset}(N_{obs}).$$

Thus a count of 20 gouges in a 1/2 km segment of track, oriented with a dominant trend of 45^o to the ship's track, calculates to 18.8 gouges per 1/2 km of track 1/4 km wide.

Assuming that the distribution of gouges immediately adjacent to the zone scanned with the sonar is similar to that on the sonograph, the density of gouges per unit area may be calculated. This is only possible because the gouge count has been normalized for right angles to the ship's track and the assumptions made that all gouges have the same trend, and that they are linear. As the gouges are at right angles by the above formula, the number of gouges calculated for a kilometer segment of trackline should be the same as the number in a kilometer square bisected by that trackline segment. Thus, the above example of 20 gouges in a 1/2 km segment of track can be converted to a gouge density of 37.6 gouges/km as follows: 18.8 gouges per 1/2 km of trackline, which is equivalent to 37.6 gouges per km of track, which is equivalent to 37.6 gouges per km^2 when gouges are at right angles to the track.

On test line 1 the gouge densities correlate with bottom slope: portions with steeper slopes have higher density values (Fig. 3). Densities are highest (88/km) in 9 m of water depth at the upper edge of a steeply sloping segment of the bottom profile. The lowest values are associated with the flat upper surface of a subtle topographic high about 2 km from shore. The overall trend on testline 1 shows a slight increase in gouge densities in the offshore direction.

Incision depth: The depth to which ice penetrated below the sea floor (incision depth) was measured rather than the overall vertical distance from the top of the ridges to the gouge floor (Fig. 2). This incision depth is a true measure of the depth of sediment reworking. The maximum incision depth was determined for each 1/2 km interval from the fathogram.

Maximum incision depths on test line 1 appear to be related to the maximum densities of gouging (Fig. 3). One might conclude that a greater number of ice-bottom interactions increased the chances for the deeper gouges. Intuitively, less incision depth might be expected inshore as the size of the cutting tools decreases due to draft limitations. This would appear not to be the case, at least not within the area and depth ranges examined on test line 1.

Disruption width: Within each track segment the widest gouge disruption created by a single ice event was measured, taking into account the horizontal exaggeration of the sonograph records. The disruption width was measured (Fig. 2) as the incision width could not be accurately determined from the fathograms due to ridge slumping and sedimentation. The largest feature within the scanned bottom did not always cross the trackline and thus often was not recorded on the fathogram.

Maximum disruption widths for the 1/2 km segments on test line 1 tend to increase in an offshore direction (Fig. 3) with a maximum observed width of 40 m. Gouges over about 15 m in disruption width are almost always the result of the action of a multi-pronged ice keel. The wide gouges are not associated with the deepest gouges. In fact, the opposite may be ture. Deep gouges commonly are narrow.

New gouges, 1976

By comparing the 1975 and 1976 sonographs of Line 1 for morphologic traits such as intersections of lineations, characteristic angles, and notable debris piles (Reimnitz and others, 1977), area matches could be made(Fig. 4). By careful analysis of the 1976 sonographs, new ice gouge features were identified. Time ticks were used to key the sonar records to the fathograms for depth and width measurements.

The 1975 Survey was run in the middle of September, shortly before freeze-up, while in 1976, reoccupation of the test line occurred shortly after the sea ice break-up in early August. Thus most of the new gouges seen in the 1976 records most likely occurred during the arctic winter when the area was ice covered.

The actual trend, incision depth, incision width, and disruption width was determined for each of the 39 new gouges, along with observations on their morphologic character (Fig. 5). For comparative purposes gouge densities, maximum incision depths, and maximum disruption widths were determined for the same 1/2 km intervals used for the summary (Fig. 3).

Gouge trend: The dominant northeast-southwest trends of 1976 gouges is clearly different than the dominant trend seen in the 1975 records (Figs. 3 & 5). The change in orientation is evident along the entire length of the survey line. The new gouge trend is more onshore or more in keeping with ice moving into Harrison Bay (Fig. 1). The bulk of the new gouges have the same trend and are very straight(Figs. 4 & 5) suggesting that they may have formed during the same ice event when the ice acted as a single unit.

Gouge density: The densities of new gouges are remarkably evenly distributed over the length of the test line (Fig. 5). The highest number of new gouges occurs near the middle of the test line, in water depths of 11 - 11.5 m.

Incision depth: The average depth of incision for all of the new gouges was determined to be 31 cm. Some of the new gouges delineated on the sonographs could not be detected on the fathograms. For these gouges we assumed a depth of 10 cm for our calculations. The maximum new incision was 120 cm deep, deeper than any seen in the 1975 records (Fig. 3). In plotting the maximum incision depth observed in each 1/2 km segment (Fig. 5) it is apparent that the deeper gouges occur further seaward, and they are not restricted to areas of the highest number of gouges.

Gouge width: Two width parameters were measured for the 1976 gouges. The incision width (Fig. 2) was used in calculating rates of sediment reworking and the disruption width as measured on the fathograms was used in comparing new gouges to the summary gouge characteristics (Figs. 3 & 5). As most gouges were not crossed at right angles, width measurements from the fathogram had to be corrected for the trend of the gouges.

From the 39 new gouges, the maximum incision width observed for a single-pronged ice gouge event was 10.9 m, while the maximum disrupted width was almost 36 m wide from a multi-keeled event. The interval distribution of maximum disruption widths (Fig. 5) shows a strong correlation with the maximum incision widths.

Rate of ice gouging anu sediment reworking

Using the data on depth of incision, incision width, length of test line compared, and the time interval between surveys, a rate of ice gouging and sediment reworking may be calculated. The rates thus derived are predicated on the assumption that gouging will proceed in a systematic manner and will not replow the same area until the entire sea floor is reworked. Based on these assumptions the bottom along test line 1 would be reworked to an average depth of 31 cm every 82 years. For the 1973 to 1975 data on the the same test line we reported reworking to 20 cm or more every 50 years (Reimnitz and others, 1977). Data from 44 new gouges on test line 2 (Fig. 1) shows gouging to an average depth of 19 cm and a gouge recurrence rate of 53 years.

As ice interaction with the bottom probably does not occur in a systematic manner, a better approach to the rate problem might be to analyze individual segments of the test line for the amount of gouging occurring in each segment. From such an analysis of the 1973-1975 and 1975-1976 data (Table I), several interesting things appear although the number of new gouges is small in each interval.

The highest rates of gouging and sediment reworking in both periods of observation occur on the innermost and outer parts of the test line, with lower values between 4 and 10 km in water depths of about 10 to 11 m (Table I). Fewer but wider gouges were observed during the two-year interval between 1973 and 1975 (21 gouges) than in the single season from 1975 to 1976 (39 gouges). This may be due to the lower quality of records obtained in 1973 although the rates of gouging are of the same order of magnitude (Reimnitz and others, 1977). The widely differing character of gouging during the two periods suggests that gouging is a very sporadic process and perhaps is strongly dependent on ice and storm conditions of the preceding fall and winter.

Lewis and others (1976), give rates of gouging for the Canadian Beaufort Sea in water depths of 15-20 m. Examination of the Canadian sonographs show gouging of the same character as we observe off Alaska and we would expect similar processes. For two different areas on the Canadian shelf, they show re-plow recurrence rates of about 500 and 50 years, somewhat less than our span of interval rates in shallower water (Table 1). This would suggest that the area studied in the Alaskan Beaufort Sea is susceptible to more gouging than in the Canadian area off the MacKenzie delta, or more likely, a difference exists in methods of interpretation.

Table I - ICE GOUGE DATA- NEW GOUGES

Interval on test line 1

		2-4 km	4-6 km	6-8 km	8-10 km	10-12 km	12-14 km	14-16 km	Total/Avg.
Water depth-meters		7.6m	9.7	10.5	11.3	12.6	13.1	13.7	--------
Number of gouges/yr	1973-1975	2	4.5	0	1	.5	1	1.5	21(2 yrs)
	1975-1976	5	5	3	10	6	8	3	39
Incision width - m	1973-1975	17m	79	0	7	45	105	12	263(1 yr)
	1975-1976	13m	10	9	40	43	25	24	161
Average incision depth in cm	1973-1975	40 cm	37	0	45	30	45	27	37
	1975-1976	35 cm	12	10	31	40	31	80	31
Amount of trackline gouged, m/km/yr	1973-1975	8m	40	0	4	22	53	6	19
	1975-1976	6m	5	4	26	21	12	12	12
Rate of reworking - yrs -"no replow"	1973-1975	119yr	25	-	285	45	19	166	52
	1975-1976	157yr	202	230	38	47	81	84	81

In considering the rates of sediment reworking and the amount of bottom disturbed by gouging, our estimates are very conservative. Gouge depths do not include the height of the flanking debris ridges, nor do they include a correction for the cone angle of the fathometer which will give conservative values for narrow deep gouges (Fig. 2). The "extent of disruption" by ice keels often includes a considerable area on one or both sides of the incision (Fig. 2). Measurement of the 1976 gouges on test lines 1 and 2 indicates that widths were 1 1/2 to 3 times wider than the incision widths. If these widths are used to determine rates of reworking, the values we report above would have to be reduced by 1/3 to 2/3.

As we reported in earlier work (Reimnitz and Barnes, 1974; Reimnitz and others, 1976) higher rates of ice gouging and ice bottom interaction are related to: steeper bottom slopes, local topographic highs, geographic exposure to drifting ice, and ice zonation. The segments of test lines 1 and 2 reported here are somewhat geographically protected by updrift shoals and are located inside of the major stamukhi zone, within the zone of floating fast ice (Reimnitz and others, 1976). As it is within the stamukhi zone that winter ice deformation is most intense, we would expect rates of gouging to be greater further seaward along the test lines. To date the presence of stamukhi in summer has kept us from obtaining repetitive surveys in this area although one set of data exists for the 1973 and 1976 season in different areas.

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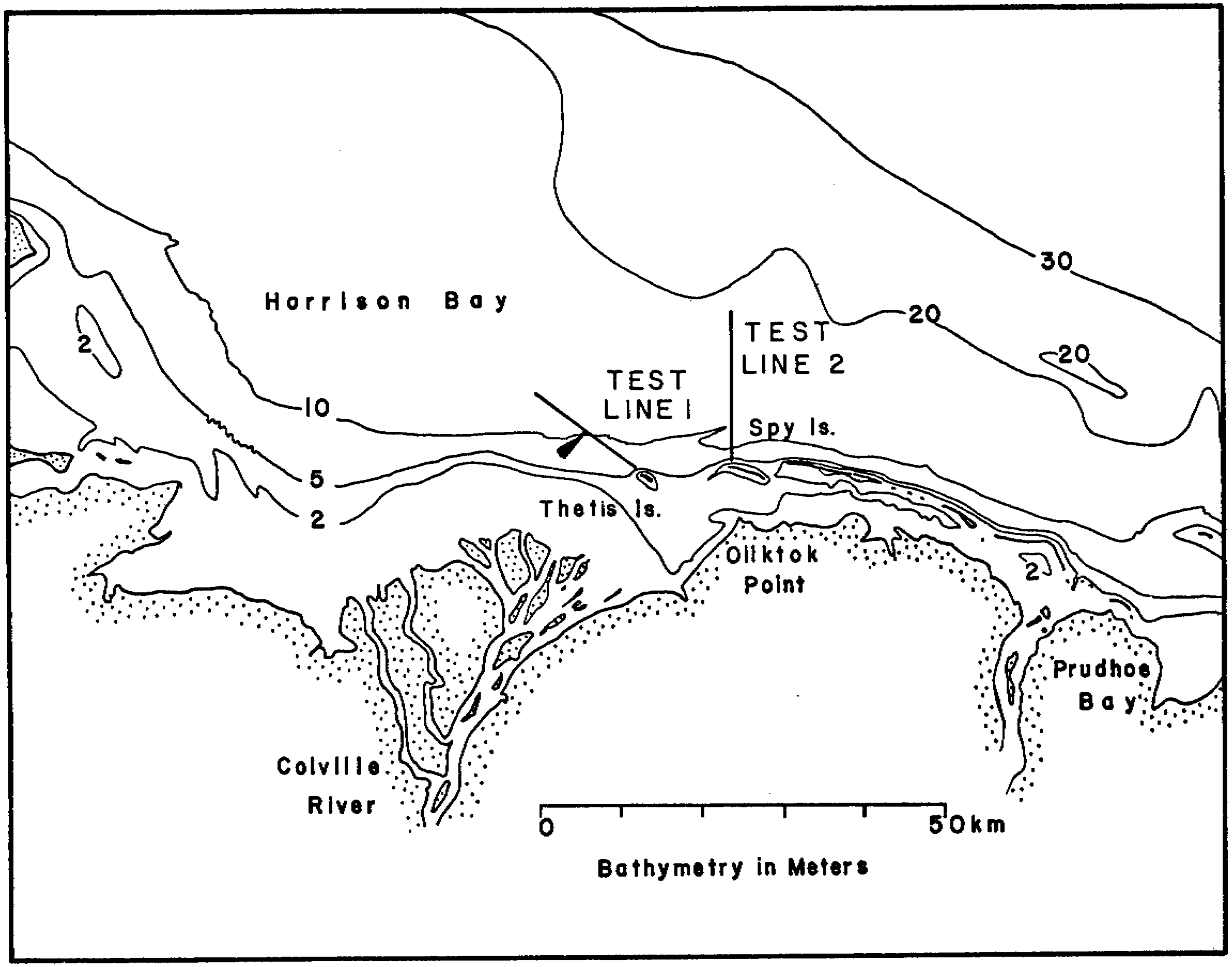

Figure 1. Location map of the study area indicating the location of test lines 1 and 2. The arrow indicates the location of the sonographs and fathograms of Fig. 4.

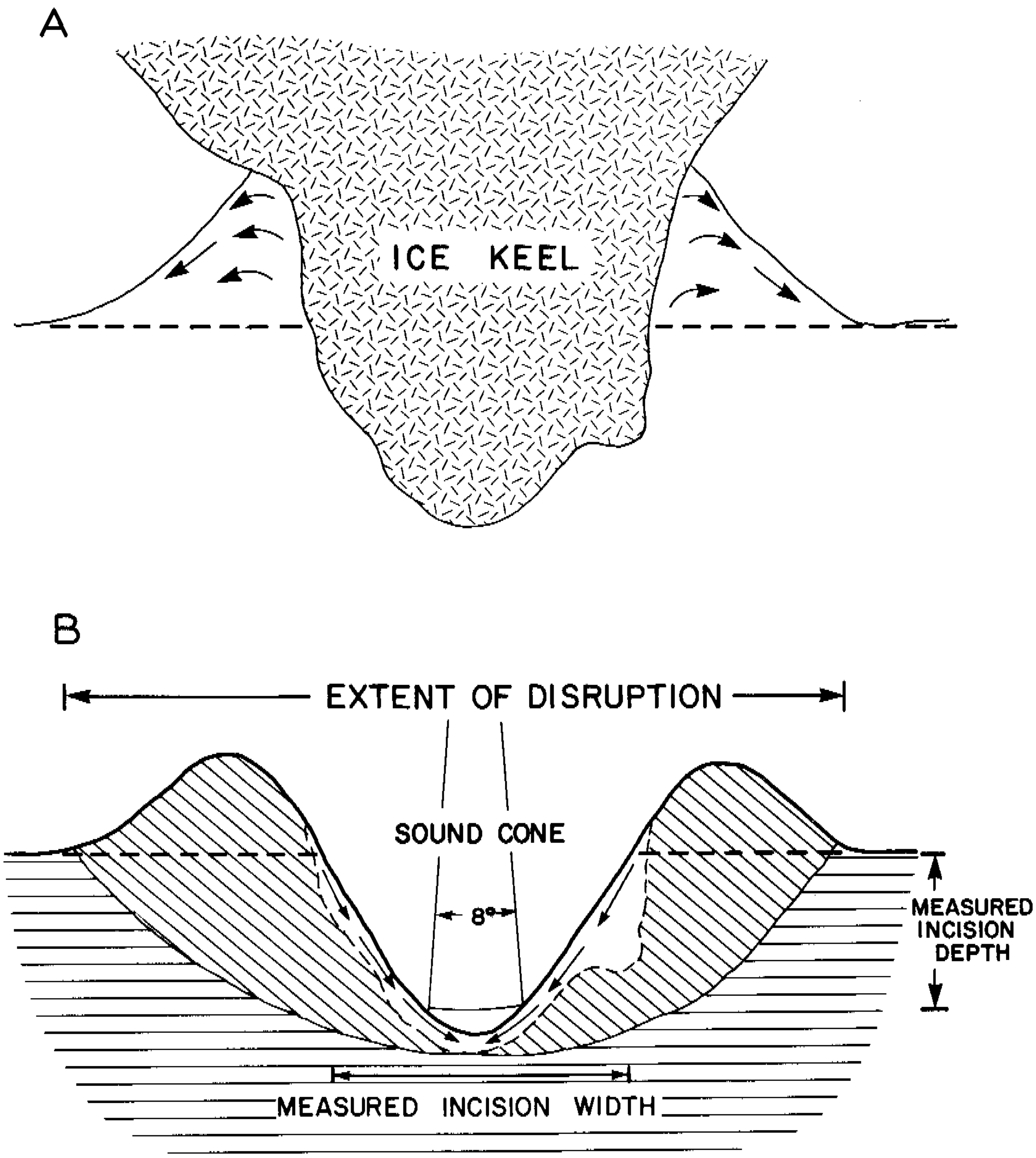

Figure 2. Drawing of an idealized ice gouge cross section explaining gouge terminology. A) Gouge being excavated by ice keel. B) The same gouge after the ice keel has passed by and some slumping of the sides has occurred. (after Reimnitz and others, 1977)

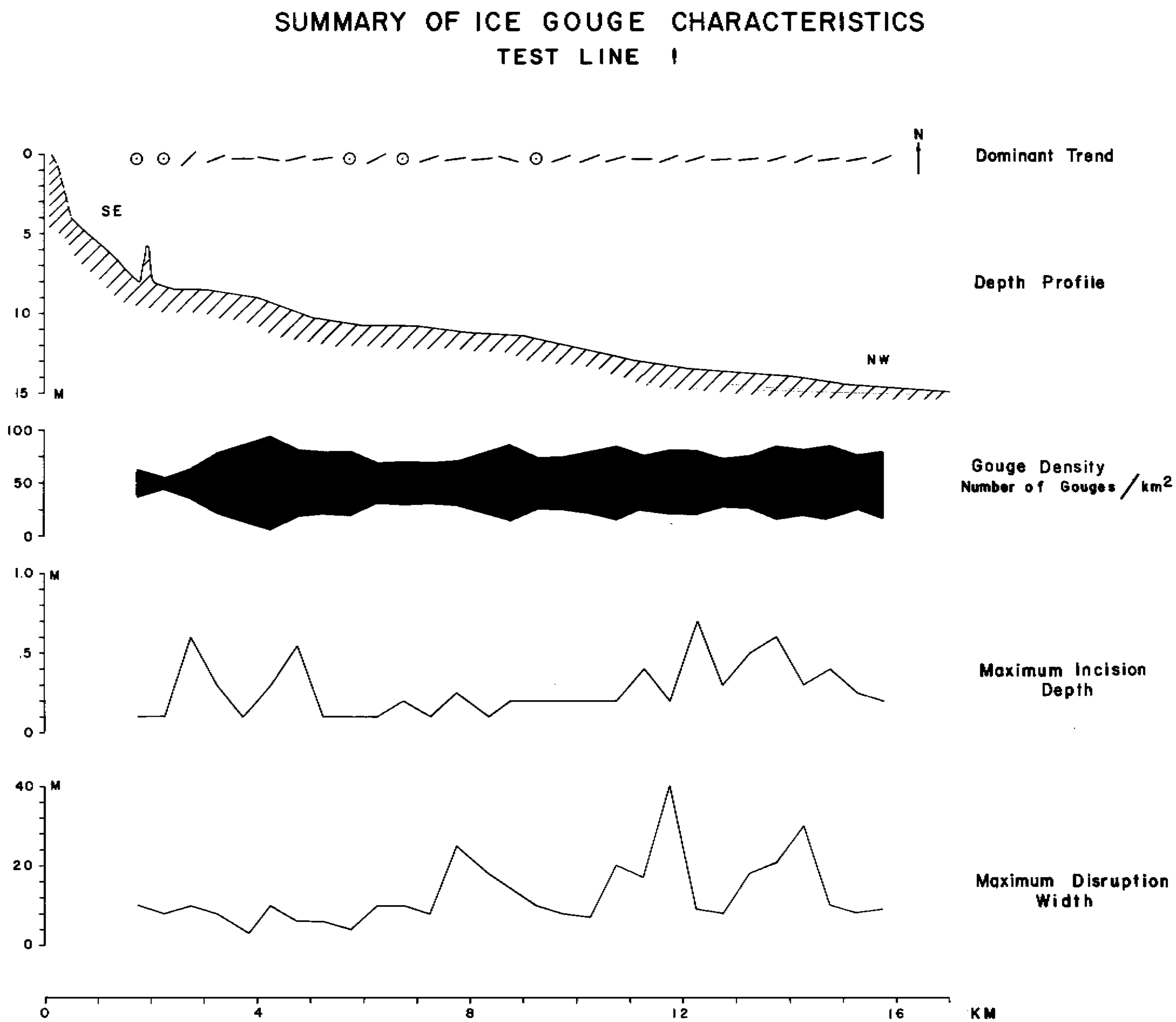

Figure 3. Summary of ice gouge characteristics from the 1975 sonographs of test line 1. Values shown were determined for ½ km segments of trackline.

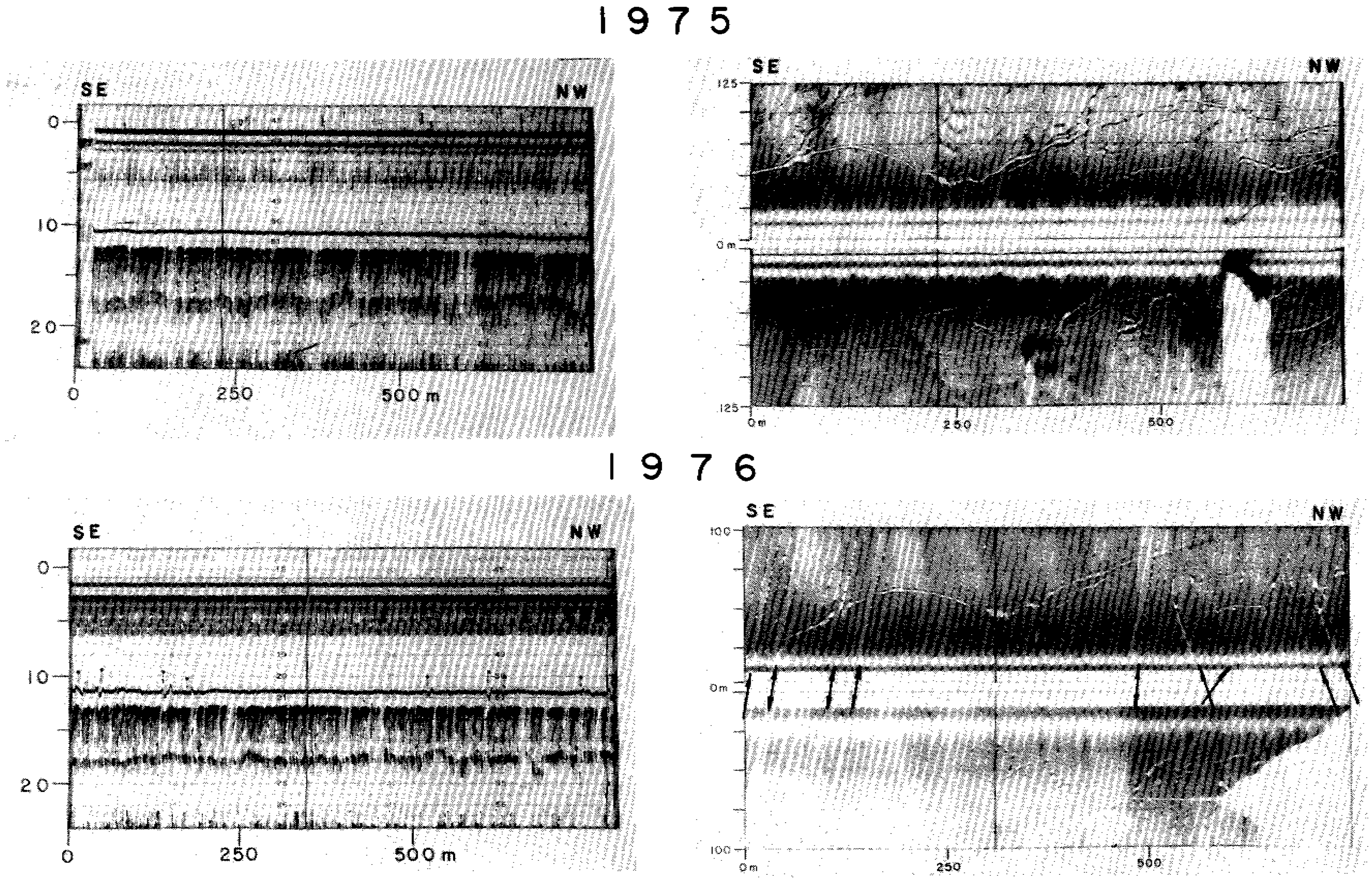

Figure 4. Comparison of 1975 and 1976 sonographs and fathograms, showing the morphology of new gouges formed between September 1975 and August 1976. Note the radical change in fathograms from 1975 to 1976. Three gouge events can be distinguished on the sonographs: a) an event forming the series of 5 parallel gouges seen on the left side of the 1976 record; b) a single gouge which weaves across the record toward the upper righthand corner; and c) the set of three parallel gouges that terminate on the sonograph on the upper part of the trace. Location of trackline is shown in Figure 1.

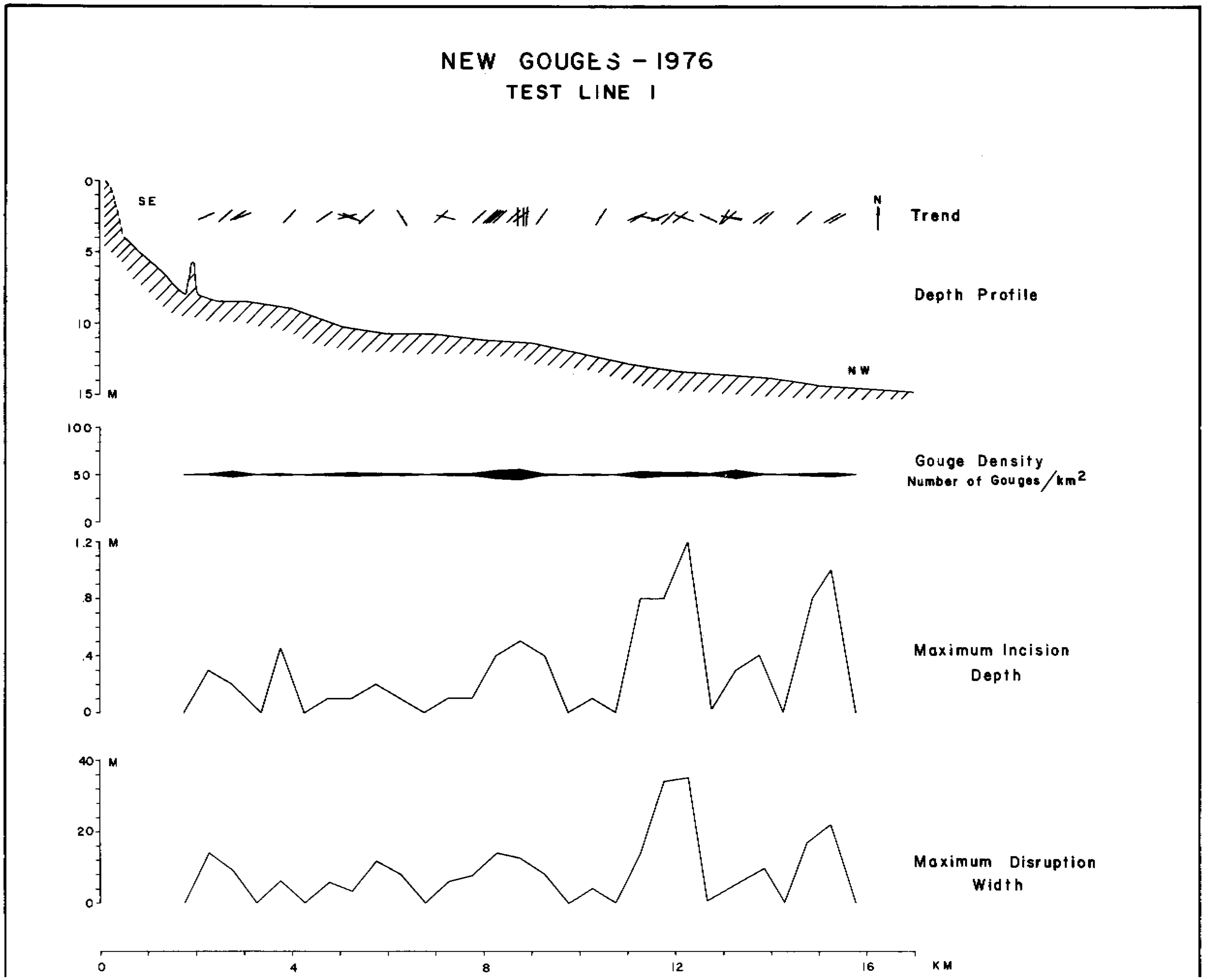

Figure 5. Characteristics of gouges created between 1975 and 1976. Data for test line 1 from sonographs and fathograms. Trend shown is for each new gouge feature. Density, depth, and width values were determined for ½ km segments of the trackline.

Attachment H

Some Characteristics of Ice Gouged Microrelief On The Floor Of The Eastern Chukchi Sea

Lawrence J. Toimil U.S. Geological Survey

Introduction

The effects of ice gouging on the morphology and microrelief of the eastern Chukchi Sea continental shelf, and on the texture and structure of it's surficial sediments have been recognized by Rex (1955), the U.S. Department of Commerce, Coast Pilot (No. 9, 1964), Barnes and Reimnitz (1974), and Toimil and Grantz (1976). Sonographs (side scan sonar records) and bathymetric profiles from well seperated transects of the shelf reveal the occurence of ice gouged microrelief to be wide-spread regionally. The records, obtained over 1,800 trackline kilometers of the shelf between water depths of 20 and 70 m (Fig. 1), provide a data base from which some general characteristics of ice gouged microrelief of the shelf may be analyzed with respect to bathymetry and geographic location. Such an analysis has been completed, the results of which are summarized here.

Data Acquisition

The data base used in the analysis was obtained during a program of reconaissance geologic and geophysical studies of the eastern Chuchi Sea under the direction of Dr. Arthur Grantz of the U.S. Geological Survey's Office of Marine Geology. The program was carried out in August 1974 in cooperation with the U.S. Coast Guard aboard the Cutter BURTON ISLAND.

Besides sonographs and bathymetric data regional information about the(Fig.2) surface and shallow sub-surface geology of the shelf was also obtained by seismic reflection profiling and sea bed sediment sampling. Most sediment samples were obtained with a modified Van Veen type grab and an Alpine type underway sampler. Bathymetric recordings were obtained using a 12 kHz hull mounted 15^{o} beam width transducer coupled to a power transceiver and dry paper recorder. The side scan sonar unit consisted of an E.G.&G. Model Mark 1B system, normally operated at a 125 m slant range and towed between 10 and 15 m above the sea bed. Survey speeds varied between 4 and 6 knots.

Data Analysis

The dominant trend (azimuth) of ice gouged microfeatures, together with their density, and maximum width were determined for 1 km long, linear trackline segments directly from the facsimile sonographs. A series of corrections have been applied to the values obtained (After Reimnitz and Barnes,1974, and Barnes et.al., this Volume Attachment G). The maximum depth of incision of individual gouged microfeatures was measured directly from corresponding bathymetric profiles. The values obtained are conservative, since only gouges directly below the ship could be measured and true depth can be measured only for gouges that are wide relative to the transducer sound cone.

Results

Because of the reconnaissance nature of the data base, and the lack of continuous trackline coverage, the different parameters taken from the records have been summarized from short track segments in the form of graphs (Figs. 3,4,&5). These graphs show the relative frequency of occurence of gouge parameters over various depth intervals. In Figure 3 the gouge density per kilometer of ships track is shown to decrease markedly with increasing water depth. Gouge densities of over 200/km occur in water depths less than 35 m but no values higher than 10/km were found at depths over 56 m. Maximum gouge incision depth, as illustrated in Figure 4, show highest values in the 36m to 50m depth range. A maximum incision depth of 4.5 m was encountered in the 36-40m depth interval(Line segment #22 in Figure 1). A copy of the sonograph of this gouges is shown in Figure 6. The summary of maximum gouge widths per kilometer of ships track(Figure 5) when compared to water depth shows an increase in the occurence of wide gouges between depths of 31 and 45 meters. Gouges wider that 100 meters are encountered within this zone. Most of these wide gouges apparently are produced by multi-keeled ice floes, as seen in Figure 7.

The dominant trends of gouges measured over one kilometer segments have been summarized for six different sectors of the Chukchi shelf(Fig. 8). A wide scatter of dominant gouge trends characterizes the shelf; a fundamental difference from the Beaufort Sea. Also dipicted are the relative densities of ice gouges encountered within each shelf sector(Fig. 8). Because this figure gives summaries of ice gouge densities for large areas of the sea floor the patchiness in distribution within the different areas is not represented. In the southern area there are numerous track segments in which no gouges were seen, while across the northern half of the shelf, few segments were free of gouges of some sort.

Conclusions

A comprehensive report on this study, giving detailed results, and relating ice gouging processes to the overall environment of the Chukchi Sea will be forthcoming. Preliminary conclusions that can be made from the initial analysis are listed as follows:

1) In previous sedimentologic studies of the Chukchi Sea the physical interaction of ice with the sea floor has been ignored. The reconnaissance data presented here shows that ice gouging plays a dominant role in the sedimentary environment of the shelf.

2) Although the density of ice gouges within the study area decreasses markedly from north to south, ice gouges were observed as far south as Cape Prince of Wales Shoal.

3) Gouges can be broken down into two families, each characterictic of a particular bathymetric setting: a) Gouges at water depths less than 35 m are characterized by high densities, lack of preferred orientation, narrow gouge widths, and shallow incision depths(Figure 9). b) Gouges at depths greater than 35 m are relatively wide, deep, occur in low densities are generally linear, and extend for longer distances along the sea floor.

4) The density of gouging is patchy, with areas of very high gouge counts occuring adjacent to areas devoid of gouges.

5) Regional preferred orientations are lacking, and only locally is there bathymetric control to the trend of gouging, such as in the vacinity of Barrow.

6) The occurance of fields of current-produced bedforms, adjacent to or within individual gouges suggest an interaction between slow moving grounded or gouging ice and swift currents(Fig. 10).

7) Wide regions of the shelf surveyed are uniform in depth, sediment type, and in ice regime, and are characterized by low sedimentation rates. Therefore we attribute the patchy distribution of ice gouge densities to strong currents reworking the bottom.

8) A gross comparison of ice gouging in the Chukchi Sea with that of the Beaufort Sea shows a number of major differences and some similarities.

The Chukchi differs from the Beaufort in that a) gouge densities are more patchy under otherwise uniform conditions, b) preferrred orientations are poorly developed in the Chukchi, c) the process of ice gouging in many instances is associated with and modified by strong current action, and d) gouge fields are reworked more rapidly by currents. The two areas are similar in maximum values of a) ice gouge densities, b) ice gouge widths, and c) incision depths.

When attempting to compare rates of ice gouging for the two areas, it would appear that the northern Chukchi Sea is similar to the Alaskan Beaufort Sea shelf. In the southern Chukchi Sea rates seem to be lower, but it must be noted that rates of sedimentation are higher and current regimes are stronger, which may quicly mask the evidence of recent gouging.

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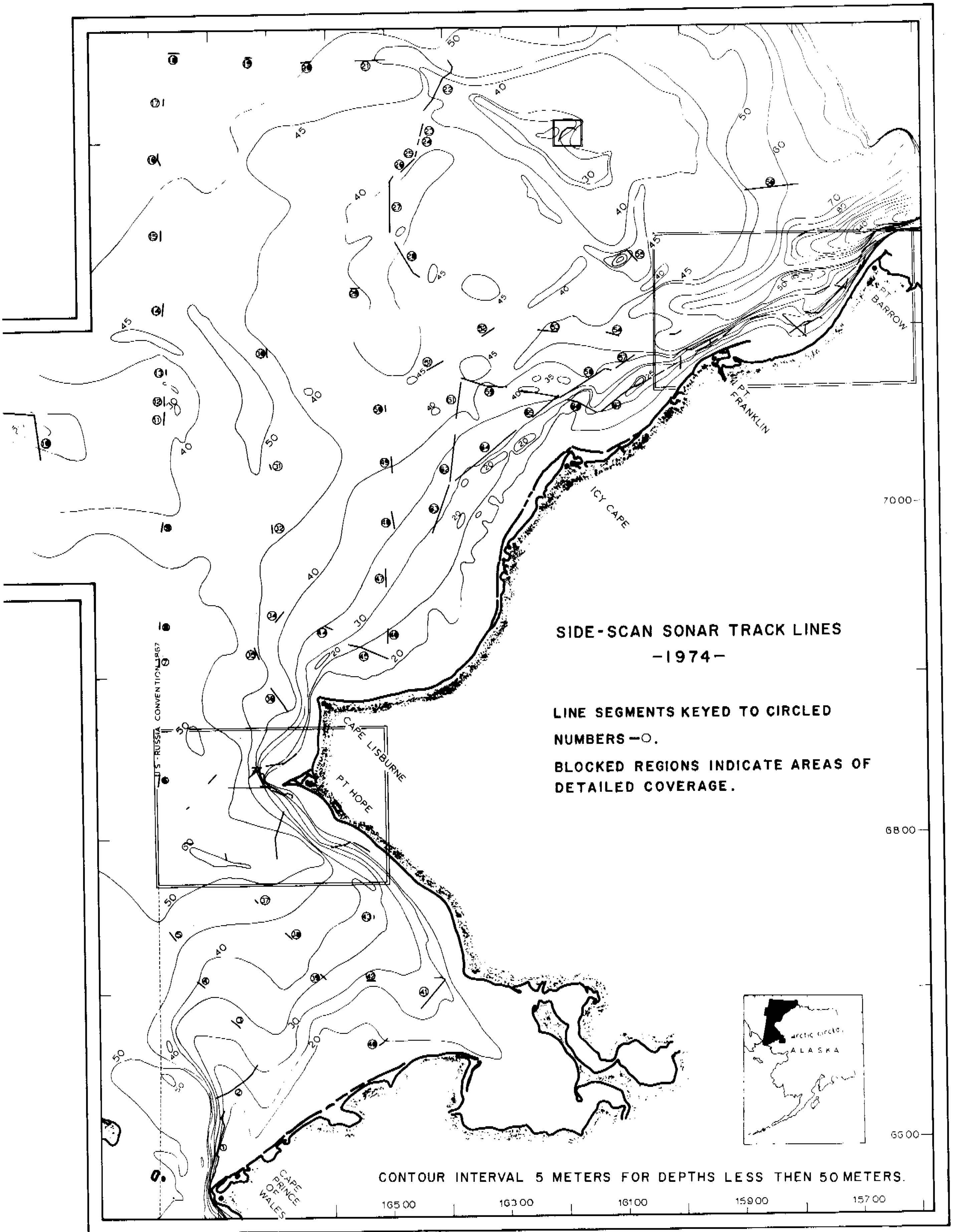

Figure 1. Location map showing segments of side scan sonar tracklines. Bathymetry from NOS chart 9402, bathymetric measurements made by the USCG Cutter BURTON ISLAND in 1972 and 1974, and data compiled by Holmes (1975).

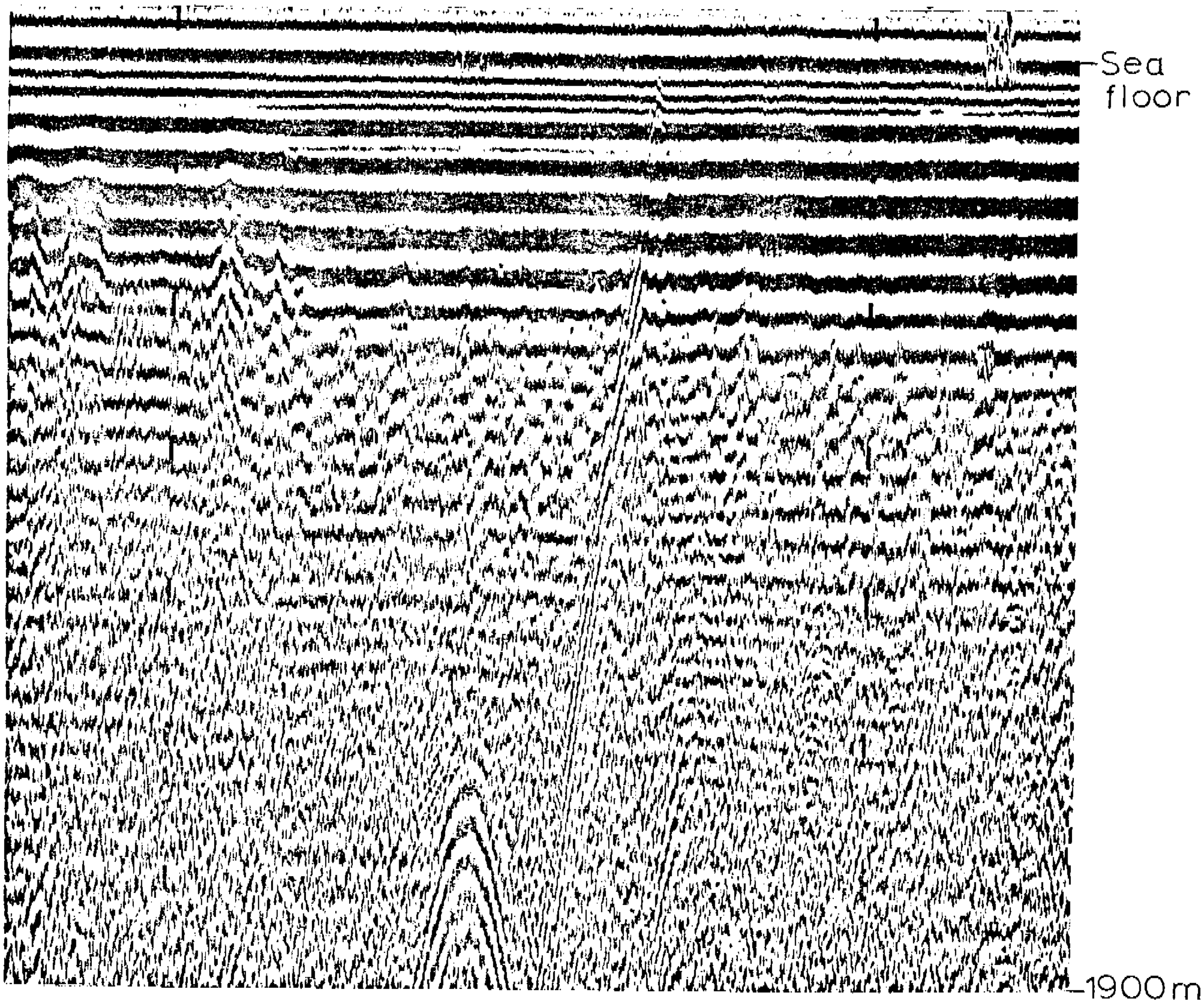

Figure 2. One of the principal objectives of the side scan sonar studies during the 1974 field operations was to test the hypothesis put forward by Grantz (personal comm.) that hyperbolic echo traces seen in previous seismic reflection profiles of the shelf resulted from the furrow-like, linear microfeatures produced by ice gouging (Reimnitz & Barnes, 1974). Hyperbolic echo traces can be expected from such microfeatures when they lie at an angle to a towed hydrophone array, or in some cases a hull mounted transducer (Hollister & others, 1974), such that sequential reflection points move along the feature and become coincident with the sea floor echo returns when the feature is crossed. Using side scan sonar to resurvey previous seismic reflection tracklines showing hyperbolic traces confirmed the presence of linear ice gouges on the sea bed. While a positive correlation between the occurance of hyperbolic echo traces and the presence of ice gouged microfeatures was found, an inverse relationship was not.

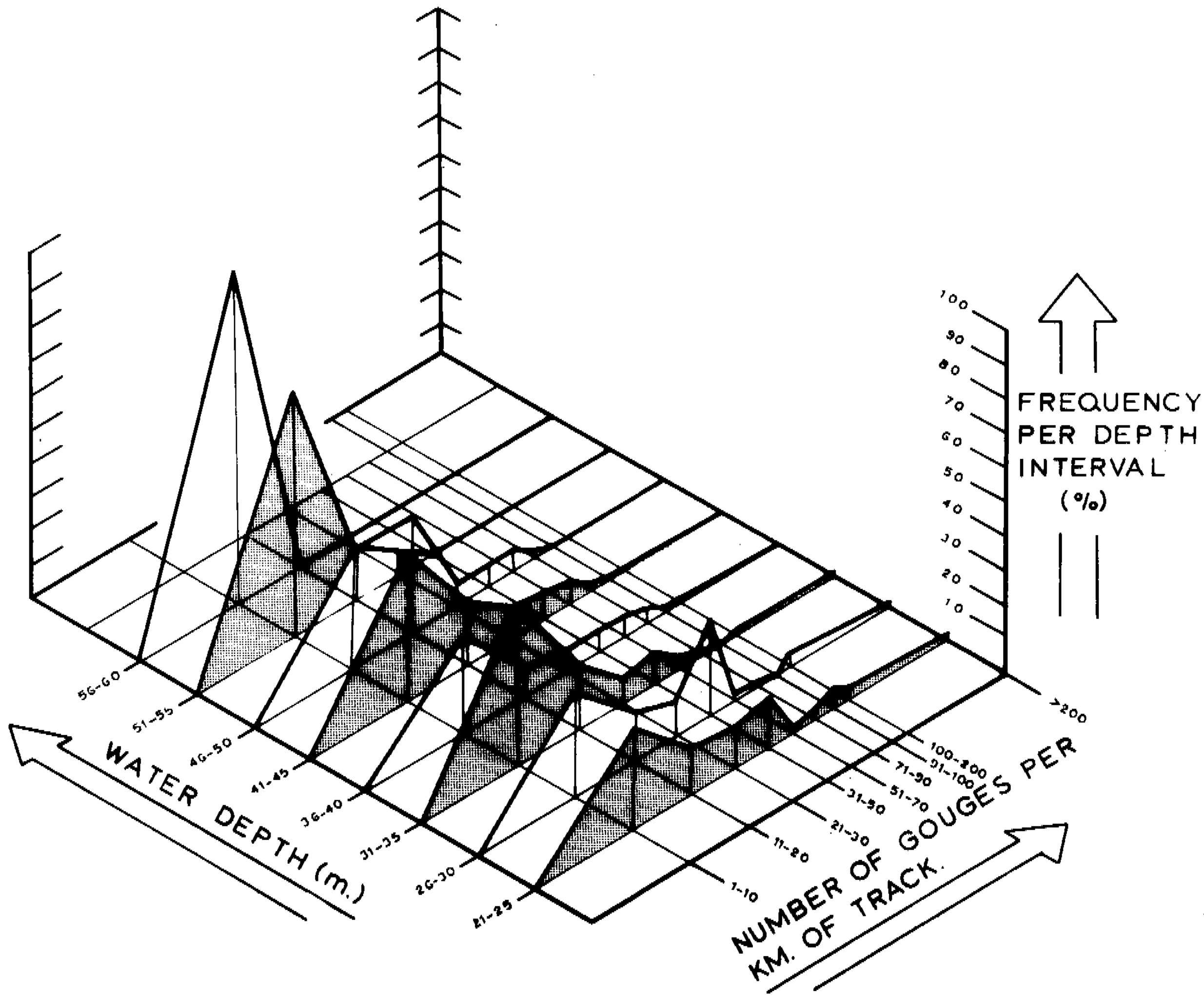

Figure 3. Summary of ice gouge density values plotted according to their frequency of occurence within a given depth interval.

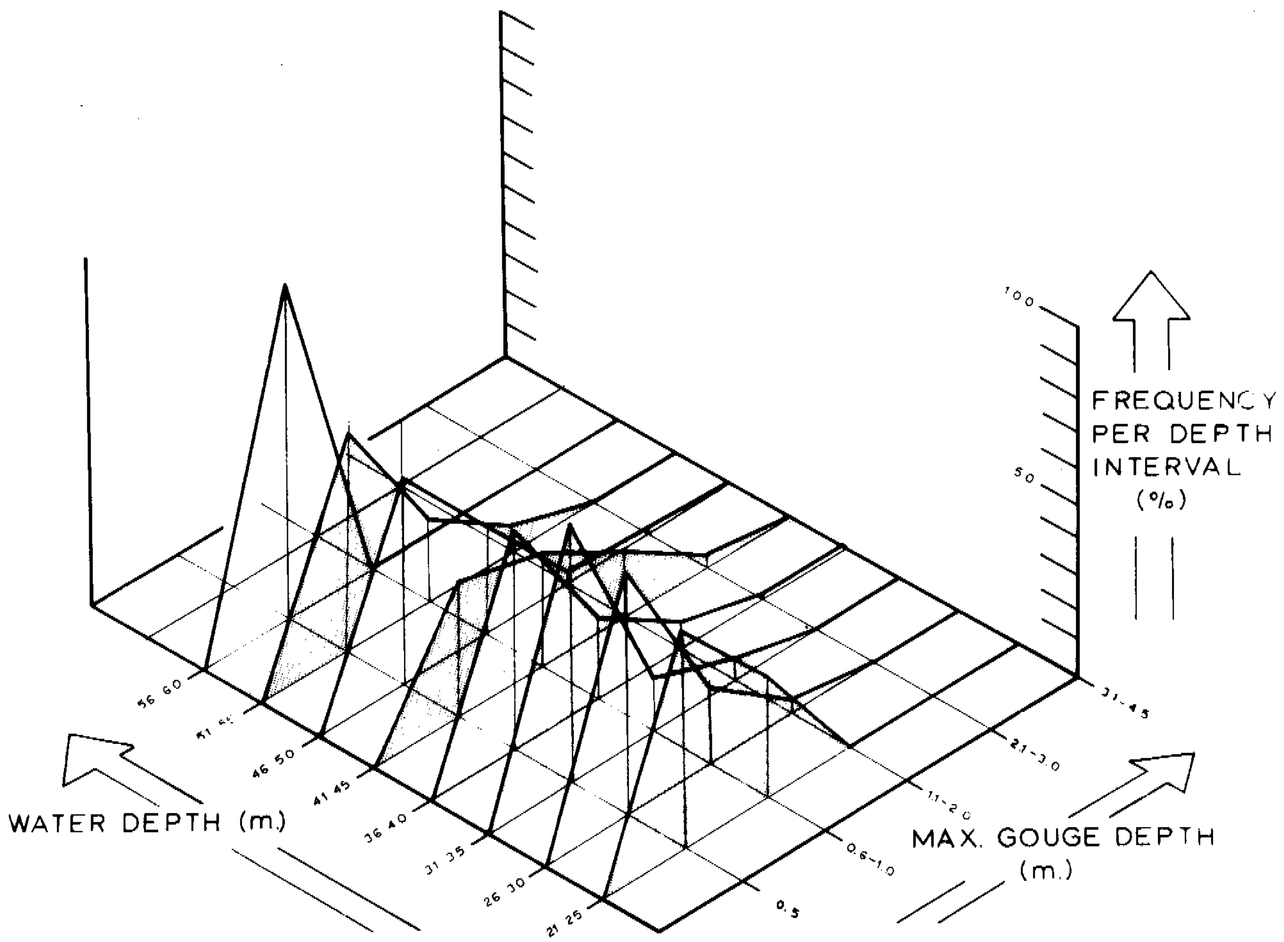

Figure 4. Summary of maximum ice gouge depth (incision depth) counts plotted according to their frequency of occurence within a given water depth interval.

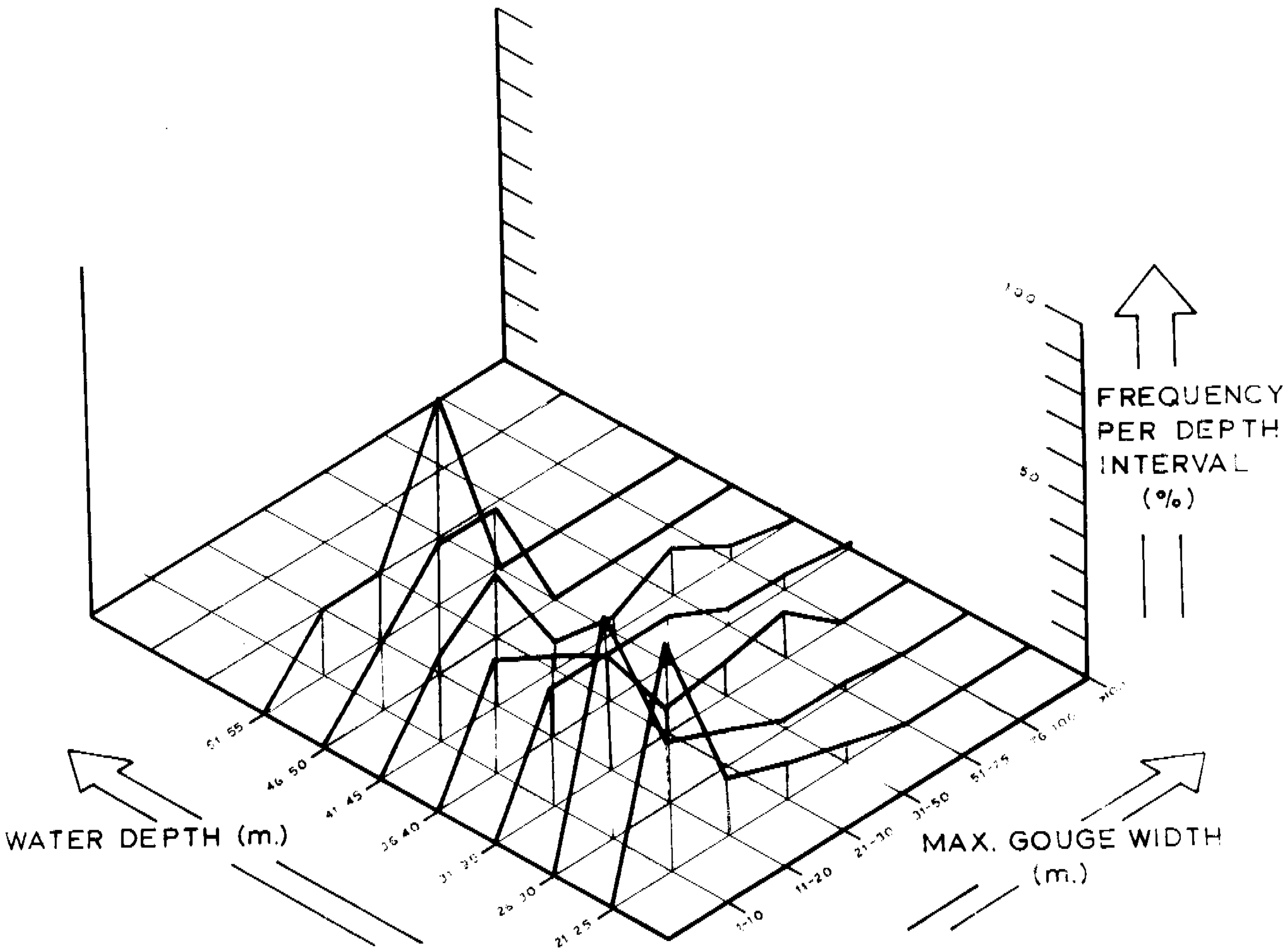

Figure 5. Summary of maximum ice gouge width counts plotted according to their frequency of occurence within a given water depth interval.

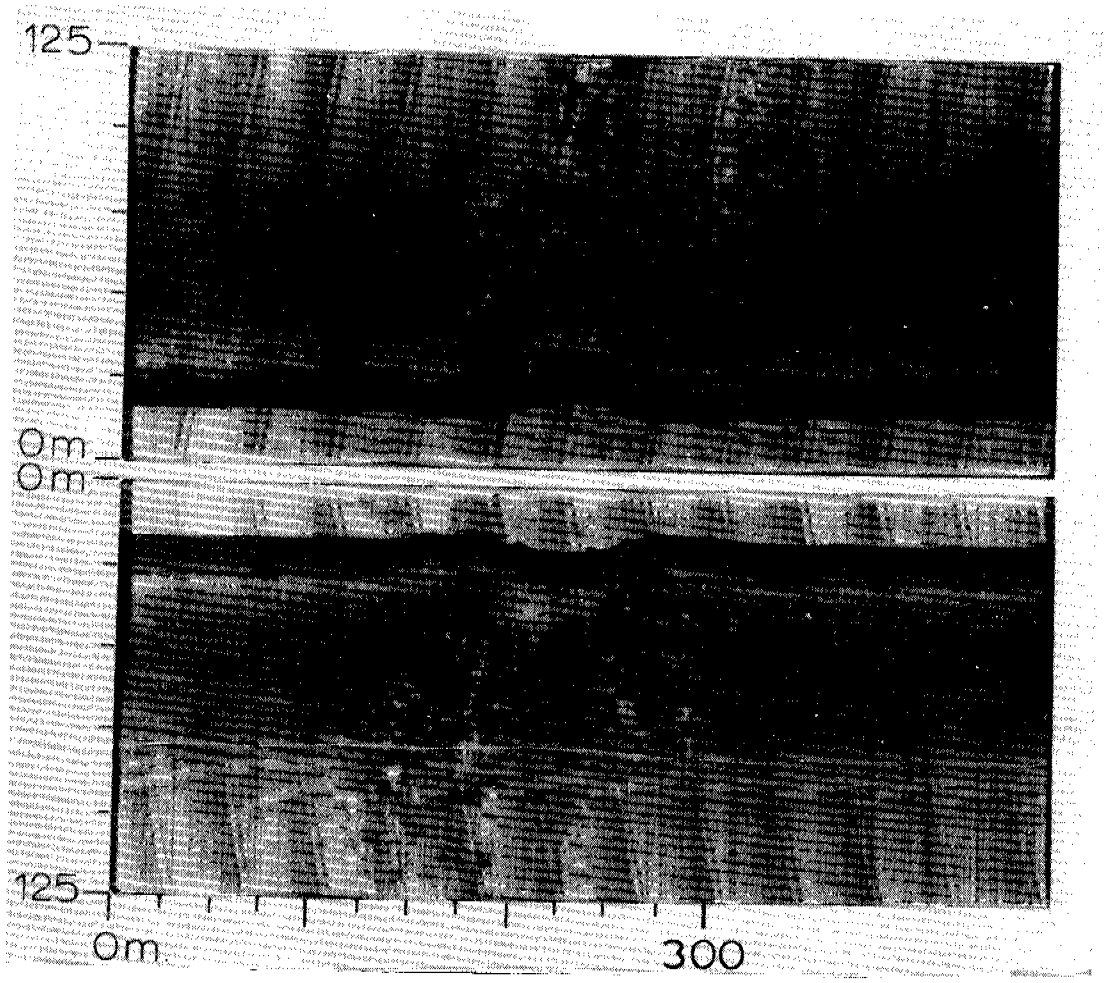

Figure 6. The greatest depth of gouge incision (4.5 m) was measured from this gouge seen in the northern part of the study area (segment 22, Fig.1).

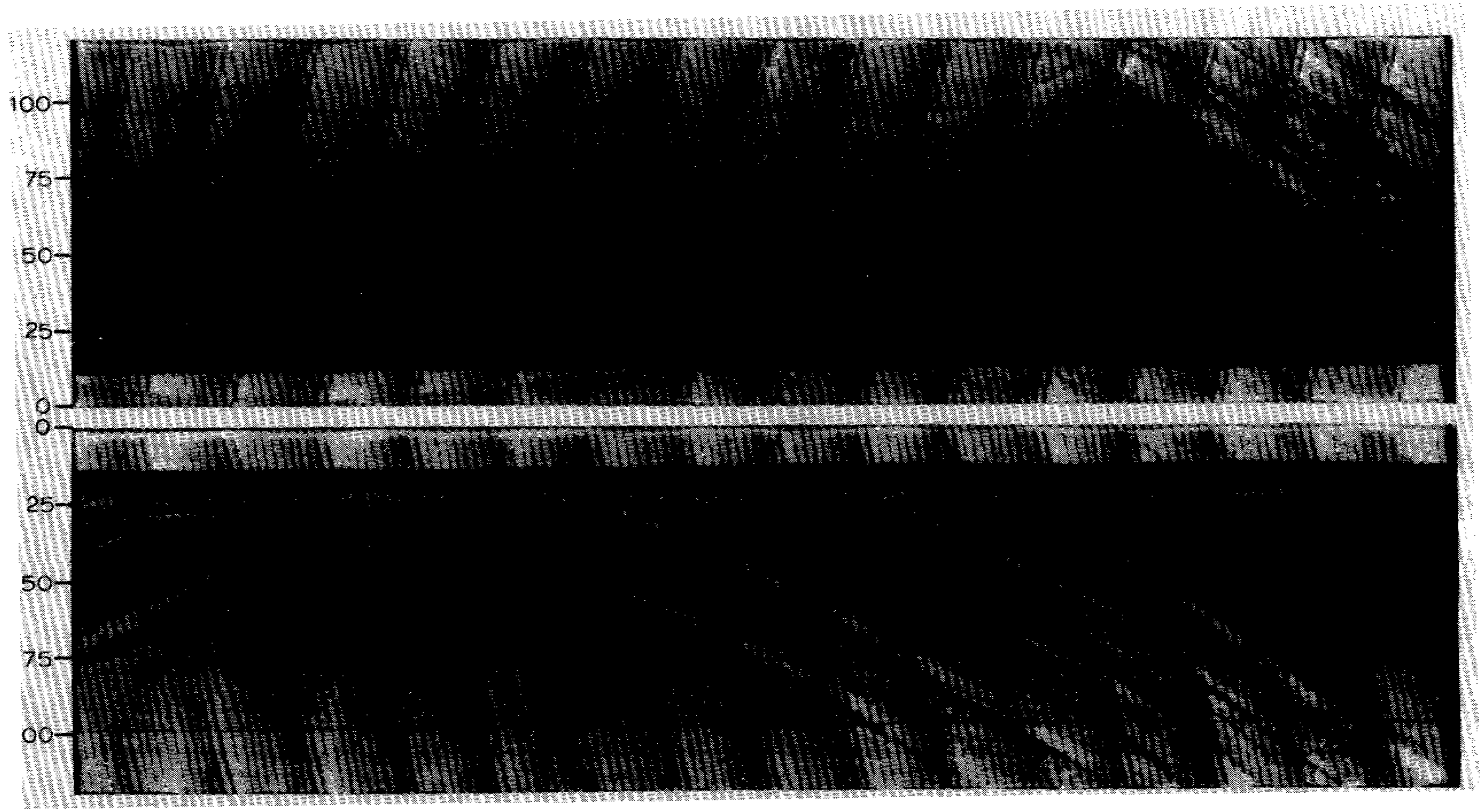

Figure 7. The widest gouges were generally formed from multi-pronged ice keels, as demonstrated by this photo.

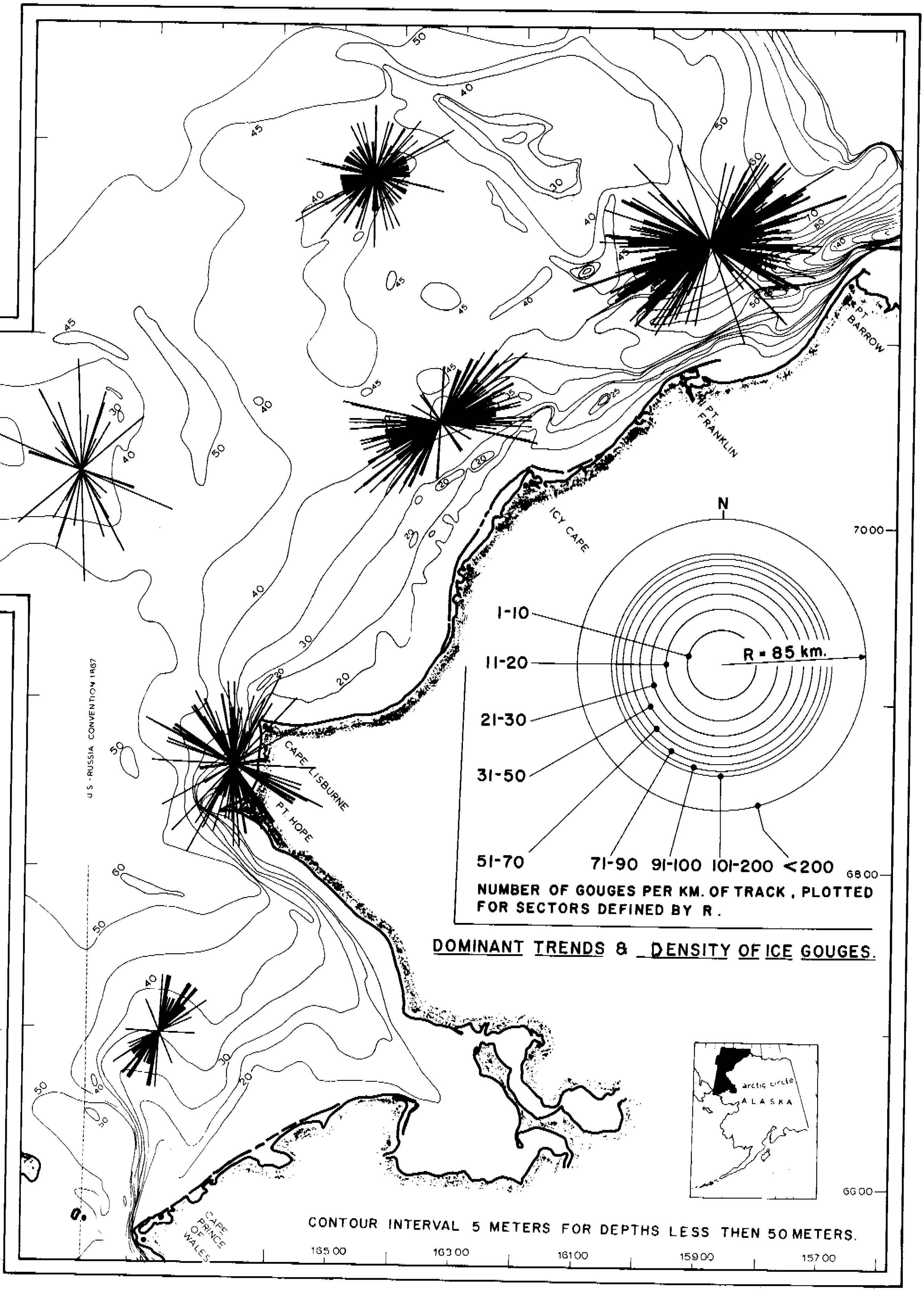

Figure 8. Plot of dominant trends and density of ice gouges per km of ship's track within six circular sectors of the shelf.

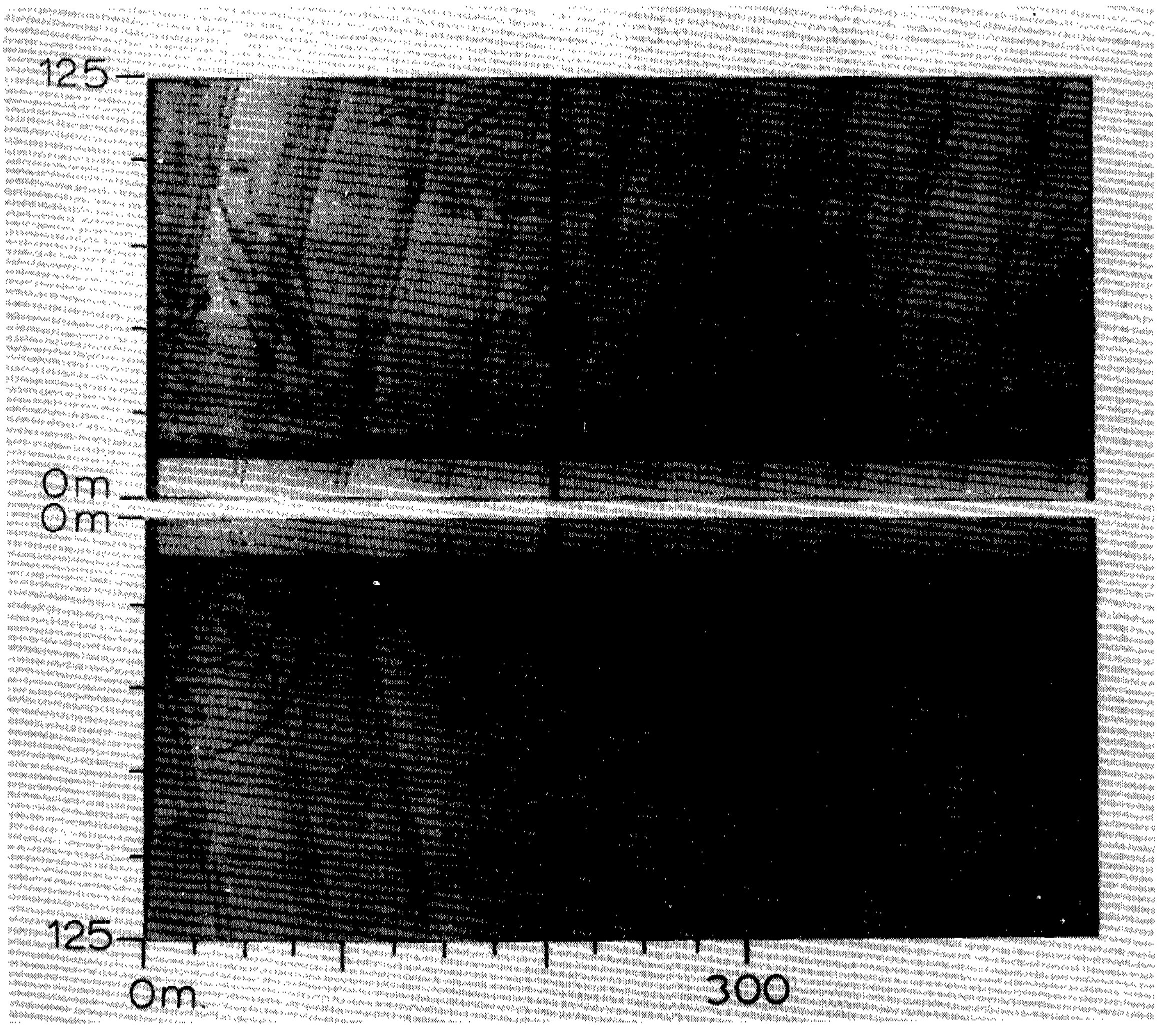

Figure 9. Sonograph obtained at 25 to 30 m water depth. The high density and poorly defined dominant trends of the gouges and their narrow, shallow character is typical for gouges observed in water depths of less than 35 m.

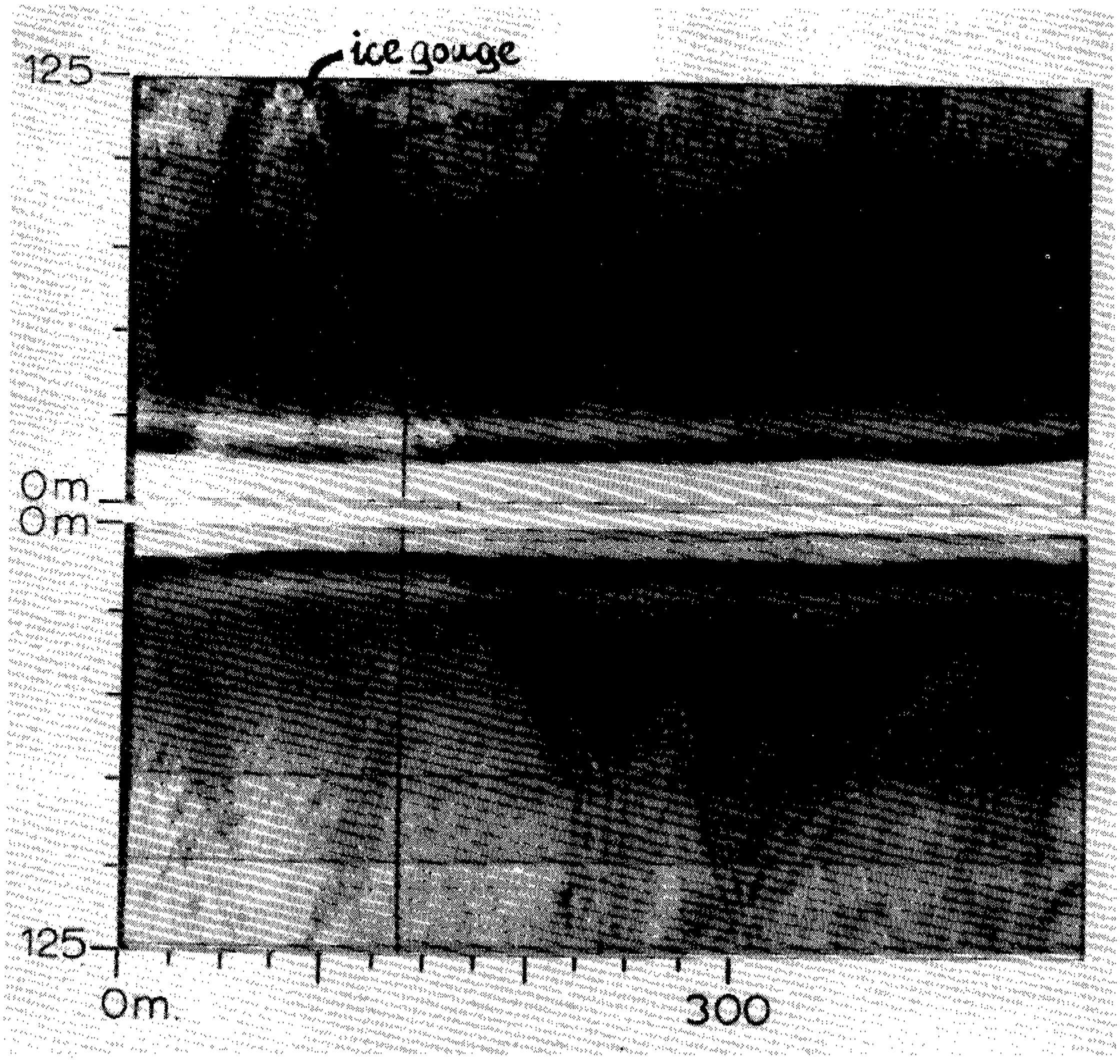

Figure 10. The influence of strong coastal currents on ice gouge processes is often recorded by the association of sand waves along the flanks and troughs of individual ice gouges.

ATTACHMENT I

Shelled benthic critters of the eastern Chukchi Sea- by Dennis Mann

INTRODUCTION

Purpose of this study is to identify the benthic infauna and epifauna of the eastern Chukchi Sea; compile species lists and distribution maps; determine recurrent groups of species (and communities); and to examine environmental parameters which may by controlling the distribution of the faunal groups. This report is part of an ongoing study of the Arctic continental shelf by the U.S.Geological Survey and other investigative organizations under the outer continental shelf (OCS) program sponsered by Bereau of Land Management. The objective of these studies is an environmental assesment of the ecology as related to petroleum development. Future offshore oil leases proposed by the Federal Government and the state of Alaska require an ecological base from which impact statements can be derived.

Samples used in this report were collected by the U.S.Geological Survey in August 1974 from the U.S.Coast Guard Cutter *Burton Island* under the direction of Art Grantz. Sampling was conducted using Van Veen grabs, gravity cores, dart cores, and bottom dredges. Only the Van Veen grabs contained material useful for this study.

PREVIOUS WORK

Areal distribution of fauna is not well known in the Chukchi Sea although most of the fauna has been adequetly described. Earliest studies of the region was conducted by the International Polar Expedition to Point Barrow, Alaska, 1881-1883 (Ray, 1885). Their main task was meterological in nature and they were not well equipted to study the biology. W.H.Dall did identify and list 33 species and 2 varieties of Mollusks collected by this expedition, over two-thirds of which were beach collected.(Dall, 1885). The Canadian Arctic Expedition of 1913-1918 collected 26 species and 3 varieties (all washed up on the beach) which were reported by Dall (1919).

George and Nettie MacGinitie carried out the first extensive dredging operation of the seafloor in the Arctic north of the Alaskan coast to study benthic organisms while at the Naval Arctic Research Laboratory. They used dog teams to haul dredges through holes cut in the ice pack. Stations occupied in this manner ranged from the shoreline to a maximum of 16 miles offshore. The results were published by George MacGinitie (1955), and a complete study of the marine mollusks was subsequently published by Nettie MacGinitie (1959).

Soviet Expeditions of the 1930's collected a large amount of data in the Chukchi Sea and Siberian coast. Analysis of this data was reported in G.P.Gorbunov (1952), P.V.Ushakov (1952), and Z.A. Filatova (1954, 1957). Other Soviet papers that were useful were by R.L.Merklin (1962), and O.M.Petrov (1966).

In addition recent works on specific Taxa are especially helpful in distinguishing the arctic fauna which are often transitional between other species, these include works by E.V.Coan (Tellina, 1971), and F.S. MacNeil (Pectinids, 1967; Mya, 1963).

STUDY AREA

The Chukchi Sea is a small (580,000 km^2), shallow (25 to 55m), sea lying between the Arctic Ocean and the Bering Straight, extending from near Wrangle Island (180^o) to Point Barrow (156^{o}W), generally bounded on the north by the 100 fm. isobath which lies from 300 miles (near Cape Lisburne) to about 30 miles offshore (near Pt. Barrow) (Ingham and Rutland, 1970). The area studied (fig. 1) extends from the Bering Strait to 72^{o}30' north latitude; is bounded on the west by the United States-Russian Convention line of 1867 (American ships have been unable to obtain permission to sample west of this line); and is bounded on the east by Point Barrow, Alaska.

The floor of the Chukchi Sea is a flat almost featureless plain with depths averaging 45 - 55 meters and regional gradients ranging from 2 minutes to unmeasurably gentle slopes (Creagar and McManus, 1966). Sediments of the seafloor are very patchly distributed as shown in figure 2, the biota which show prefence for a particular sediment type are similarly distributed.

The grounding of sea ice is a common occurence in the Arctic coastal waters and the shallowness of the Chukchi Sea makes much of the seafloor succeptable to ice gouging. Ice forms in the late summer or early fall and covers the Chukchi Sea for 7 to 8 months of the year until late spring. Shorefast ice freezes to a depth of 2 $\pm$ meters and causes the littoral zone to be nearly devoid of life.

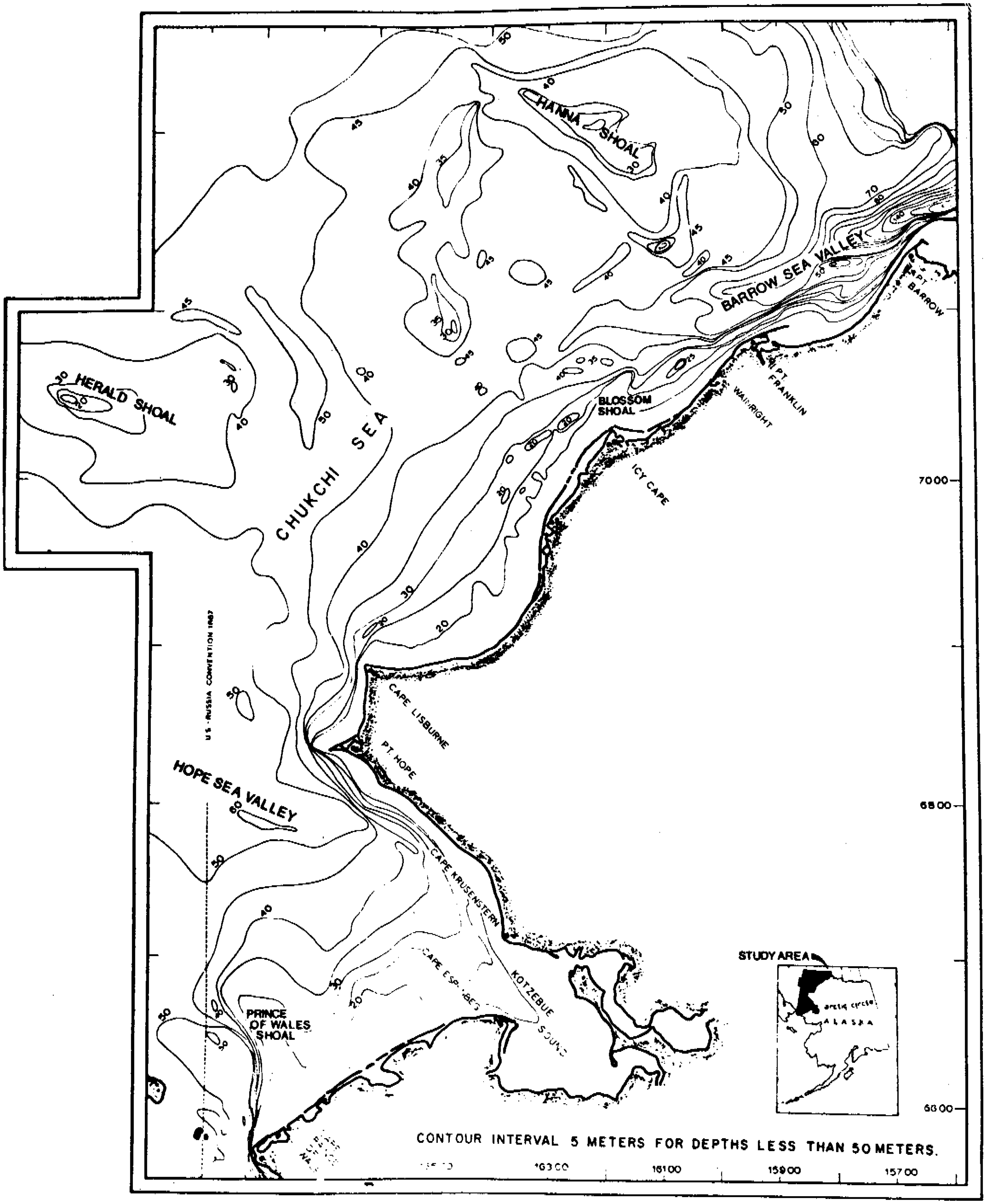

Fig.1. Study area and bathymetric map of the Eastern Chukchi Sea.
(Compiled by L.J.Toimil, U.S.Geological Survey)

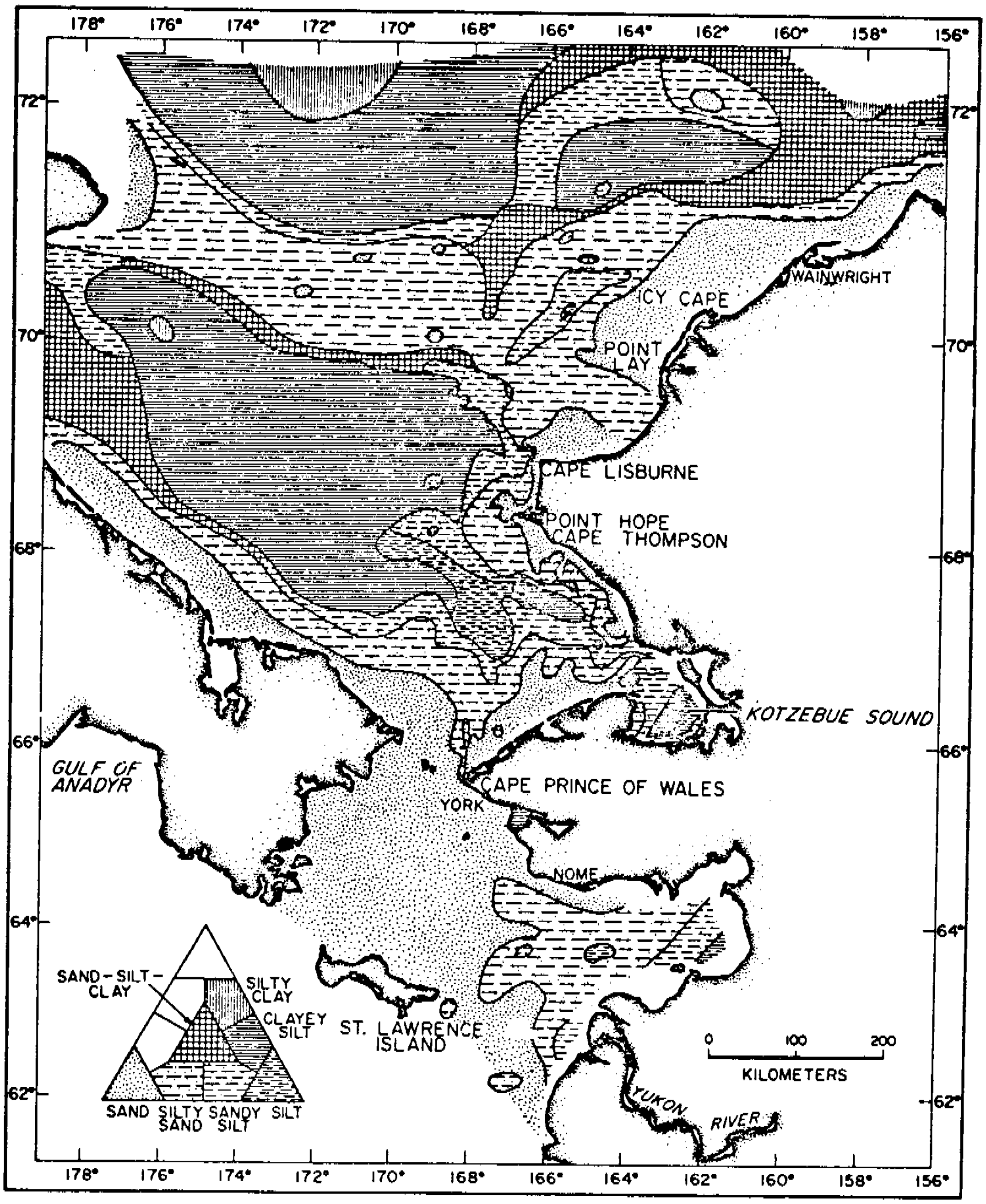

Fig. 2. Texture of bottom sediments expressed in terms of three-end-member relationship of Shepard (1954).
(From Creagar and McManus, 1967)

Some floating ice in the Chukchi Sea has keels of sufficient depth to cause gouging of the seafloor in water as deep as 75m and high density (>100 gouges per km) ice gouging extends into water as deep as 30m (Reimnitz et al, 1972; Toimil and Grantz, 1976). Study of side scan records show ice gouges depths of up to 1.5m common (Toimil and Grantz, 1976).

Ice gouging causes major disruptions in the benthic communities in both the physical crushing of the organisms as well as the mixing and plowing of the sediments, often causing fossil material to be mixed with living biota. Mollusk shells from areas of high ice gouge densities were observed to have shells which had been cracked and later healed, possibly indicating damage caused by the gouging.

METHODS OF STUDY

The sampling procedure consisted of lowering a $0.1m^2$ Van Veen sampler until sufficient material was collected for analysis. The sampling was qualitative rather then quantitative since the ability of the Van Veen sampler to penetrate bottom is greatly affected by the size of the substrate material. In fine material a full grab may be taken where in coarse or rocky substrates only a small amount of material may be recovered.

After removal of a small raw sample for size analysis the remaining sediment was washed through a 2mm screen into a holding tank. The fine sediment was saved for microfaunal analysis; the coarser sediment and biota on the screen were bagged. Initially the samples were stored on board the ship in 10% neutralized formalin,and later put in refrigerated storage at the U.S.Geological Survey in Menlo Park, California. The shelled organisms were fairly well preserved but the unshelled organisms did not survive the long storage period prior to the analysis of the samples. As a result the Mollusks form the basic data for this report with the inclusion of some of the more resistant unshelled biota.

The benthic faunal work was begun in the summer of 1975. Biologic material was sorted out of the coarse splits and sorted according to taxa. Identification was carried out using the available literature on Arctic species and by contacting inhouse specialists when nessesary. Species occurences were counted for each sample and the data was tabulated, put on computer cards,and run through a Q-Mode factor analysis to determine statistical benthic communities.

It should be noted that the sampling procedure eliminated the deep burrowing species such as *Mya*; the near shore species; and the storage procedure lost most of the Annelids, and soft bodied organisms.

Q-MODE FACTOR ANALYSIS

Klovan and Imbrie (1971) published a Q-Mode factor analysis program (CABFAC) in which up to 1500 items (samples) can be compared with up to 50 variables (species). The user can control the number of variables (columns) and items (rows) in the data matrix, the stopping criteria, the number of factors to be rotated in the verimax rotation (maximum of 10), and format the software input and output. The CABFAC program is constructed so that all the available options can be exercised with control cards at the start of the users data deck. The program is written in Fortran IV and runs on an IBM 360/50 computer. J.Gardener of the U.S.Geological Survey modified the program to accomidate 60 variables, and so it will run on the computer in Menlo Park.

Original raw count data from the samples was converted so that each species was represented as a percentage of total live occurences in each sample- giving more weight to the rarely occuring types. In the analysis these percentages are converted into vectors which can then be rotated in multi-dimentional space in order to find clusters of species occurences. The final product of the Q-Mode analysis groups samples by the species they have in common. This is valuable for the recognition of faunal areas or biofacies.

Table I shows the results of the analysis as applied to the Chukchi Sea data. 40 species were compared to 101 samples, rare species were eliminated from the matrix as well as samples with only a few organisms in order to shorten the running time of the program. The Roman numerals indicate the computer derived factor and the related species. The number following the taxa names relate to the abundance of the species in the factor. A brief description of the average substrate type for each factor is also included for reference.

Future studies will add depth and other parameters which may alter the present groups.

Q-MODE COMMUNITIES

I	*Nucula tenuis*	6.2	Soft silty clay to pebbly clay
	Macoma moesta	.76	
	Macoma calcarea	.28	
	Yoldia scissurata	.21	
	Solariella obscura	.27	
	Leda minuta	.27	
	Cyclocardium crassidens	.18	
	Hemithyris psittacea	.14	
II	*Balanus crenatus*	6.1	Sandy to pebbly
	Hiatella artica	1.5	
	Clinocardium ciliatum	.47	
	Gomphina fluctuosa	.36	
	Macoma calcarea	.23	
	Boreotrophon truncatus	.45	
	Hemithyris psittacea	.37	
	Leda minuta	.28	
	Serripes groenlandicus	.29	
III	*Macoma calcarea*	6.2	Soft silty clay
	Yoldia myalis	.64	
	Tachyryncus erosus	.53	
	Natica clausa	.44	
	Clinocardium ciliatum	.23	
	Cyclocardia crebricostata	.28	
IV	*Leda radiata*	6.2	Soft silty clay
	Leda minuta	1.1	
	Solariella obscura	.51	
V	*Astarte montagui*	6.1	Coarse sand and pebbles
	Astarte borealis	.64	
	Axinopsida orbiculata	.78	
	Cyclocardium crassidens	.63	
	Chlamys pseudislandica	.81	
	Echinarius parma	.32	
VI	*Cyclocardium crassidens*	.96	Coarse sand amd pebbles
	Hiatella artica	1.5	
	Balanus rostratus	5.3	
	Hemithyris psittacea	2.4	
	Astarte bennettii	.49	
	Chlamys pseudislandica	.60	
	Cyclocardia crebricostata	.43	
	Tachryncus reticulatum	.49	
VII	*Macoma moesta*	6.0	Sandy silty clay
	Clinocardium ciliatum	1.2	
	Yoldia amygdalea	.96	
	Yoldia myalis	.44	
	Echinarius parma	.49	

VIII	*Astarte borealis*	3.6	Sandy silty clay with cobbles, pebbles
	Yoldia myalis	3.5	
	Hemithrus psittacea	1.5	
	Boreotrophon truncatus	1.2	
	Tachyryncus reticulatum	1.4	
	Cyclocardia crassidens	1.3	
	Leda minuta	1.3	
	Astarte bennettii	.5	
	Hiatella artica	.6	
	Gomphina fluctuosa	.5	
	Yoldia scissuratus	1.0	
	Margarites costalis	1.0	
	Natica clausa	.8	
	Tachyryncus erosus	.5	

The recurrent groups of species listed above do not compare well with the communities proposed by Thorson (1957). Thorson's communities are both statistical and ecological units, where the above groups are purely statistical. Substrate seems to be the most important factor controlling the distribution of species in the Chukchi Sea. The epifaunal species like *Hemithyrus psittacea* and *Balanus sp.* only can occur where the substrate includes something for them to attach themselves. Several of the Q-mode groups interfinger depending on relative abundance of the preferential substrate of each group; for instance communities II and III are similar to Thorson's *Macoma calcarea* community where an increase in silt will increase the number of *Macoma calcarea* and with an increase in sand more *Clinocardium ciliatum* and *Serripes groenlandicus* are present. In areas of high ice gouging the faunas are disturbed and do not fit well into any faunal group.

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SPECIES LIST

A species list of benthic infaunal and epifaunal organisms is being compiled for the eastern Chukchi Sea. The list currently consists of specimens collected during the August, 1974 cruise of the U.S.Coast Guard Cutter Burton Island. The data will be expanded and updated as more specimens are collected and when the compilation includes information from other publications and data reports. An attempt has been made to use only the most current specific names for the organisms, but not a`` have been verified to date. A collection of specimens has been sent to the U.S. National Museum for comparison with the type specimens stored there. This listing supercedes that included i the September to December quarterly report.

SPECIES DISTRIBUTION PATTERNS

A series of range maps have been compiled to demonstrate the distributional pattern of the benthic organisms in the eastern Chukchi Sea. All samples were collecter using a 0.1 m^2 Van Veen sampler on the August 1974 cruise of the U.S. Coast Guard Cutter Burton Island. For clarity only the Van Veen samples are shown on the sample location map (Fig. 3). The numbers ore U.S. Geological Survey Menlo Park series locality numbers. Solid circles on the range maps represent live occurrences, open circles represent locations where only empty shells were found(pages 14-93). Distribution maps are in the same order as the species listing on the following pages.

GASTROPODA

GASTROPODA

CEPHALOPODA

Octopodidae

Octopus sp.

AMPHINEURA

Ischnochiton albus (Linnaeus, 1767)

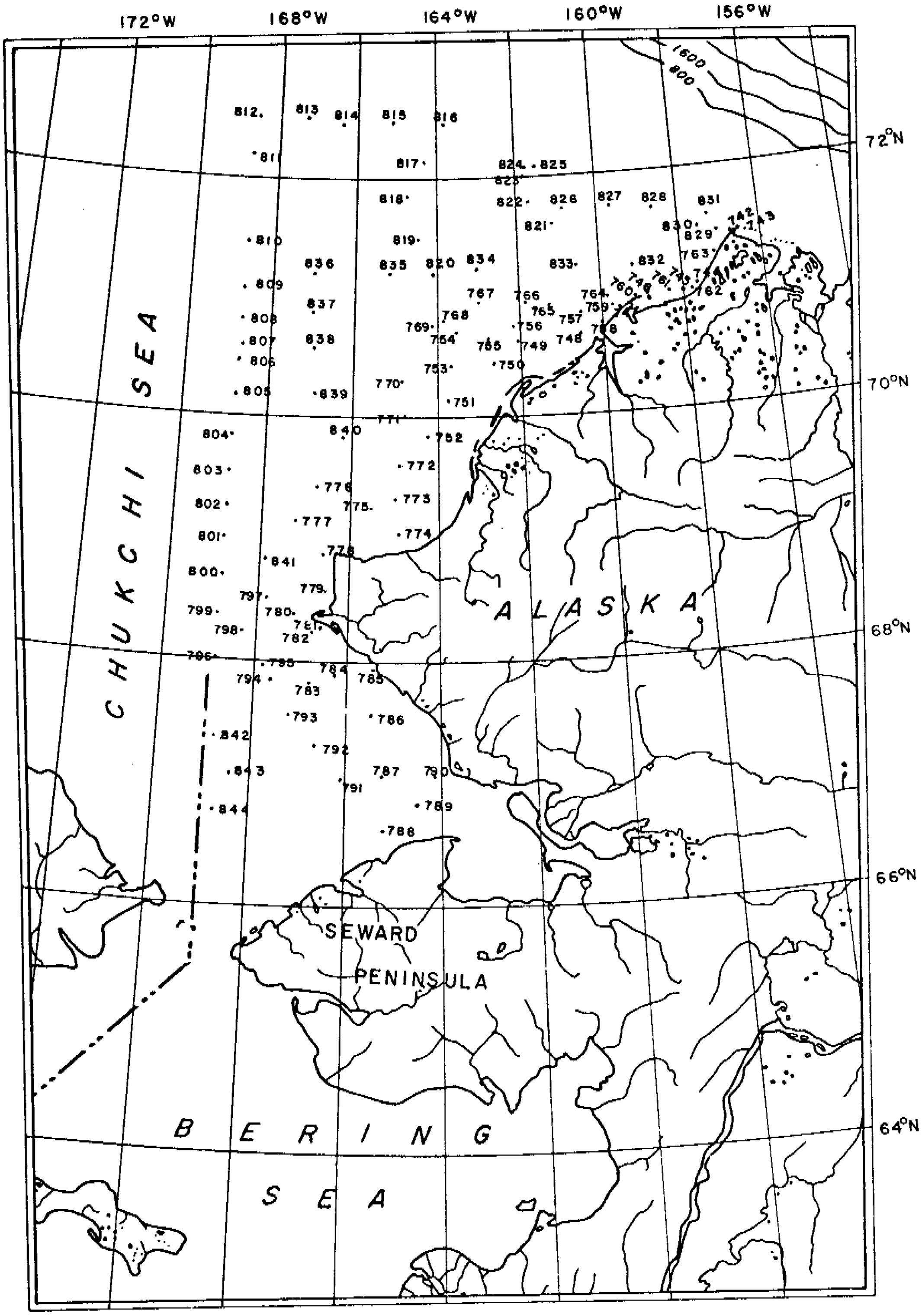
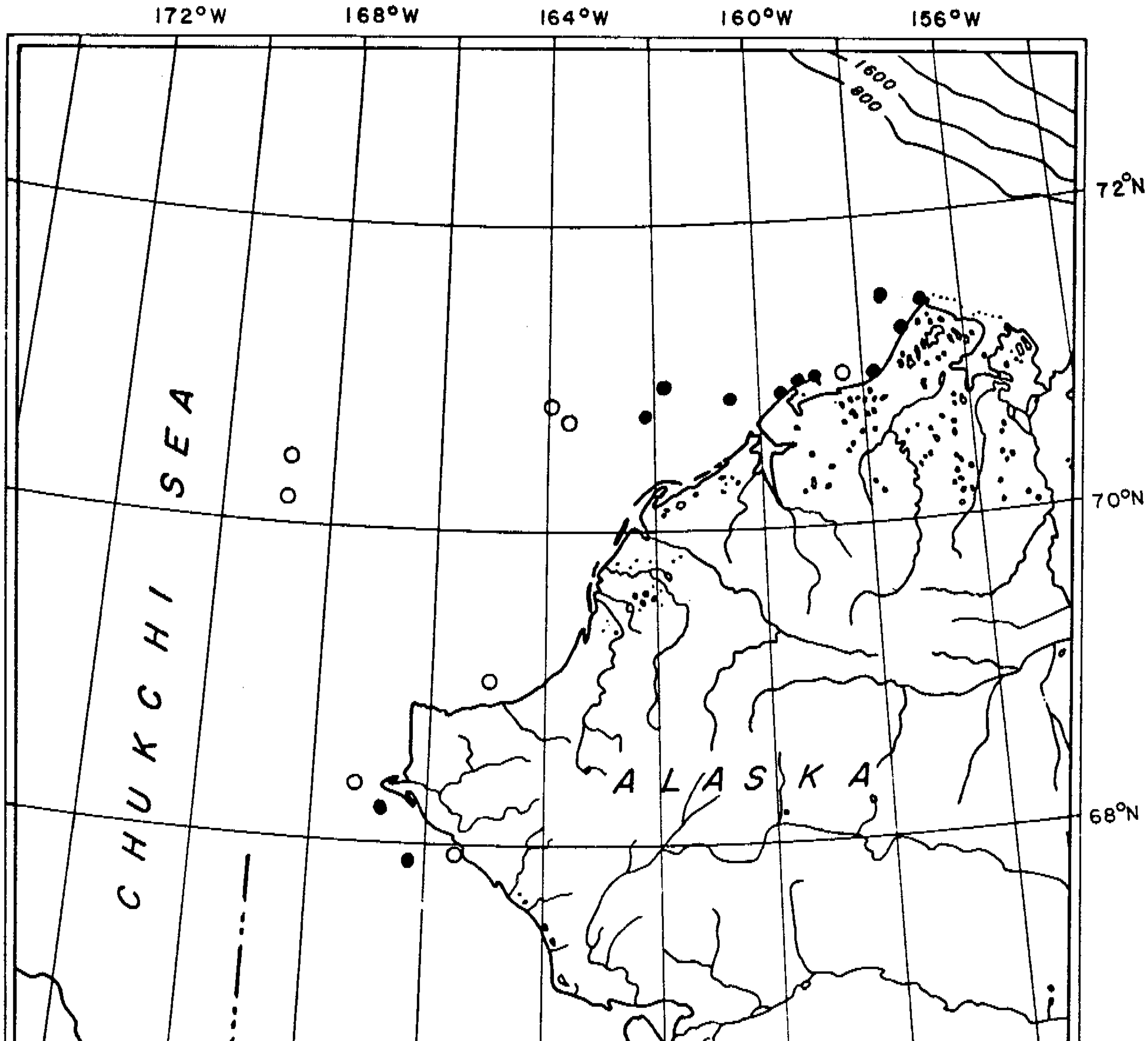
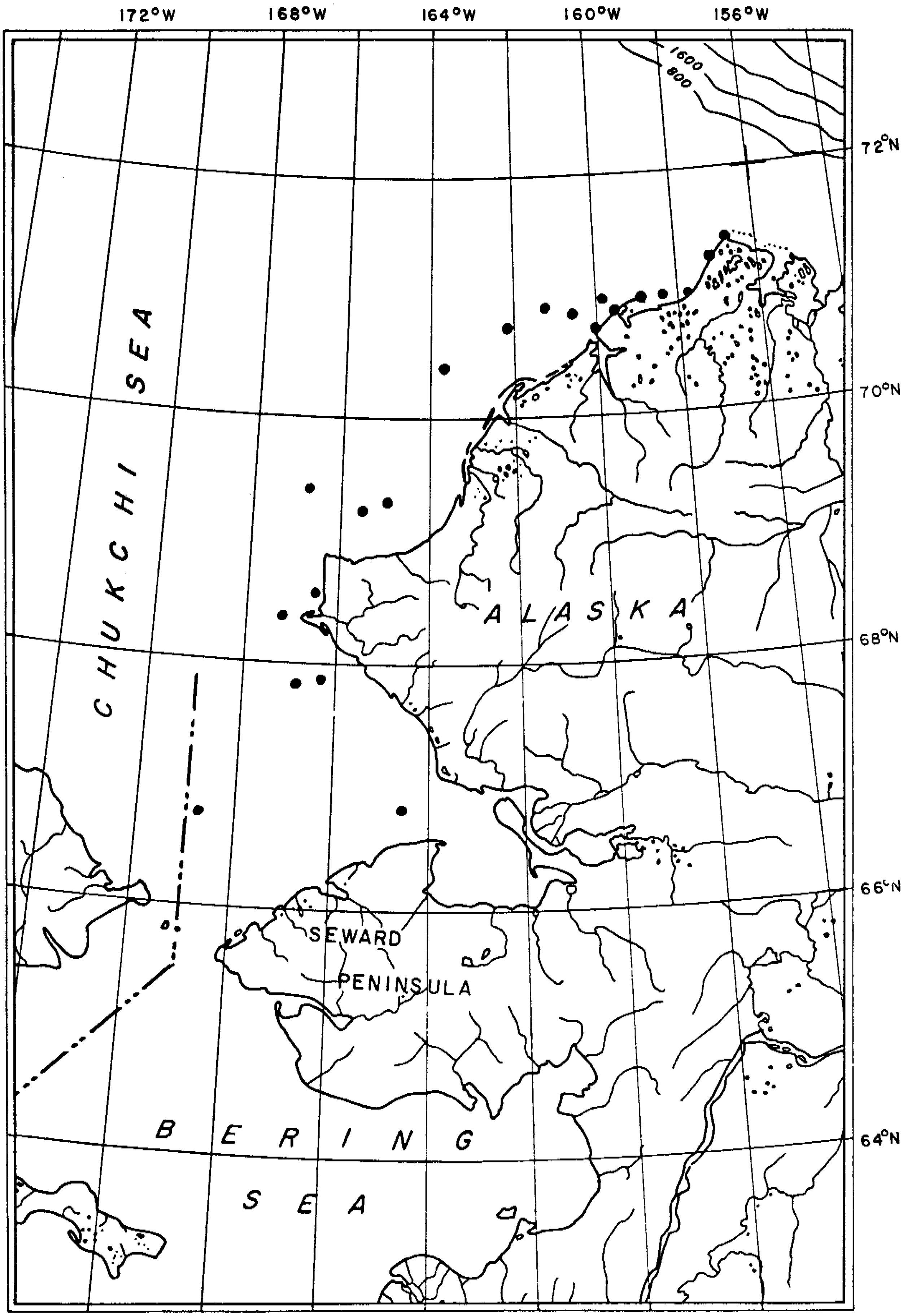


Figure 3. Map showing distribution of sample location. Numbers are U.S. Geologic Survey, Menlo Park series location numbers.



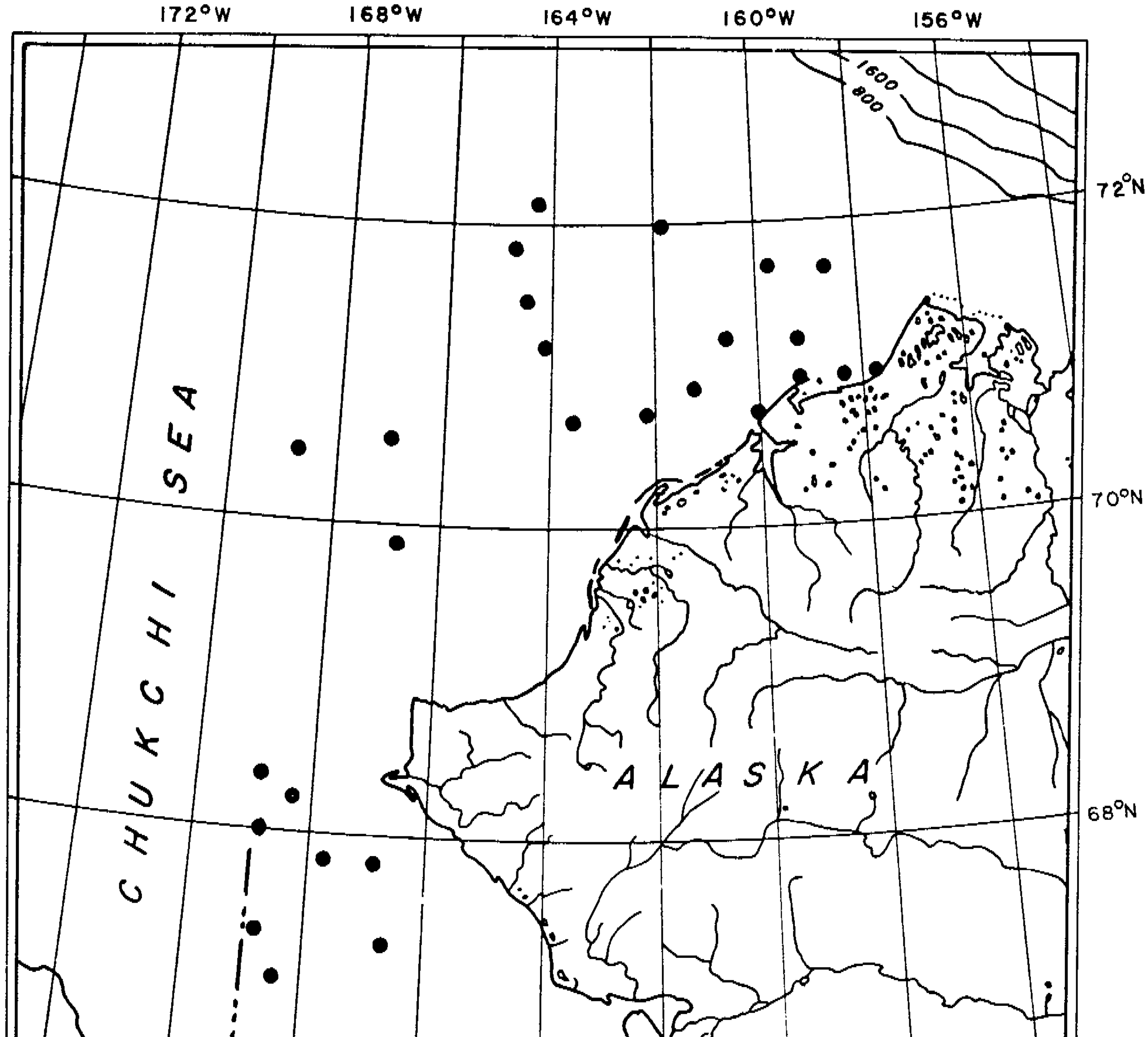
Hemithyris psittacea (Gmelin, 1792)



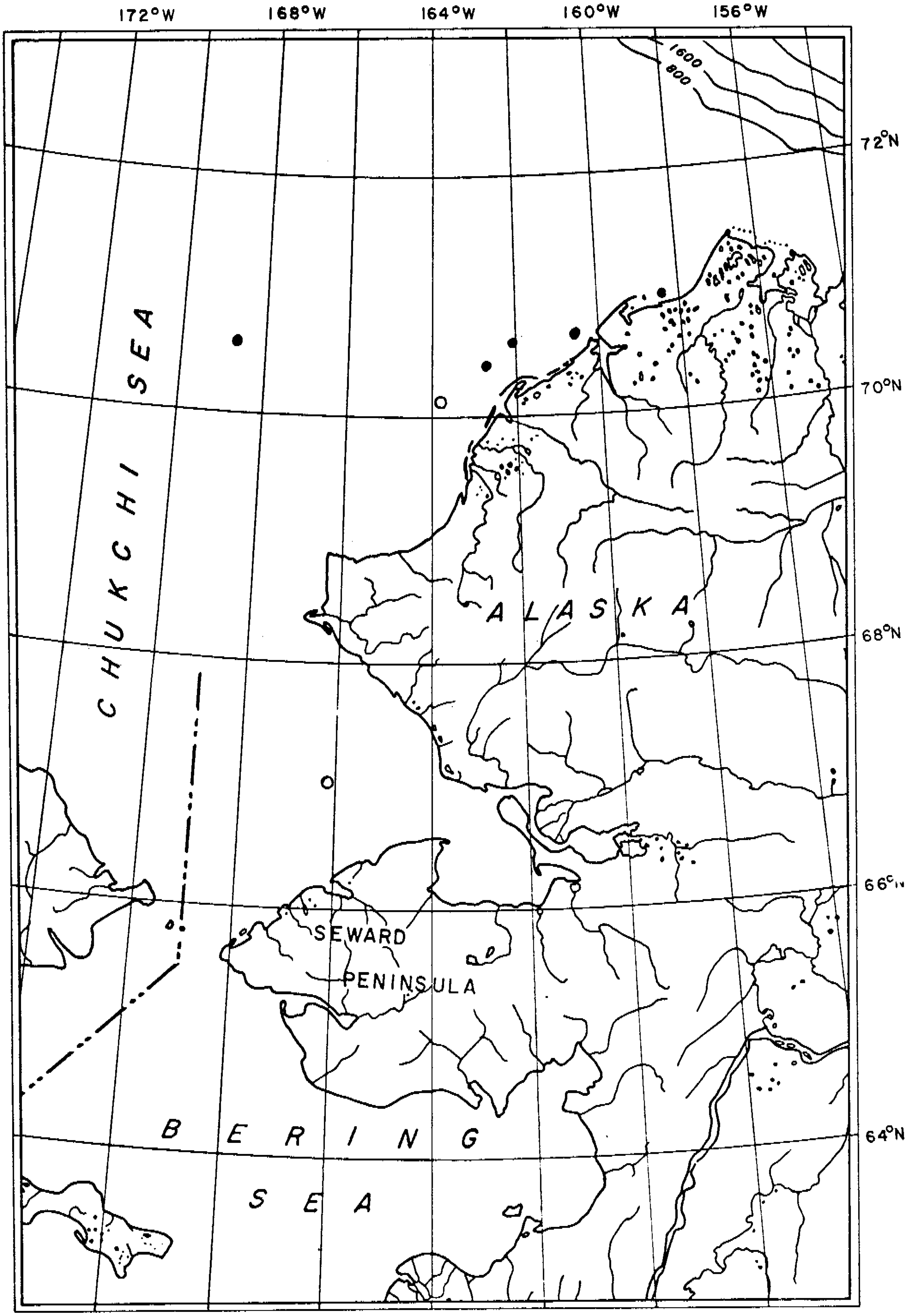
Balanus crenatus Brugiere, 1789

Balanus rostratus alaskensis Pilsbry, 1916

Elphidiella sibiricum



133 *Pectinaria californiense* Hartman



Echinarius parma (Lamarck)

Strongyocentrotus drobachiensis (Muller)

Psolus phantopus (Strussenfeldt)

137 *Psolus fabricii* (Duben and Koren)

Admente couthouyi (Jay, 1839)

Admente middendorffiana (Dall, 1885)

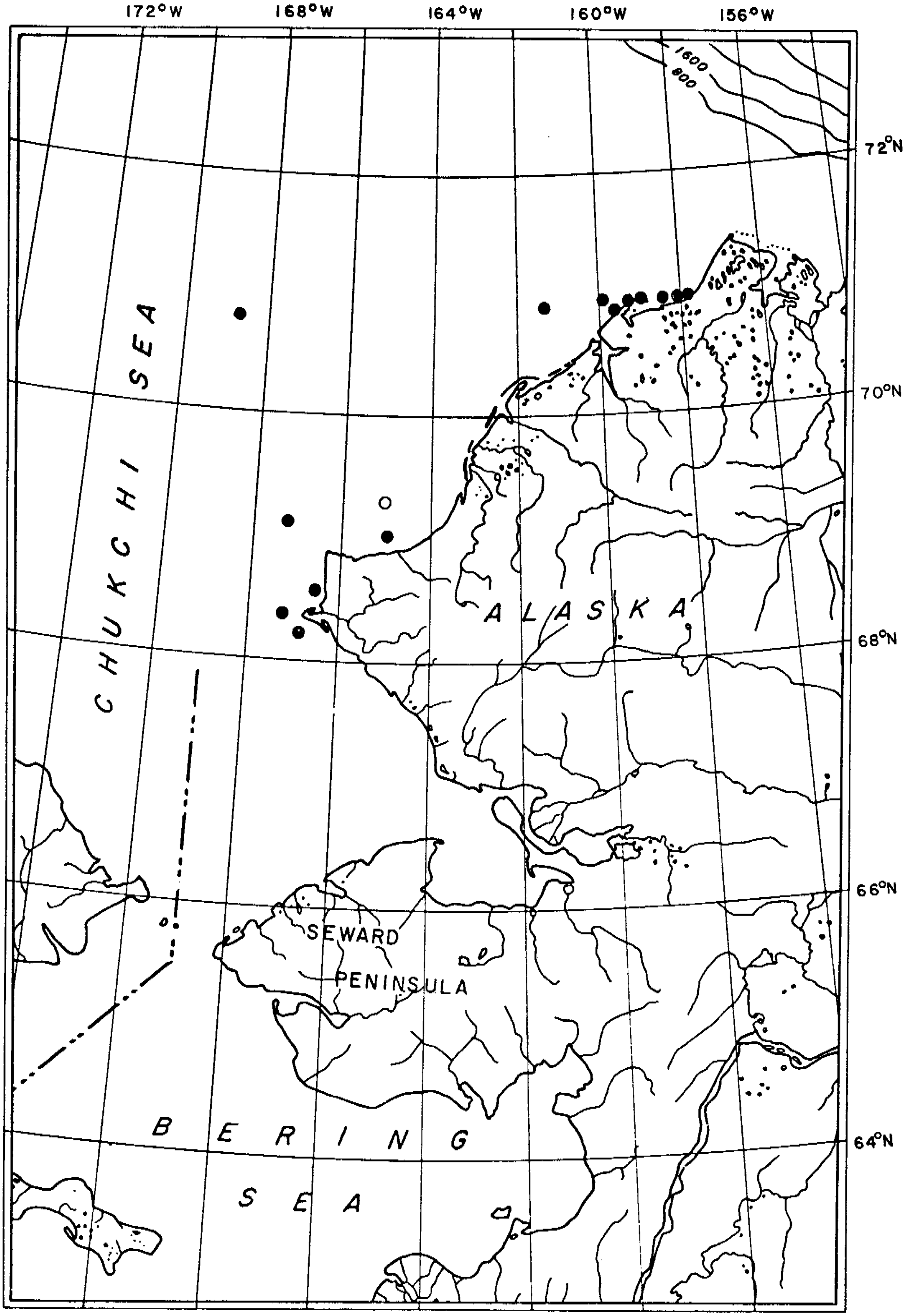
Acmaea testudinalis (Muller, 1776)

Beringus beringi (Middendorff, 1849)

Boreotrophon clathratus (Linne, 1767)

Boreotrophon clathratus var. gunneri (Loven, 1846)

Boreotrophon pacificus (Dall, 1902)



145 *Boreotrophon truncatus* (Strom, 1768)

Buccinum ciliatum Fabricius, 1780

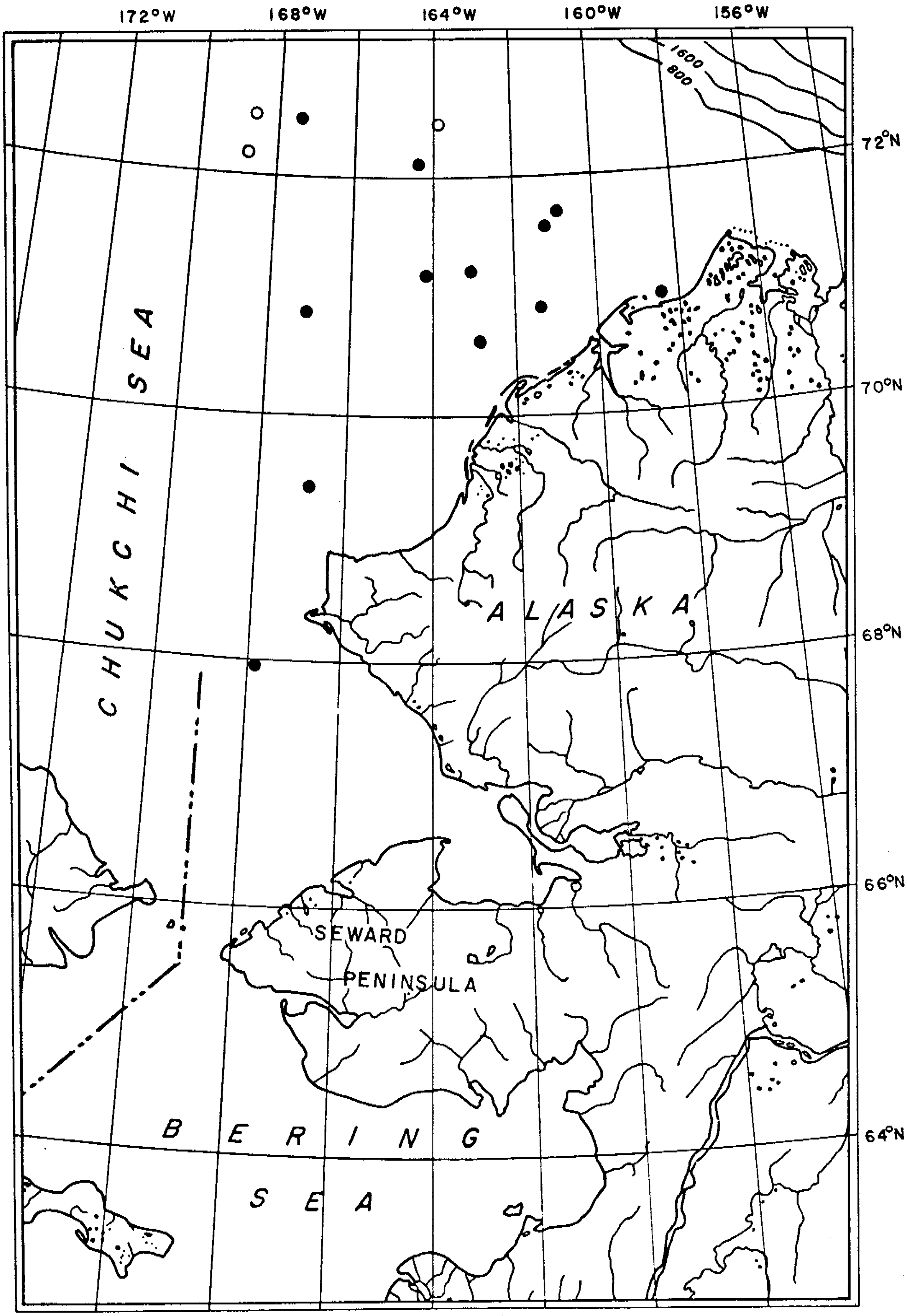
147 *Buccinum glaciale* Linne, 1761

 Buccinum polare Gray, 1839

149 *Buccinum tenue* Gray, 1839

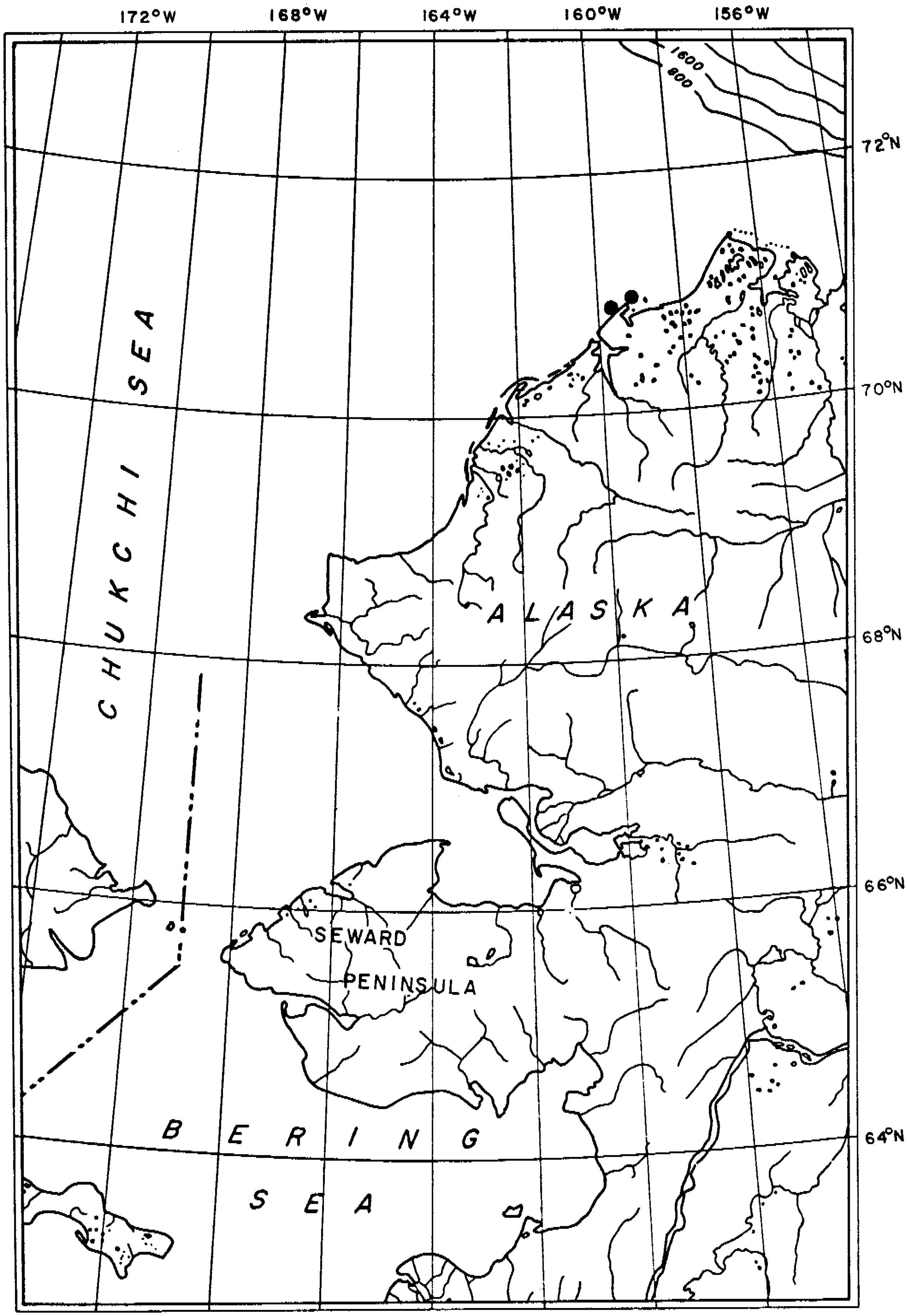
Buccinum undulatum (Linnaeus, 1761)

Crepidula grandis Middendorff, 1849



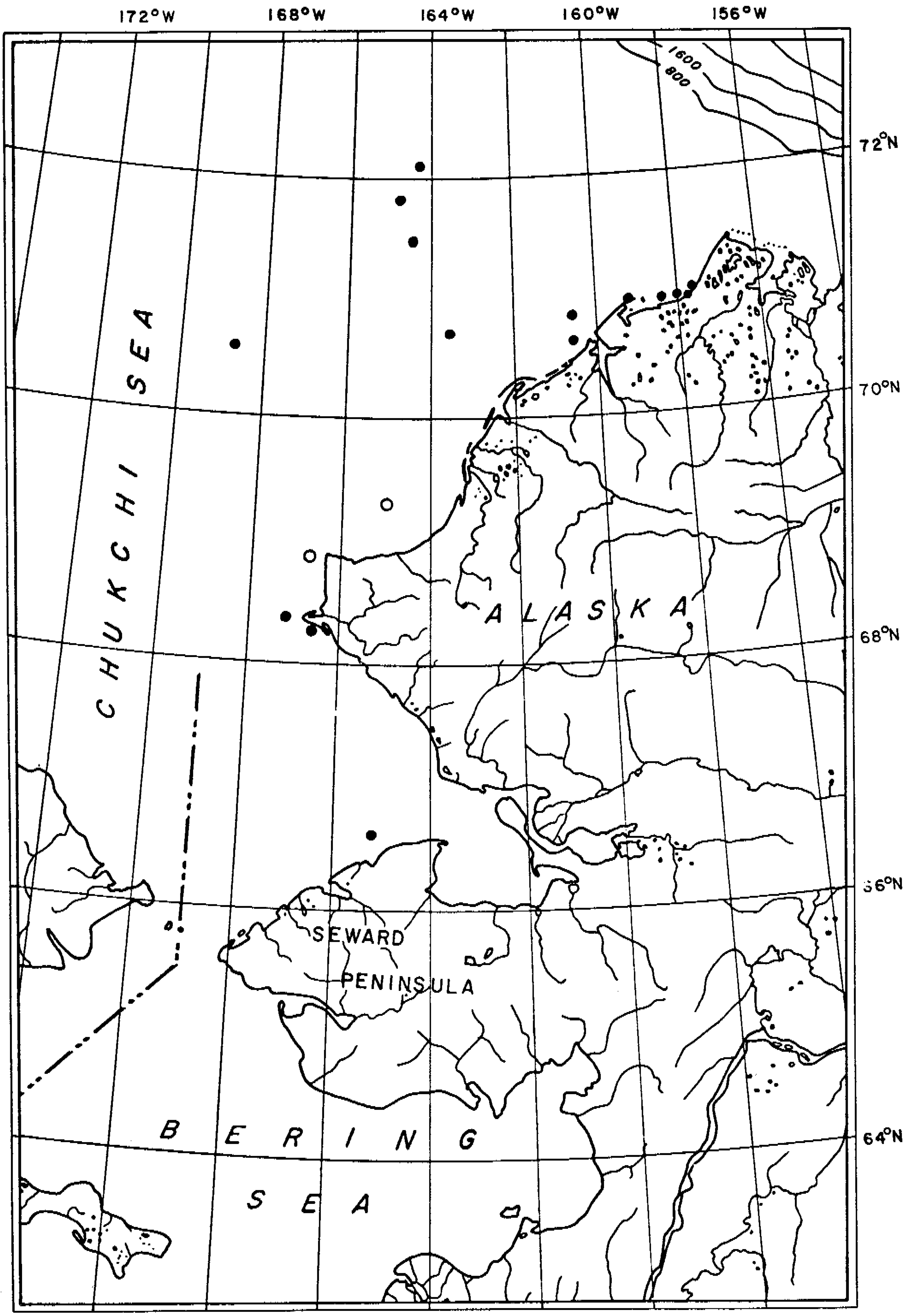
Cylichna alba (Brown, 1827)

153 *Cylichna occulata* (Mighels, 1841)



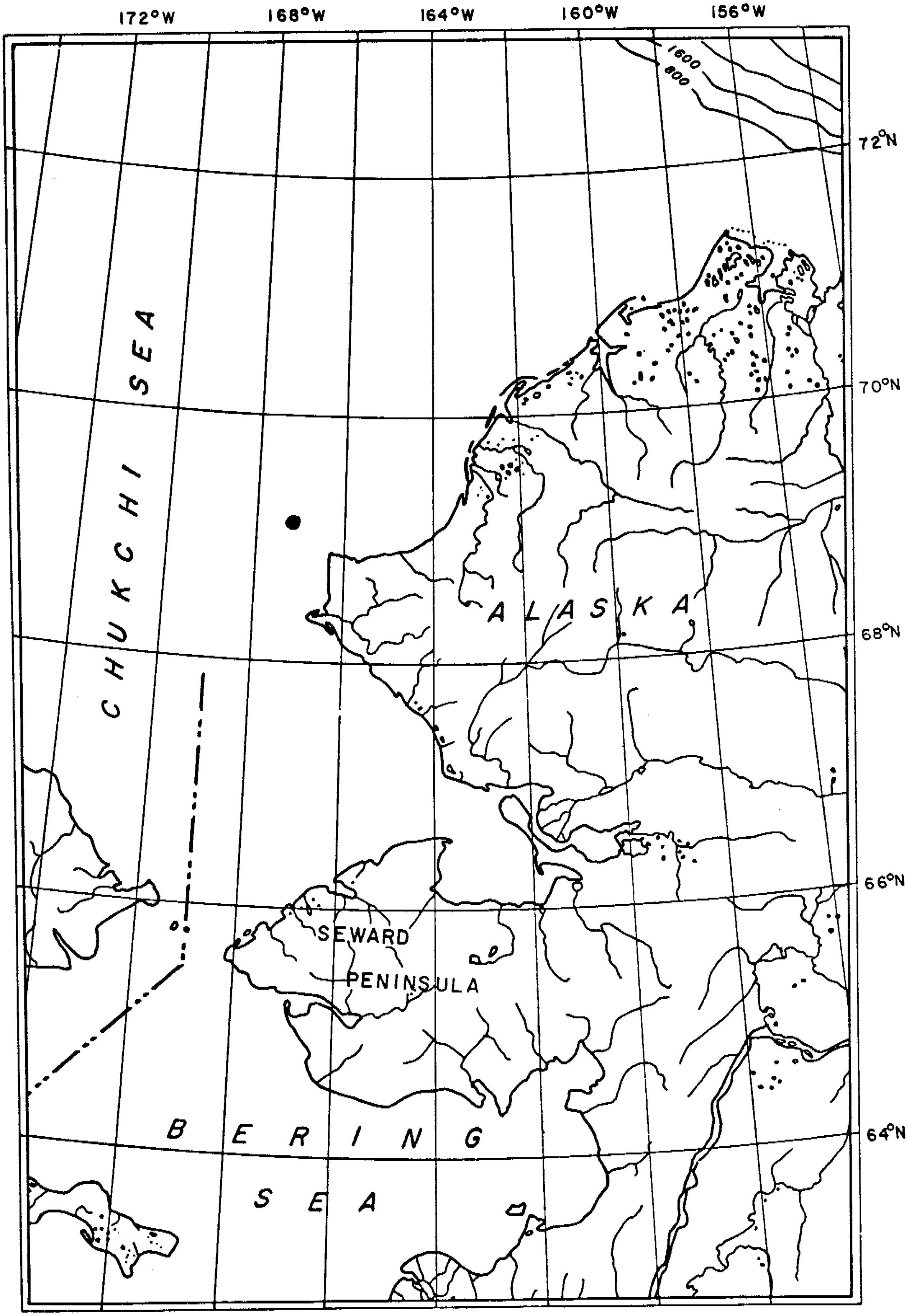
Epitonium greenlandicum (Perry, 1811)

Lepeta caeca (Muller, 1776)



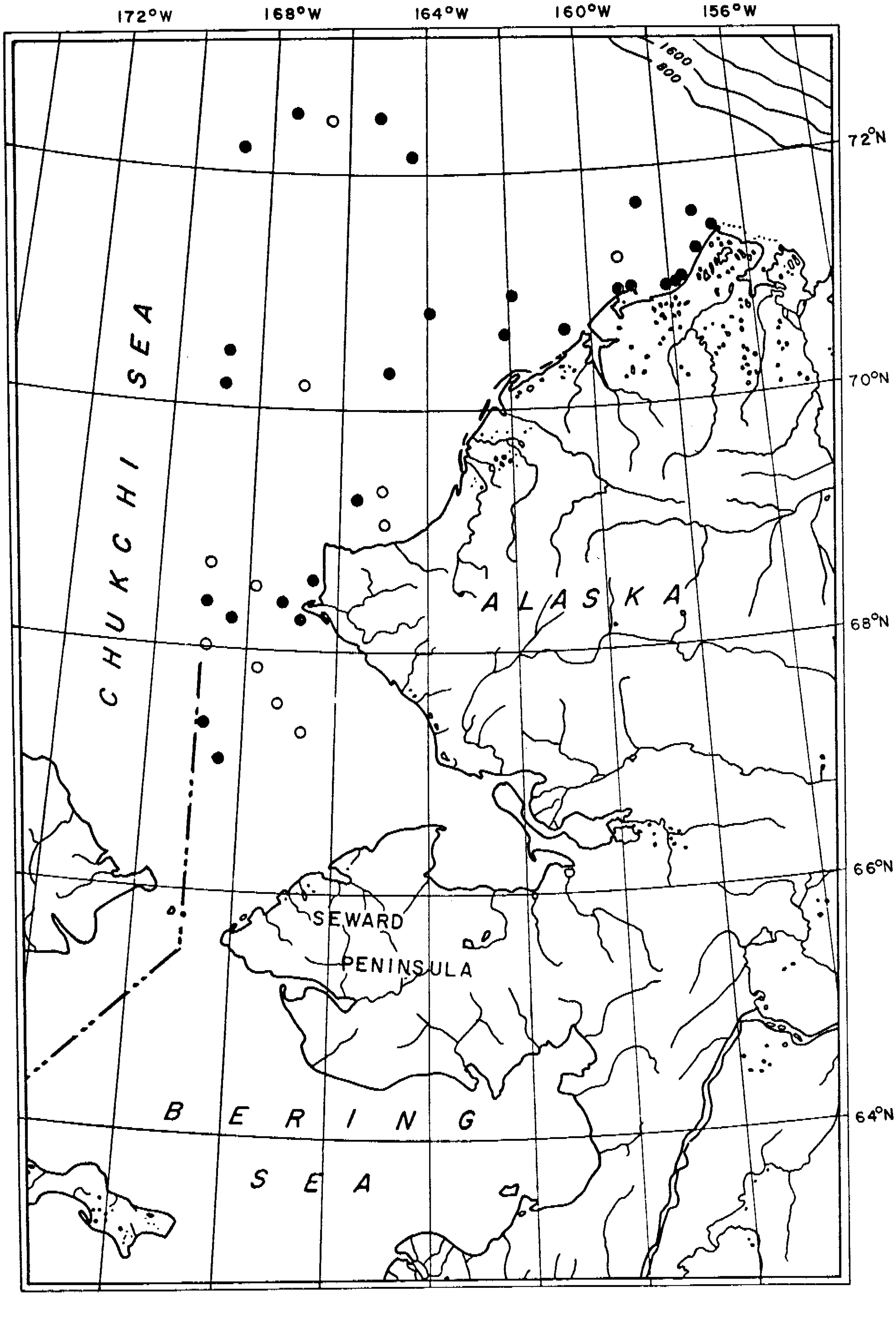
156 *Margarites costalis* (Gould, 1841)

Margarites frigidus Dall, 1919



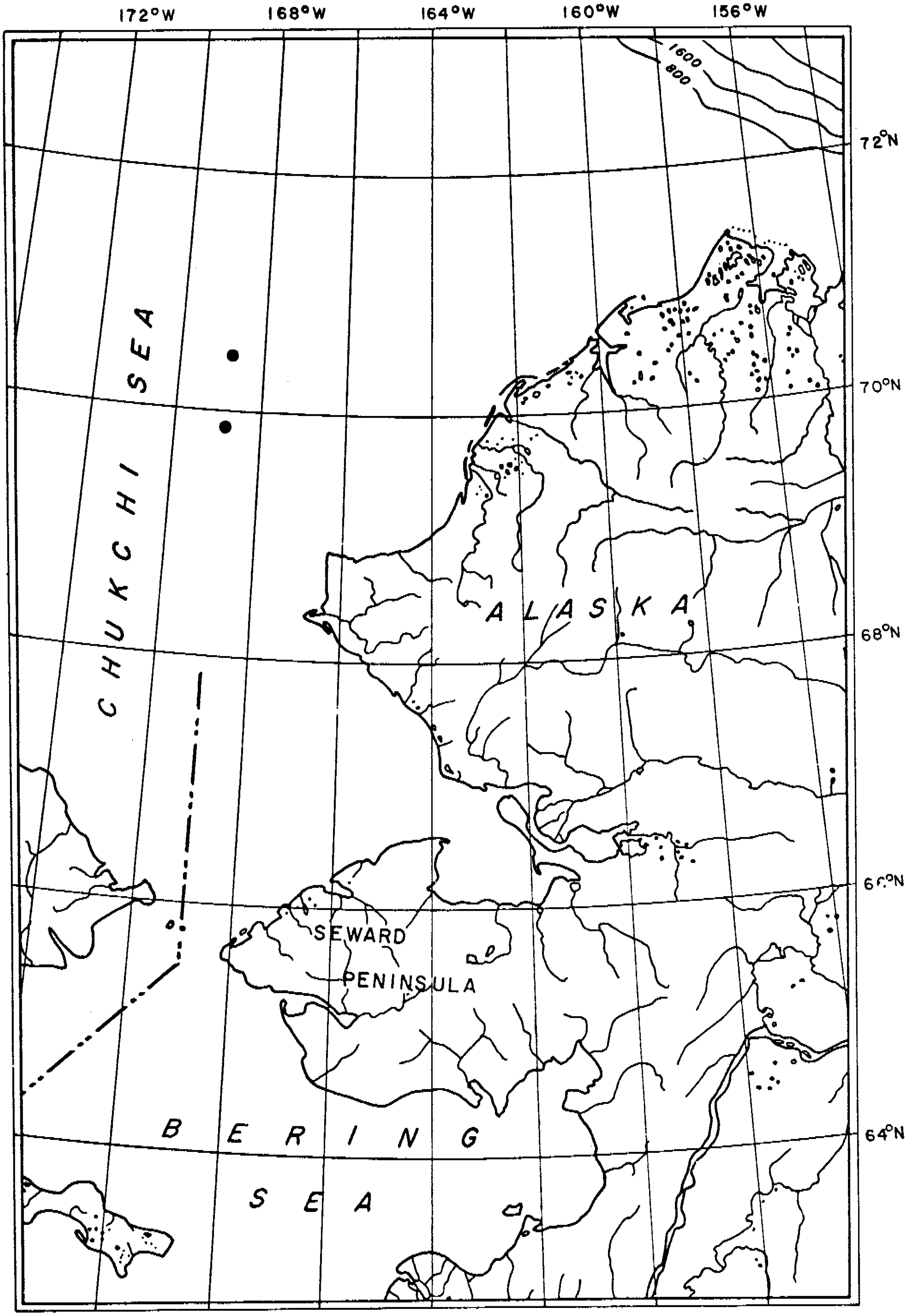
Margarites striatus (Broderip and Sowerby, 1817)

Margaritopsis probiloffensis (Dall, 1919)



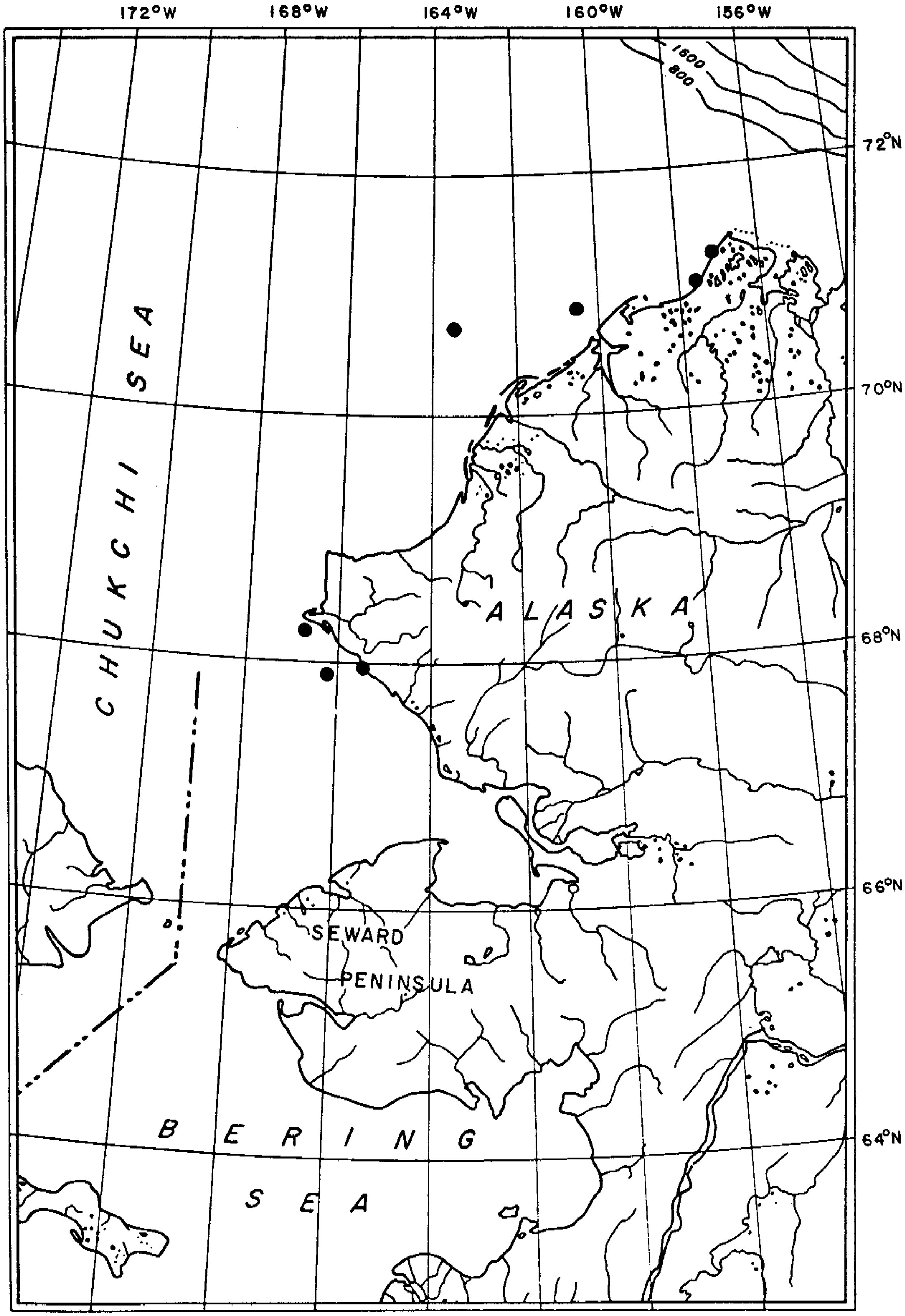
Natica clausa Broderip and Sowerby, 1829

161 *Neptunea satura heros* (Gray, 1850)



162 *Nodotoma impressa* (Morch, 1869)

163 *Oenopota elegans* (Moller, 1842)

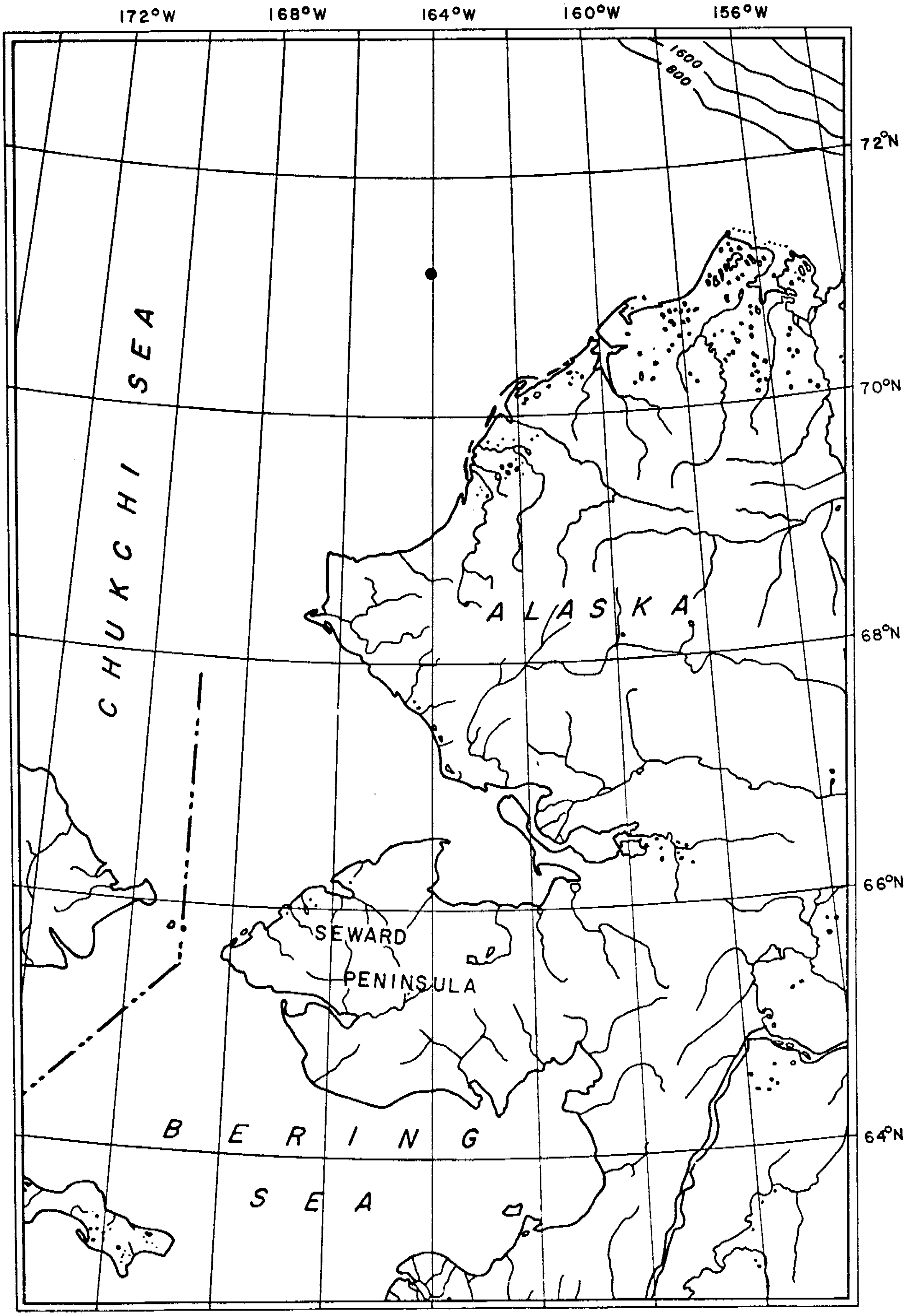


Oenopota tenuicostata (G.O.Sars, 1878)

165 *Piliscus commodus* (Middendorff, 1851)

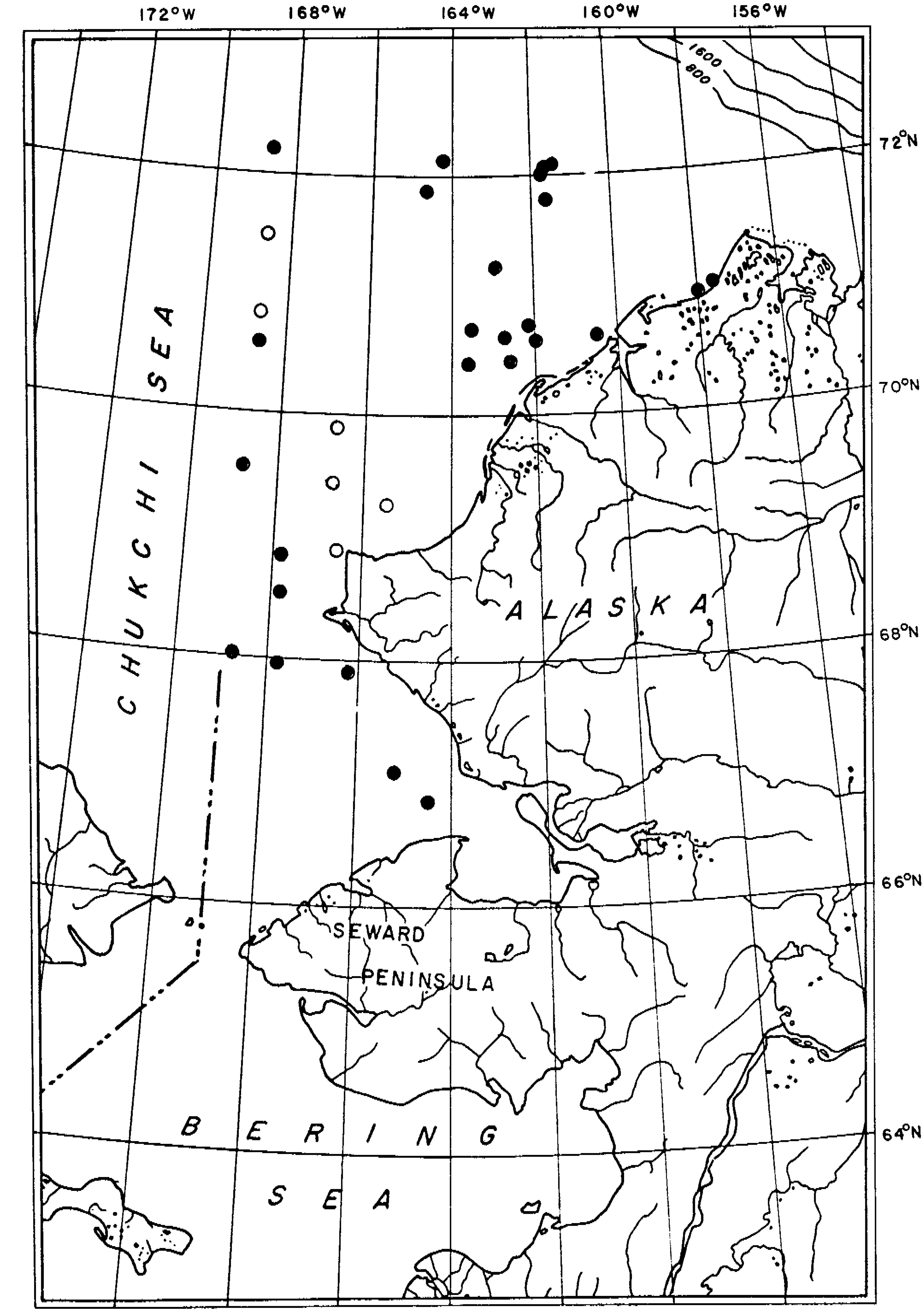
Plifuscus kroyeri (Moller, 1842)

Polinices palladus (Broderip and Sowerby, 1829)

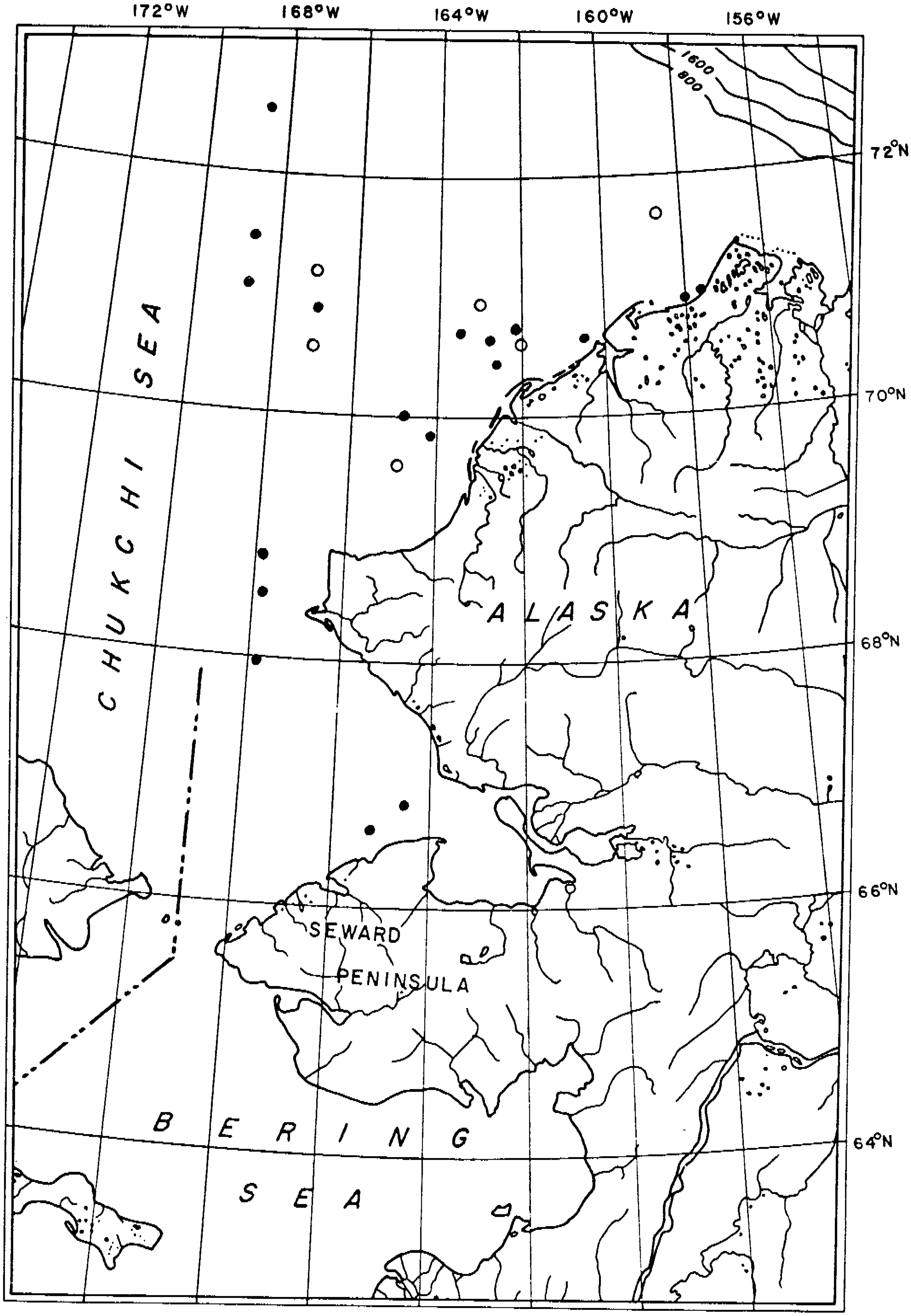


Ptychatractus occidentalis Stearns, 1871

Puncturella noachina (Linnaeus, 1771)

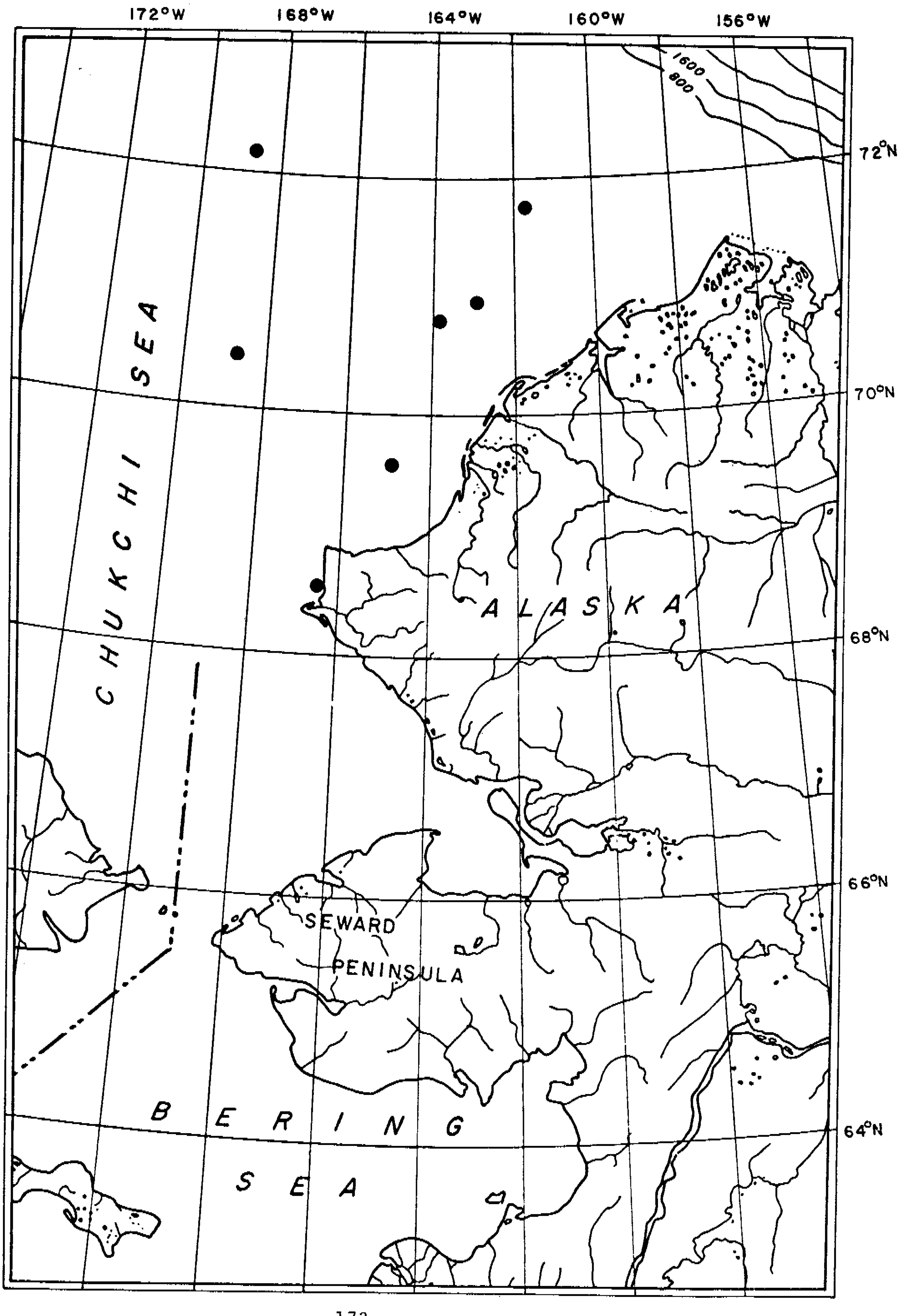


170 *Solariella obscura* (Couthouy, 1838)



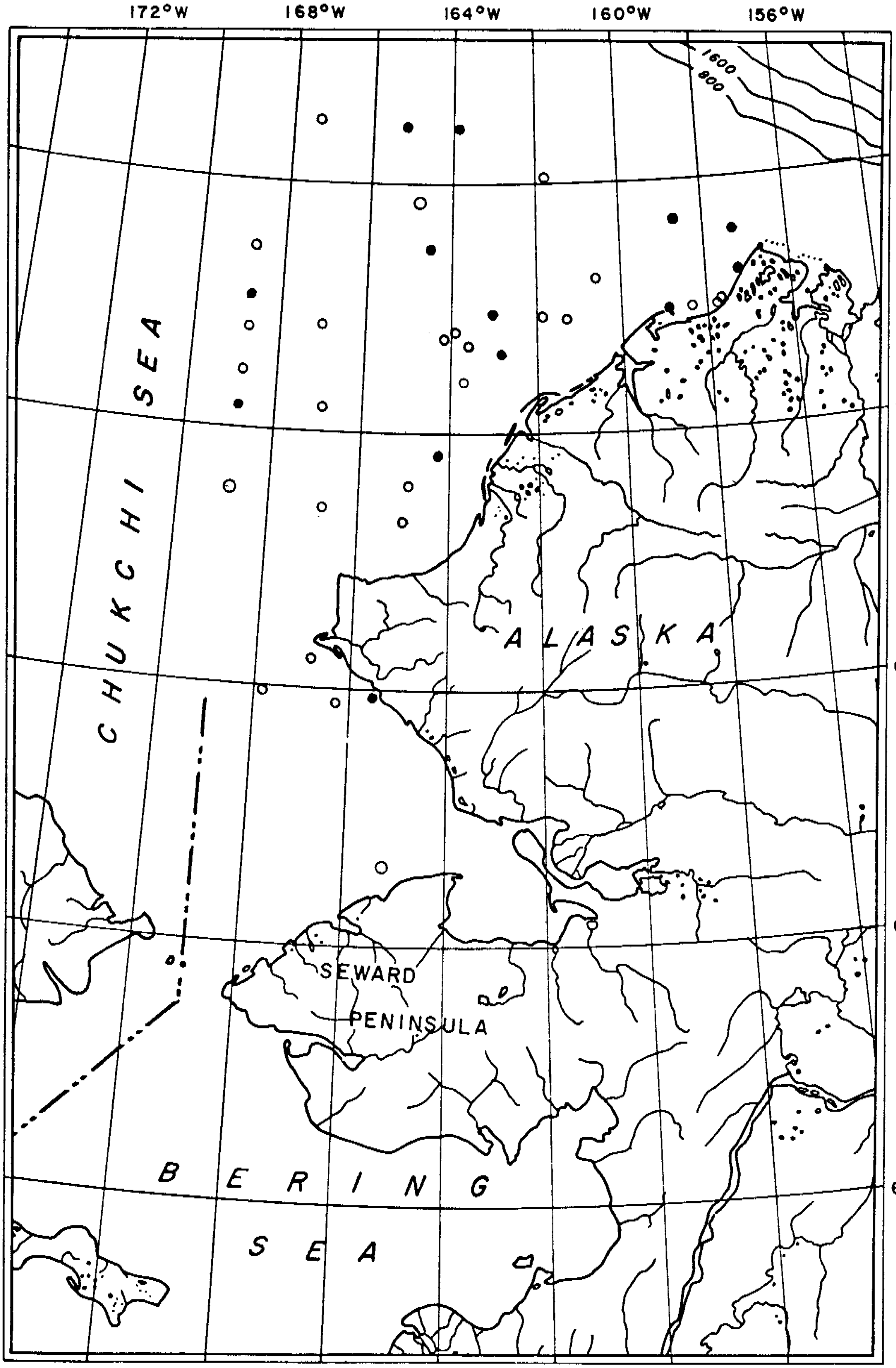
Tachyrynchus erosus (Couthouy, 1838)

Tachyrynchus reticulatum (Mighels and Adams, 1842)

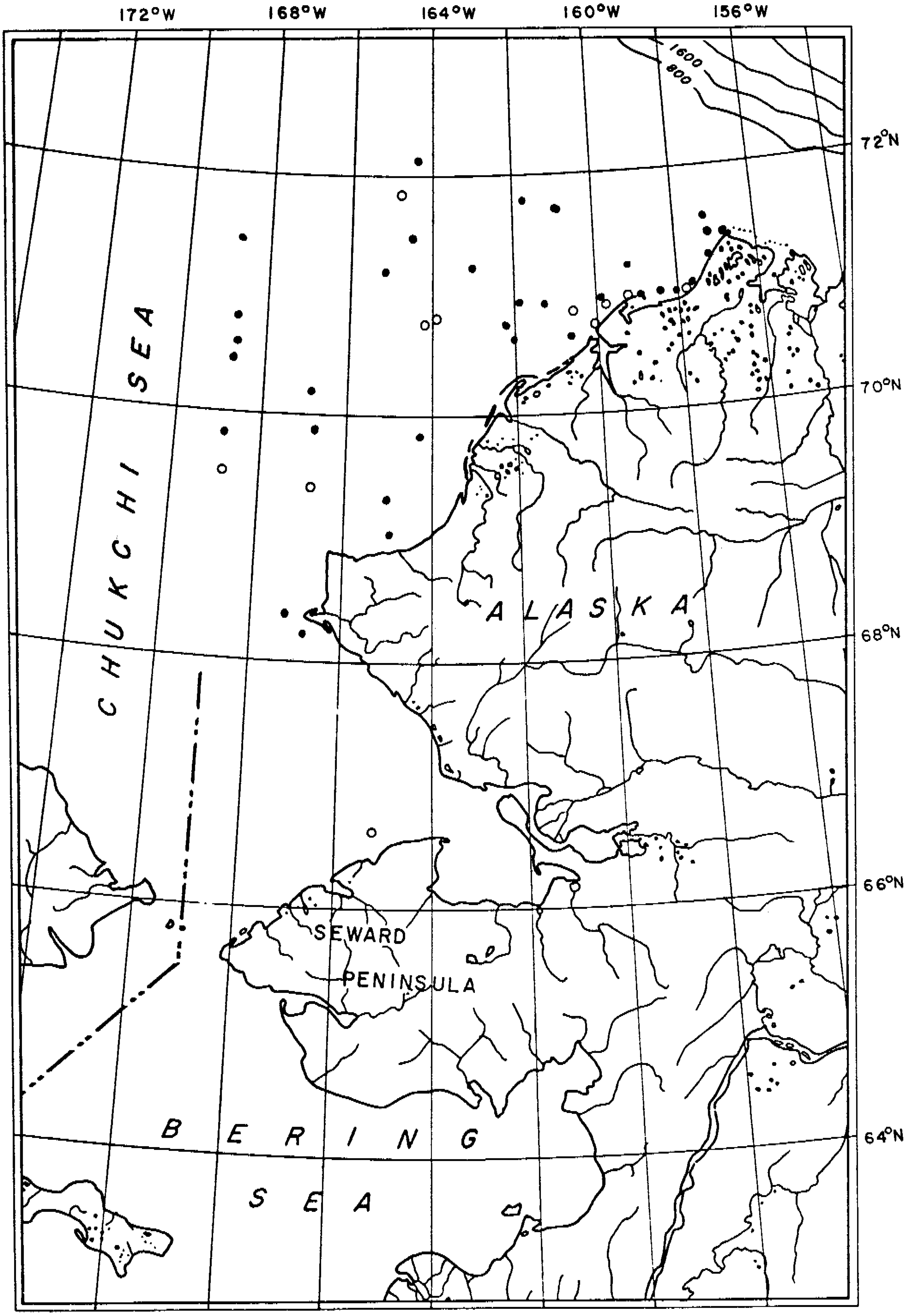


Trichotropis kroyeri Philipp, 1849

Astarte bennettii Dall 1903



Astarte borealis (Schumacher, 1817)



Astarte montagui (Dillwyn, 1817)

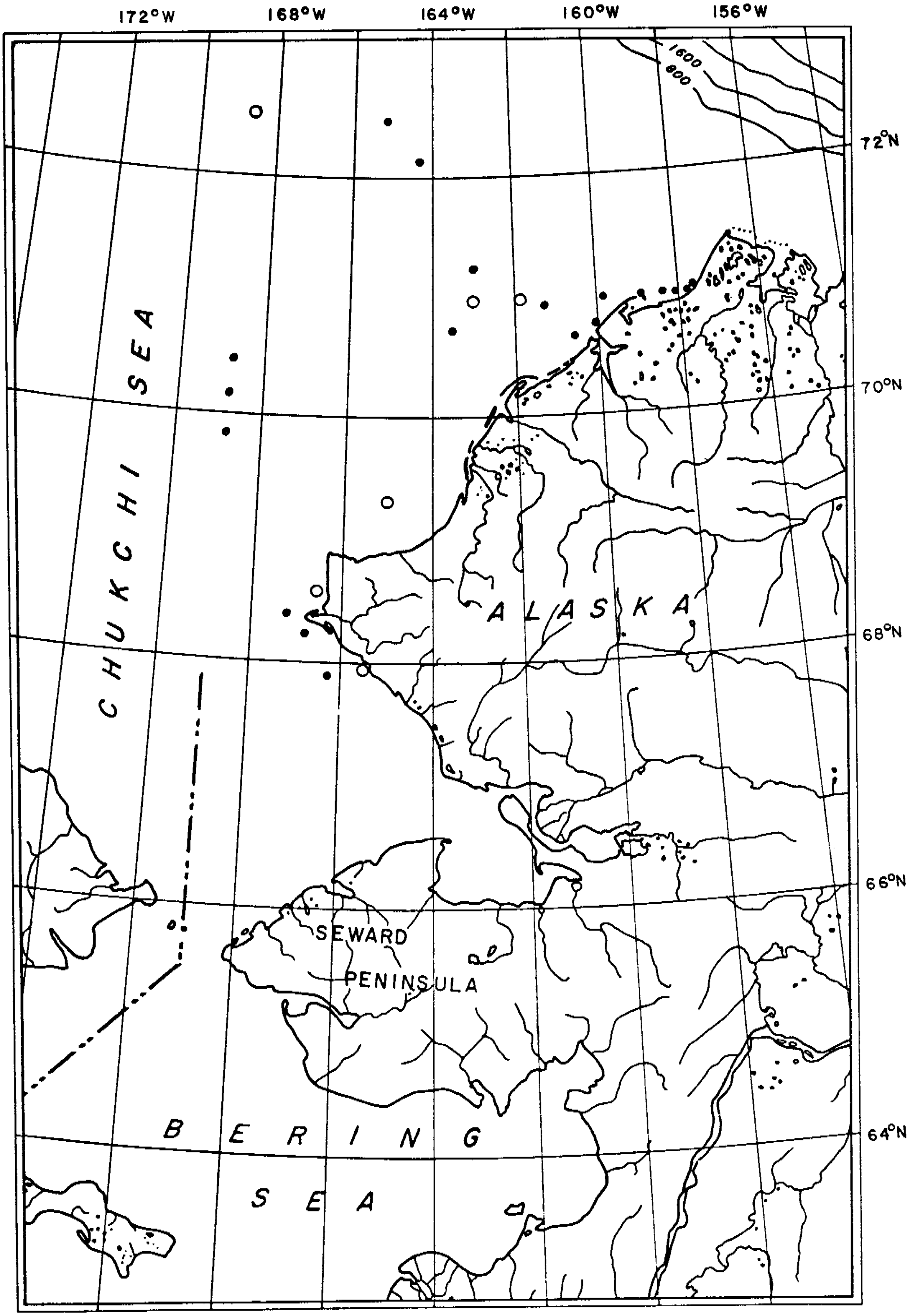
Asthenotharus adamsi (MacGinitie, 1959)

Axinopsida orbiculata (G.O.Sars, 1878)

Chlamys pseudislandica MacNeil, 1967

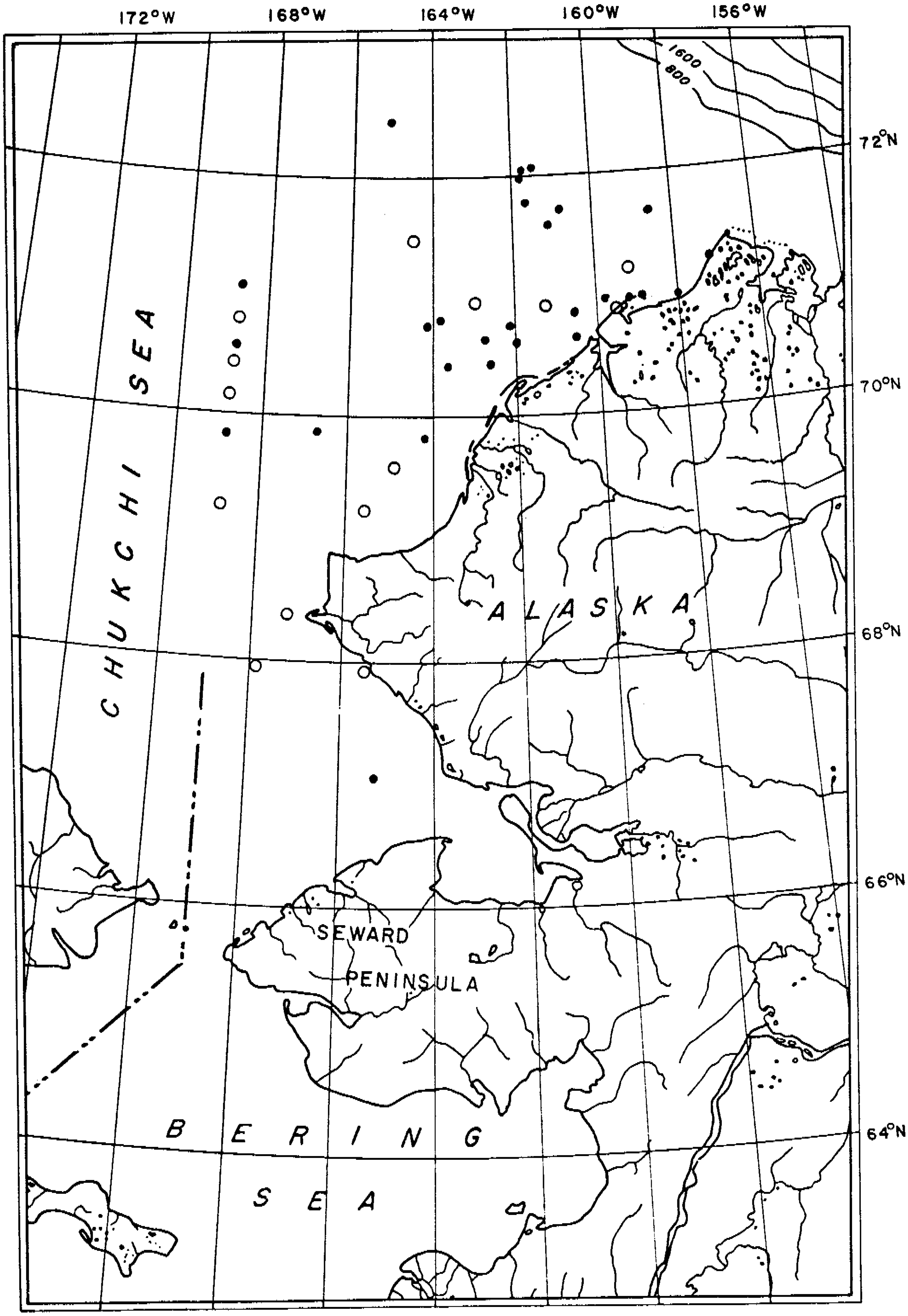
Clinocardium californiense (Deshayes, 1839)

Clinocardium ciliatum (Fabricius, 1780)

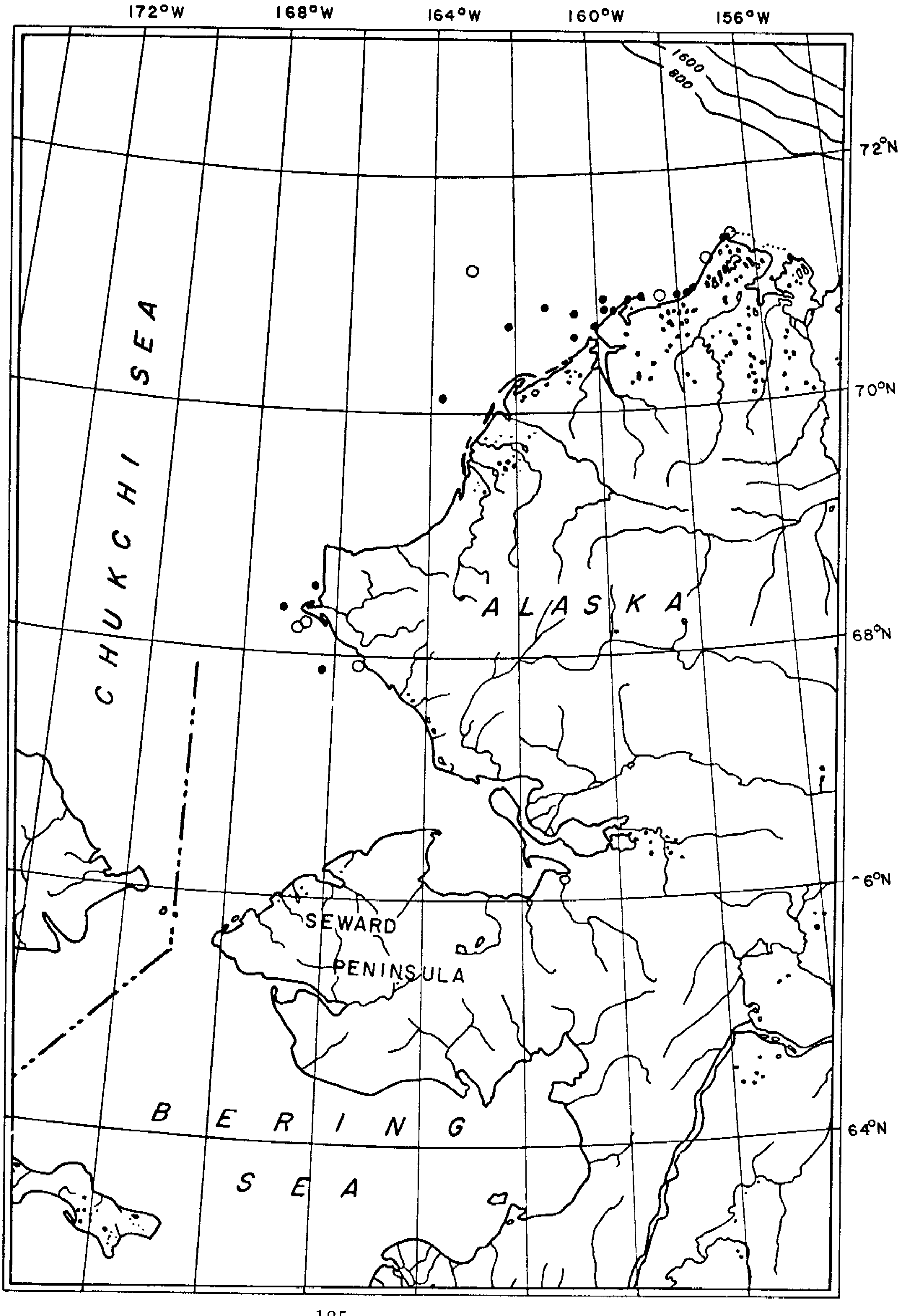


Cyclocardium crassidens (Broderip and Sowerby, 1829)

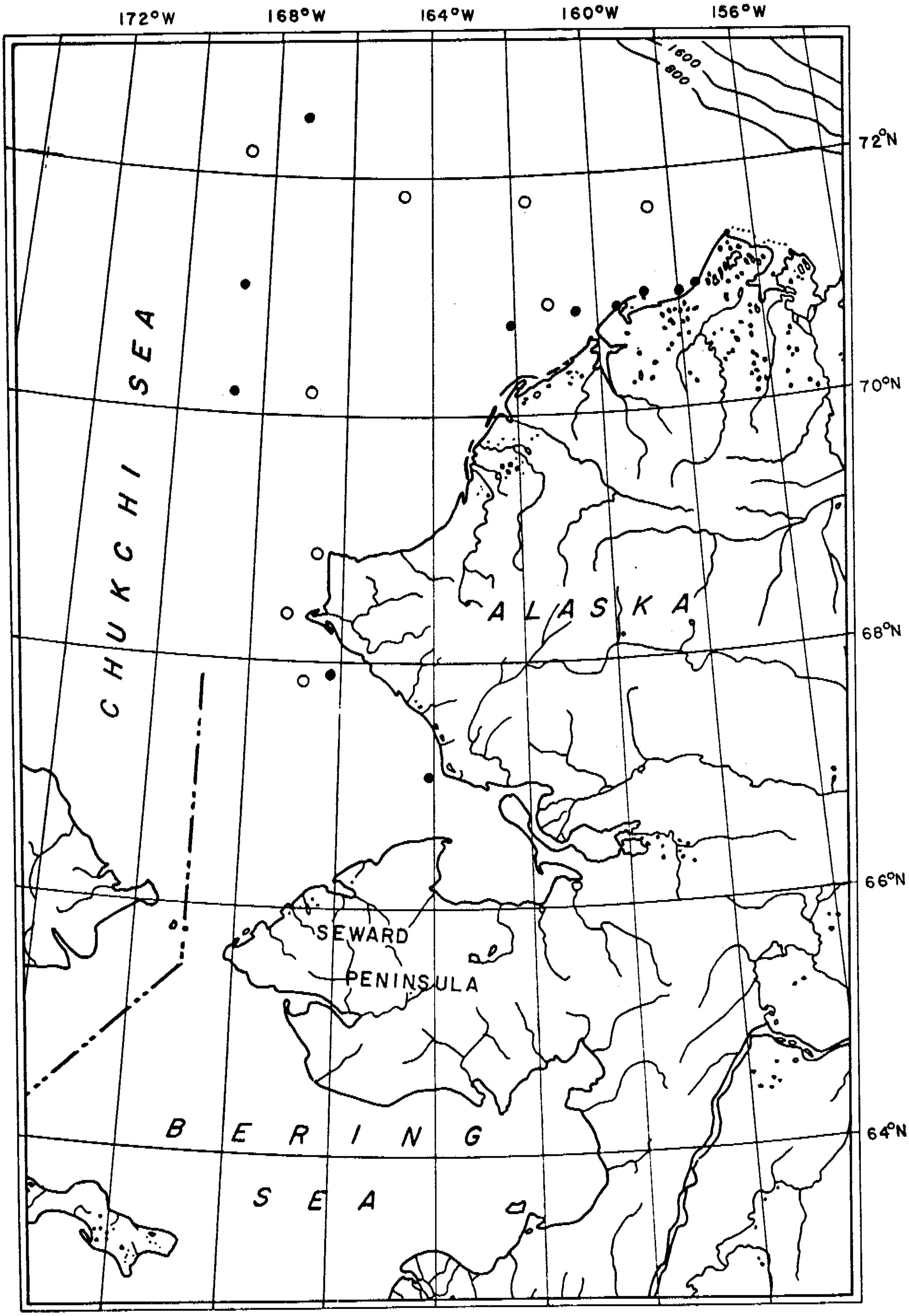
Cyclocardium crebricostata (Krase, 1895)



Gomphina fluctuosa (Gould, 1841)

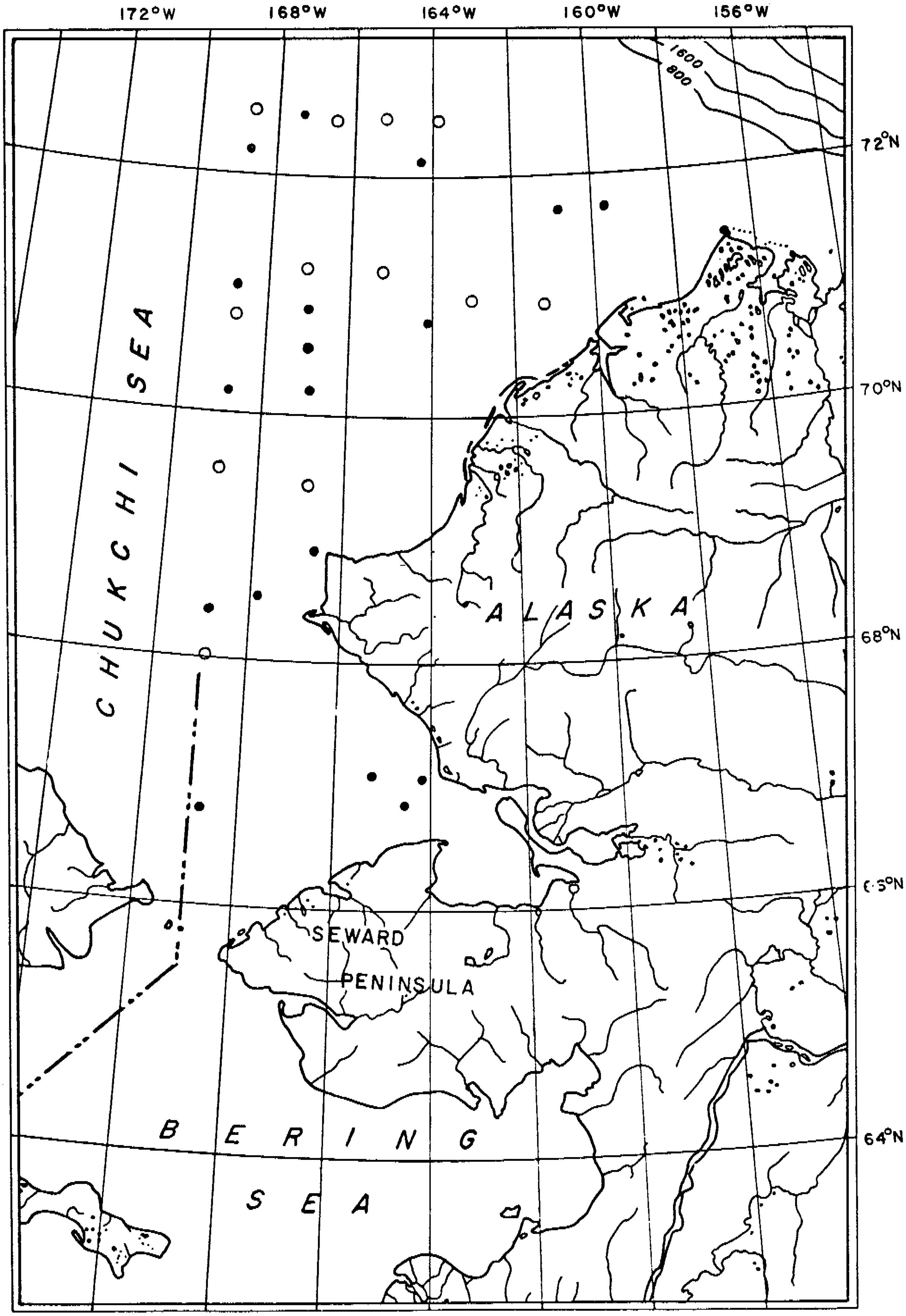


Hiatella artica (Linne', 1767)



Leda minuta (Fabricius, 1776)

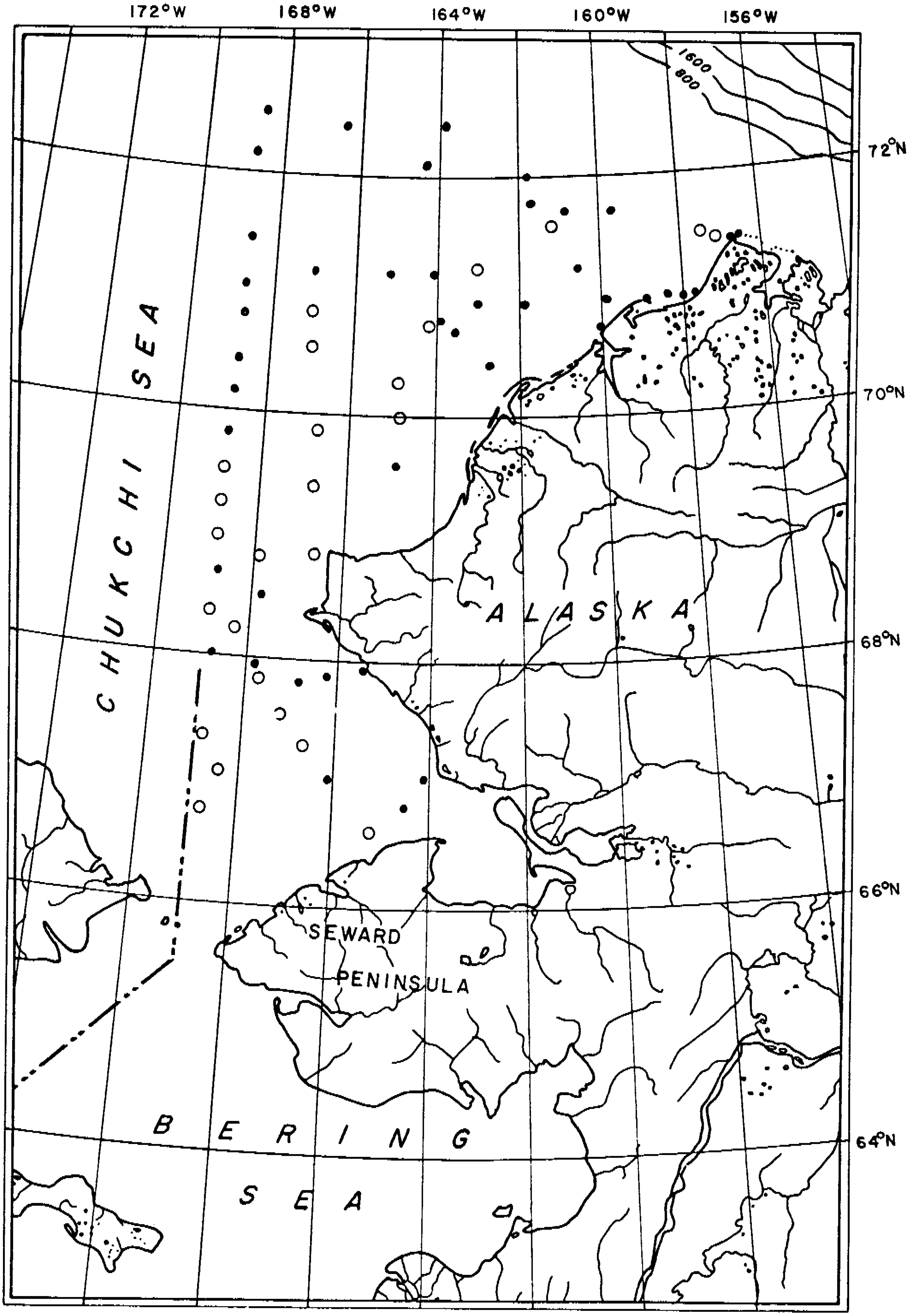
Leda pernula (Muller, 1779)



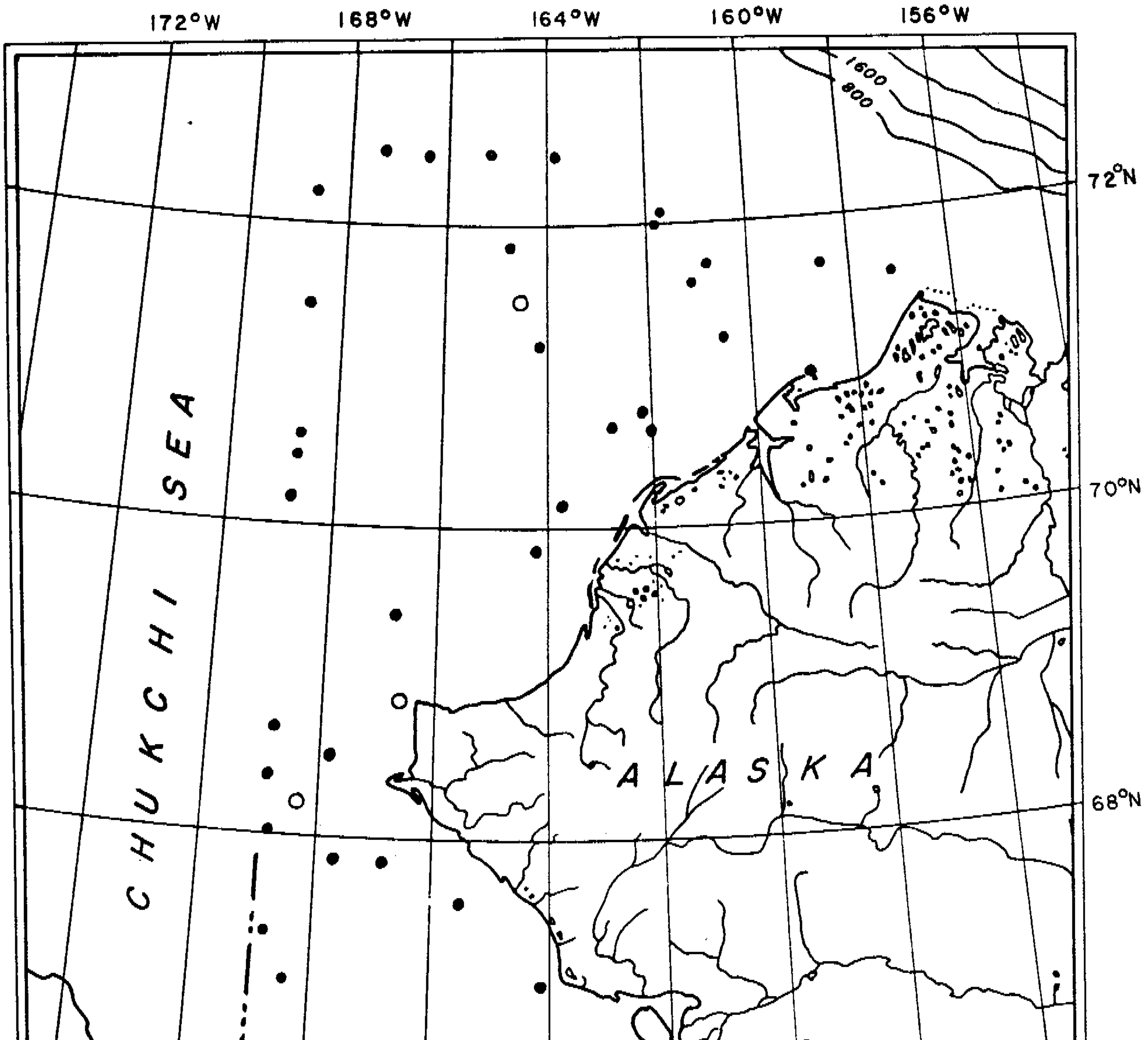
Leda radiata (Krause, 1885)

Lyonsia arenosa Gould, 1861

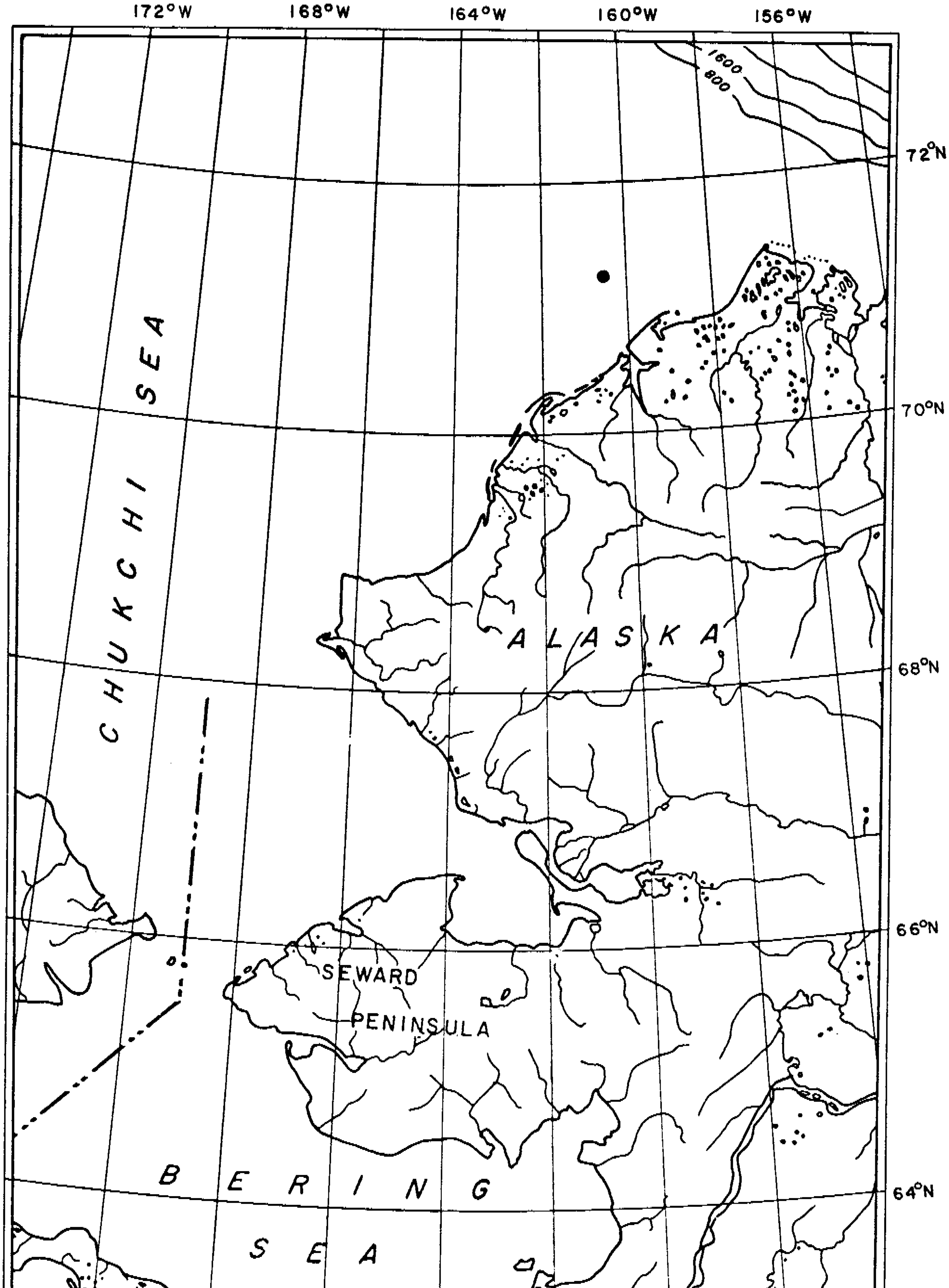
Macoma brota Dall, 1916



Macoma calcarea (Gmelin, 1791)



192 *Macoma moesta* (Deshayes, 1855)



Macoma obliqua (Sowerby and Broderip, 1817)

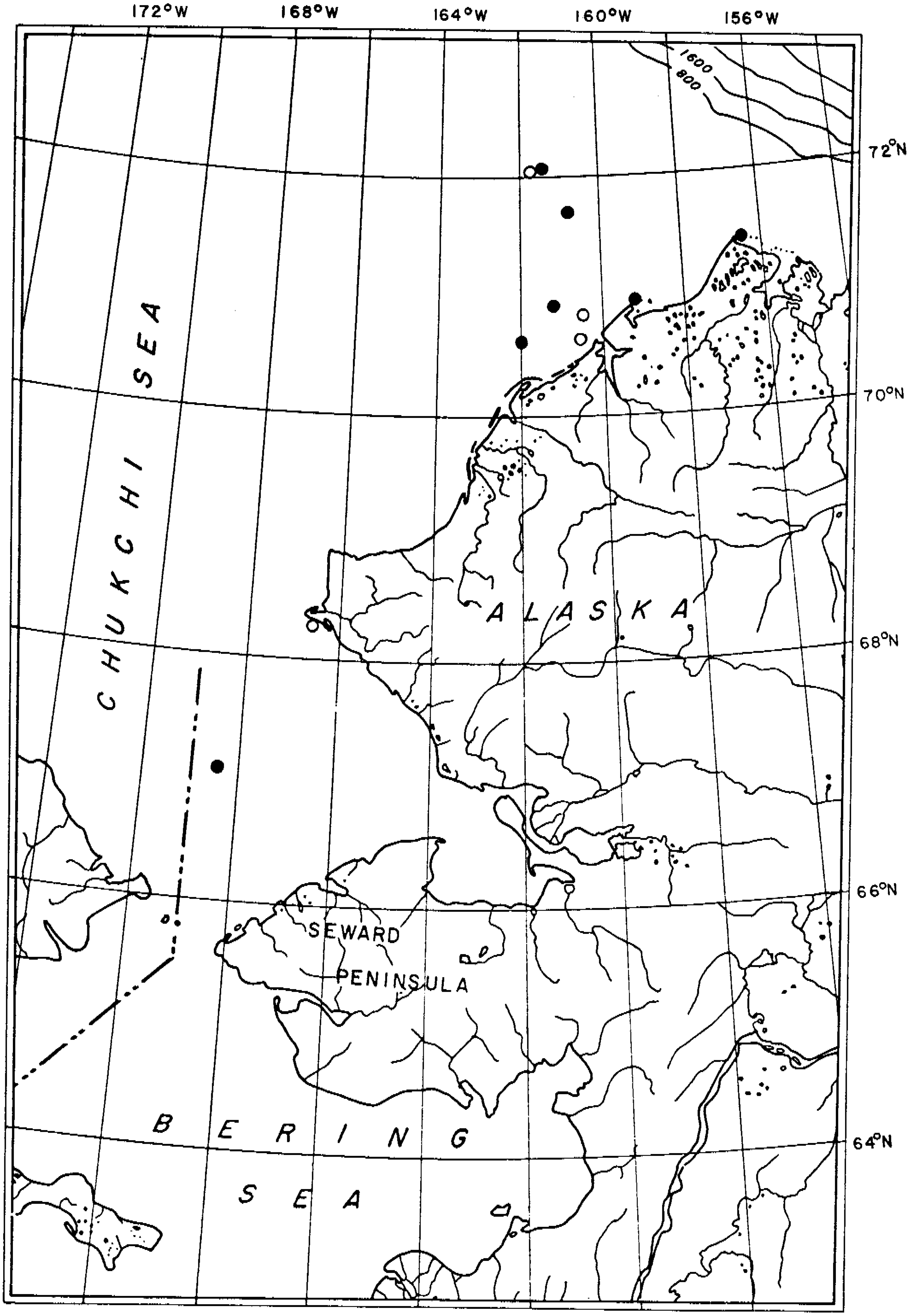
Montacuta planata (Dall, 1885)

Musculus corregatus (Stimpson, 1851)

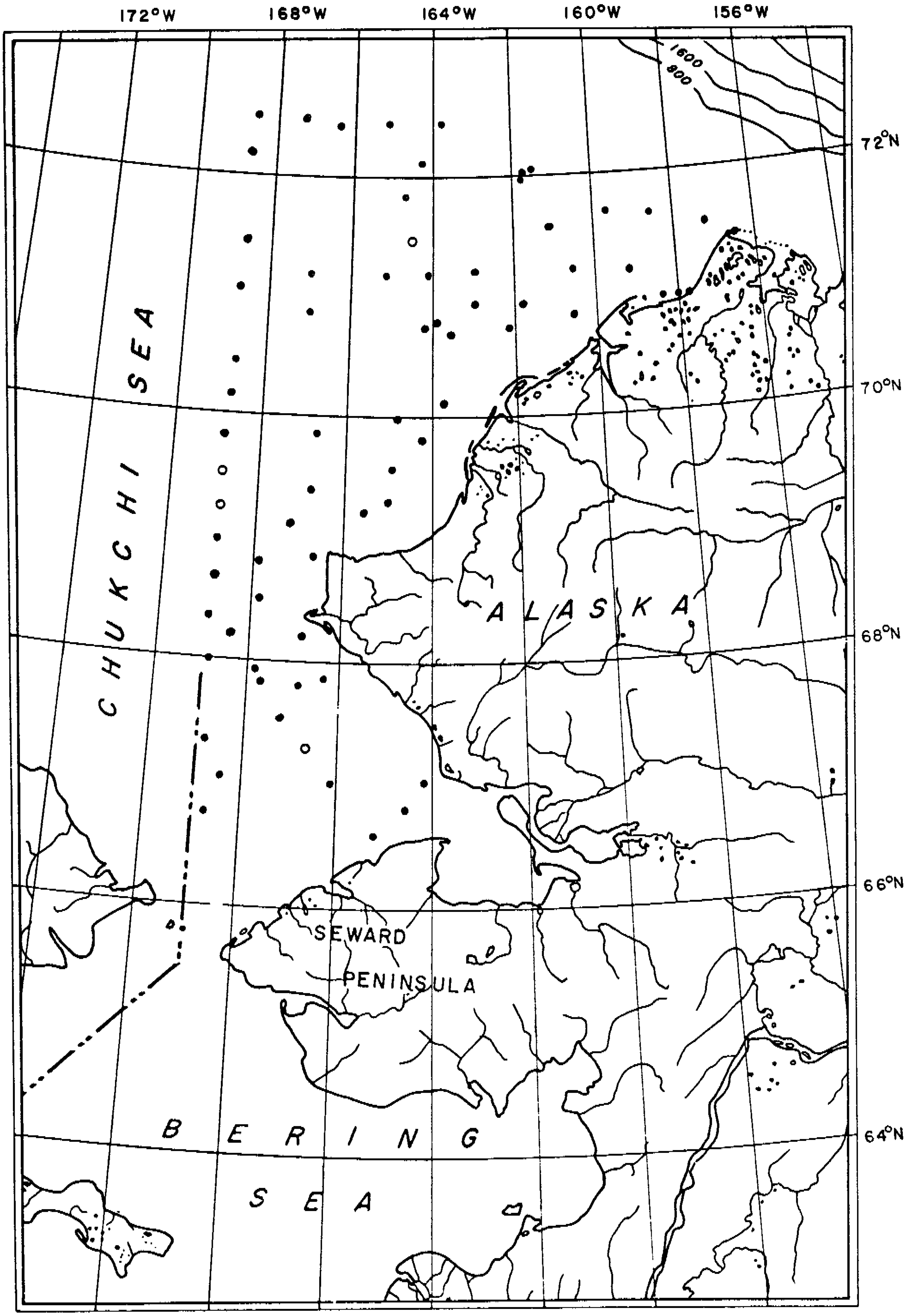
Musculus discors (Linnaeus, 1767)

Musculus niger (Gray, 1824)

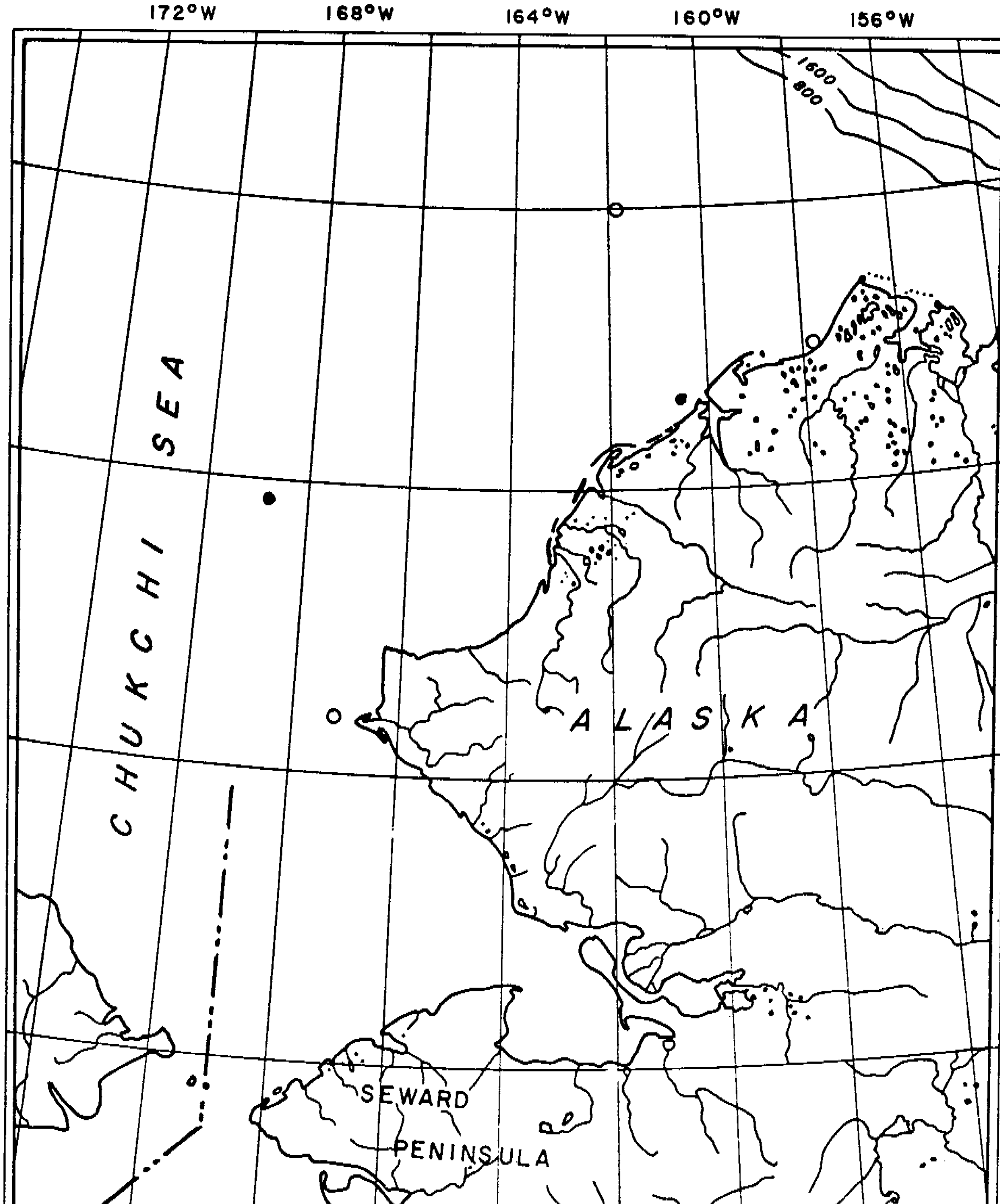
Mya elegans (Eichwald, 1871)



Mya pseudoarenaria Schlesch, 1931



Nucula tenuis (Montagu, 1808)

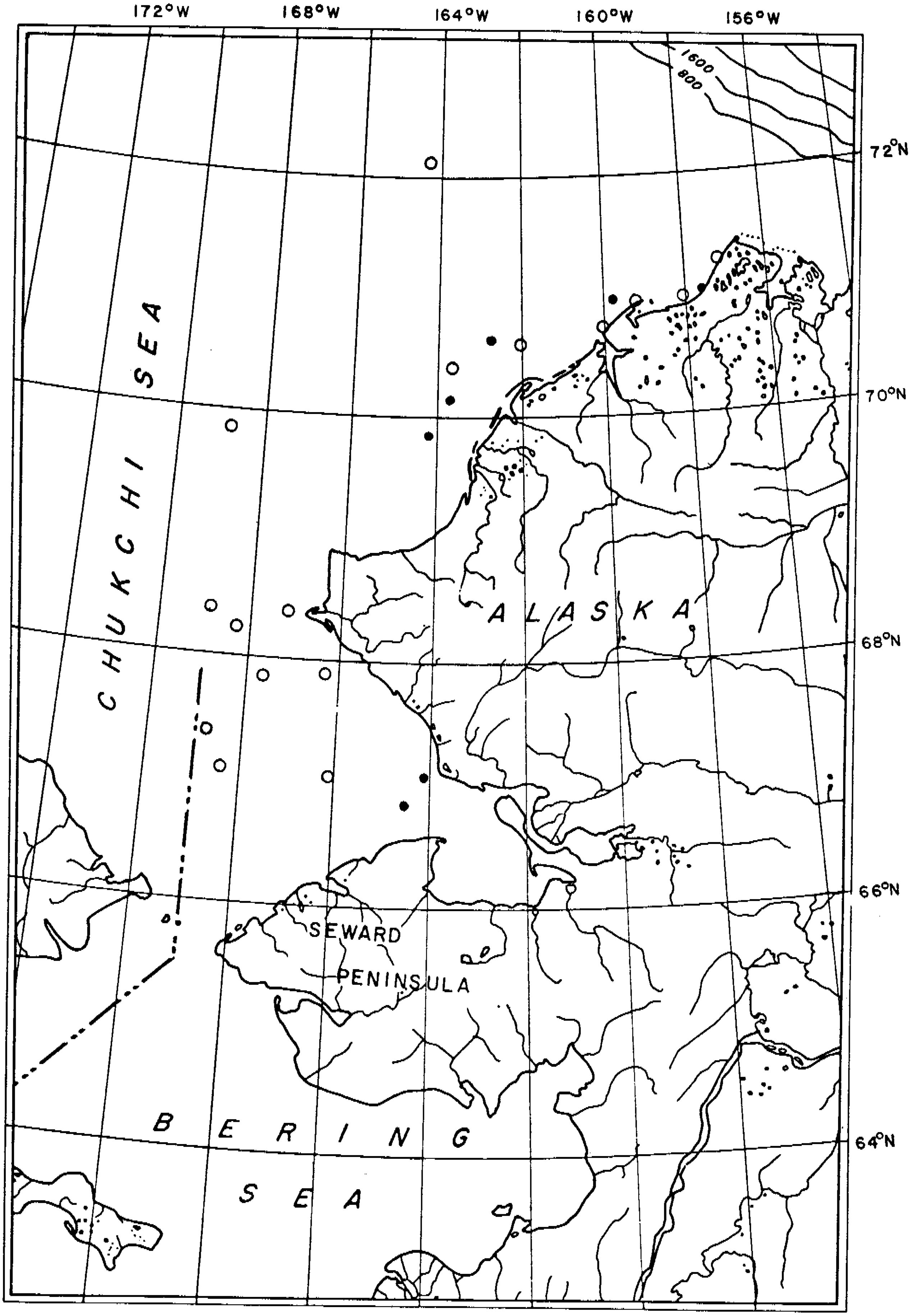


Pandora glacialis Leach, 1819

Panomya artica (Lamarck, 1818)

Periploma sp.

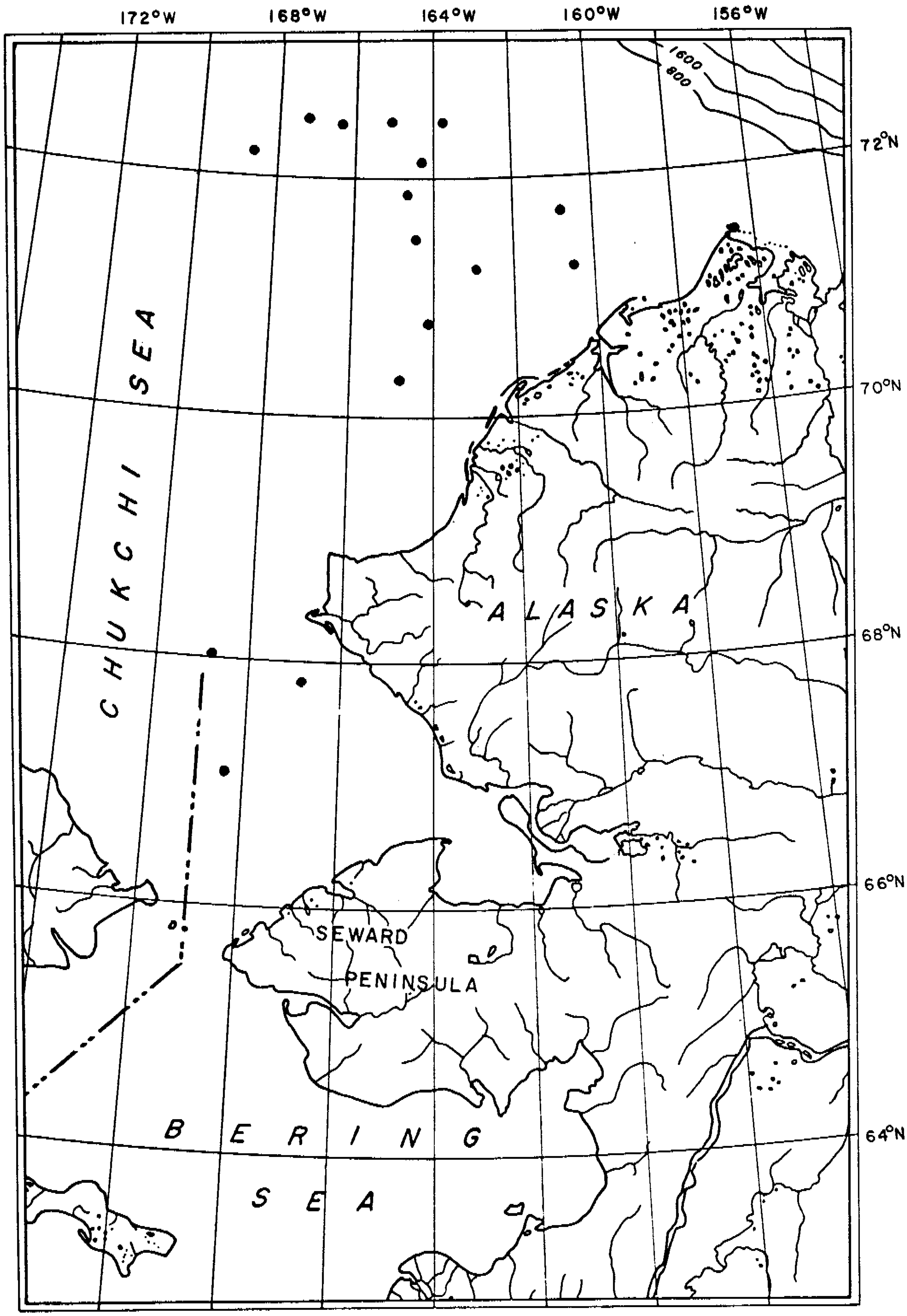
Pseudopythina compressa Dall, 1899



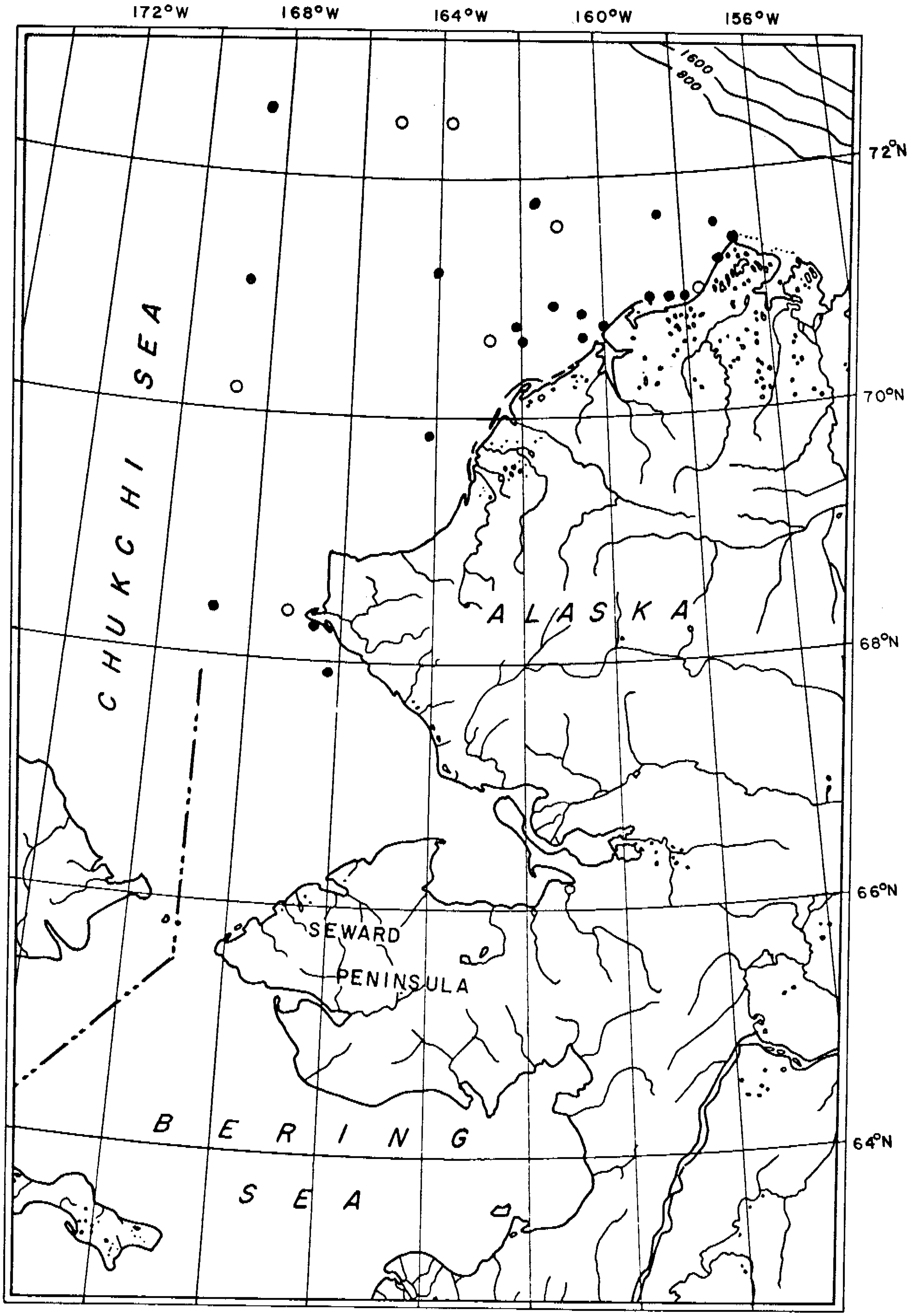
203 *Serripes groenlandicus* (Bruguire, 1789)

Tellina lutea Broderip and Sowerby, 1829

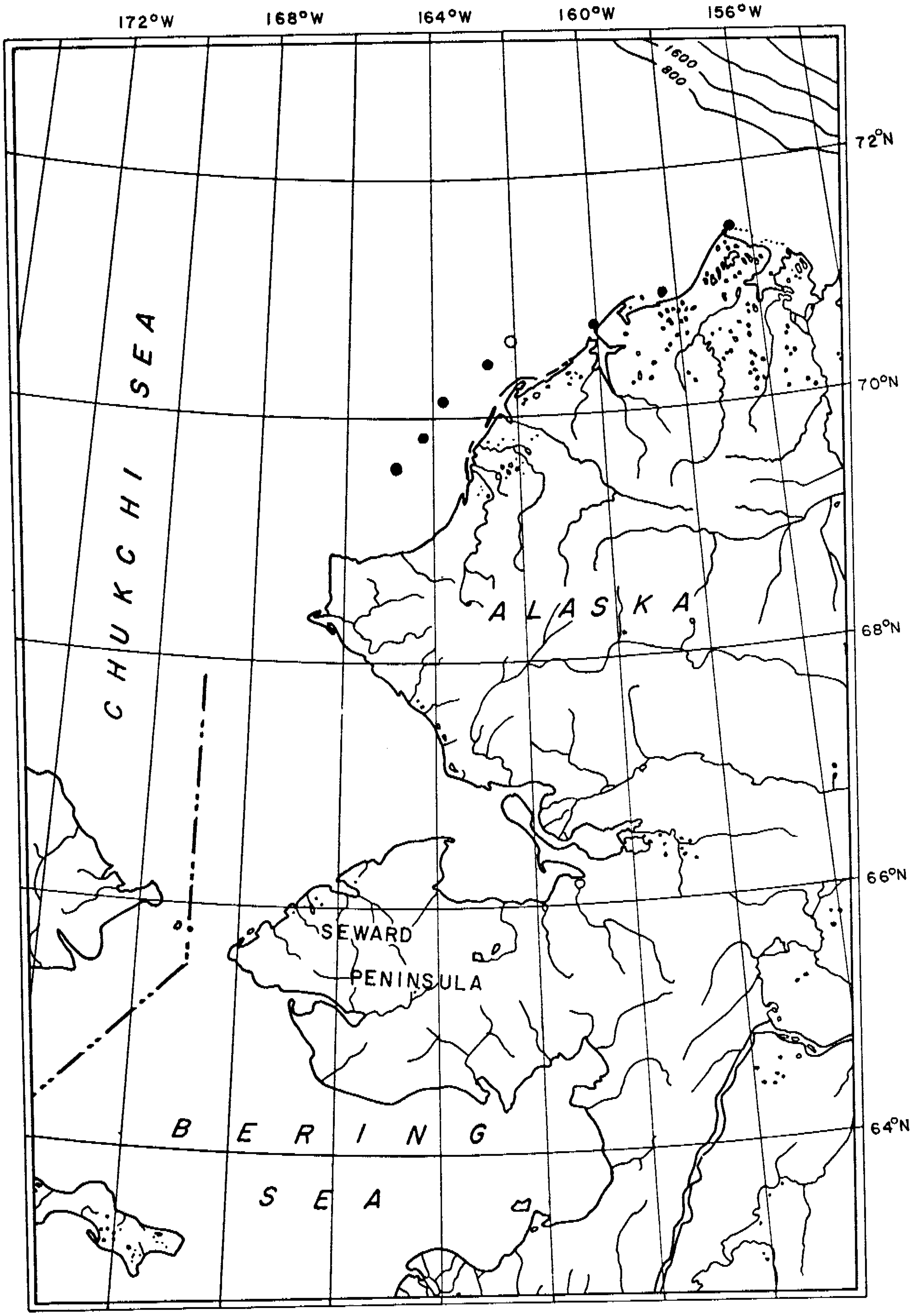
Thracia myopsis (Moller, 1842)



206 *Yoldia amygdalea* Valenciennes, 1846



Yoldia myalis (Couthouy, 1838)



Yoldia scissuratus Dall, 1897

ATTACHMENT J

Diving notes from three Beaufort Sea sites

Erk Reimnitz and Larry Toimil

During the course of our surveys with side scan sonar, high resolution seismic profiler, and fathometer we have delineated a large number of areas that need further investigation on the Beaufort Sea shelf. Shortly after initiation of inner shelf work in the area we became aware of the presence of two types of "anomalous materials". Cobbles and boulders, and stiff, "overconsolidated" silty clay, which should produce unique patterns on sonographs. In some areas, where seismic reflection records show Holocene marine sediments to be thin or lacking, and the sonographs showed "funny bottom" at the same time, we felt that the interpretation was rather straight forward, and that it was merely a matter of distinguishing between "boulder patch" and "stiff silty clay". But there remained several areas of funny bottom where identification of reflectors and interpretation of bottom type was difficult. A number of the anomalous bottom areas have been investigated by underwater television and direct diving observations. These investigations led to surprises for the marine geologist: there are many more causes for funny bottom on sonographs than we imagined. Because some of these observations are of interest to investigators in other disciplines, especially to biologists, we will prepare short reports in form of condensed diving notes and illustrations. Two sets of diving observations are excerpted here, and related to side scan sonar records.

The general need for knowledge of arctic lagoon and barrier island systems has been recognized, and the tidal inlets are integral parts of such systems. From a large variety of observations on these inlets we will also present here data and bottom observations from one tidal inlet, that might be of interest to other investigators.

Dive Site No. 2.
Date: Sept 8, 1976
Depth: 7 m
Sonographs or fathograms: Yes
Visibility: 2-2.5 m
Photography: Yes

Location: 72°21.2'N, 147°46.3'W
Divers: Reimnitz & Toimil
Length of bottom traverse: 175 m
Currents: None detected

Introduction

High resolution seismic reflection profiles of the region between Narwhal and Howe Islands (Fig.1) indicate only a thin (1-3 m thick), patchy veneer of Holocene sediments. In many places measurable Holocene sediments are absent entirely. Within such areas bottom observations using Scuba reveal numerous boulders, believed to be of the Flaxman Formation (Leffingwell, 1919) exposed and scattered about the sea bed. The boulders are associated with a rich and diverse benthic community and are coincident with a characteristic elongation of sea floor echo return signals obtained using a Simrad depth recorder. When plotted the distribution of elongated return signals encompass an area we have termed the boulder patch" (lined area shown in Figure 2a).

On Sept. 8, 1976 an area within the boulder patch was surveyed using a side scan sonar system together with a Simrad depth recorder from the R/V Karluk. Sonographs obtained during the survey show subtle increases in the acoustic reflectivity of the sea bed across broad zones (Fig. 2b) associated with elongation of bottom return

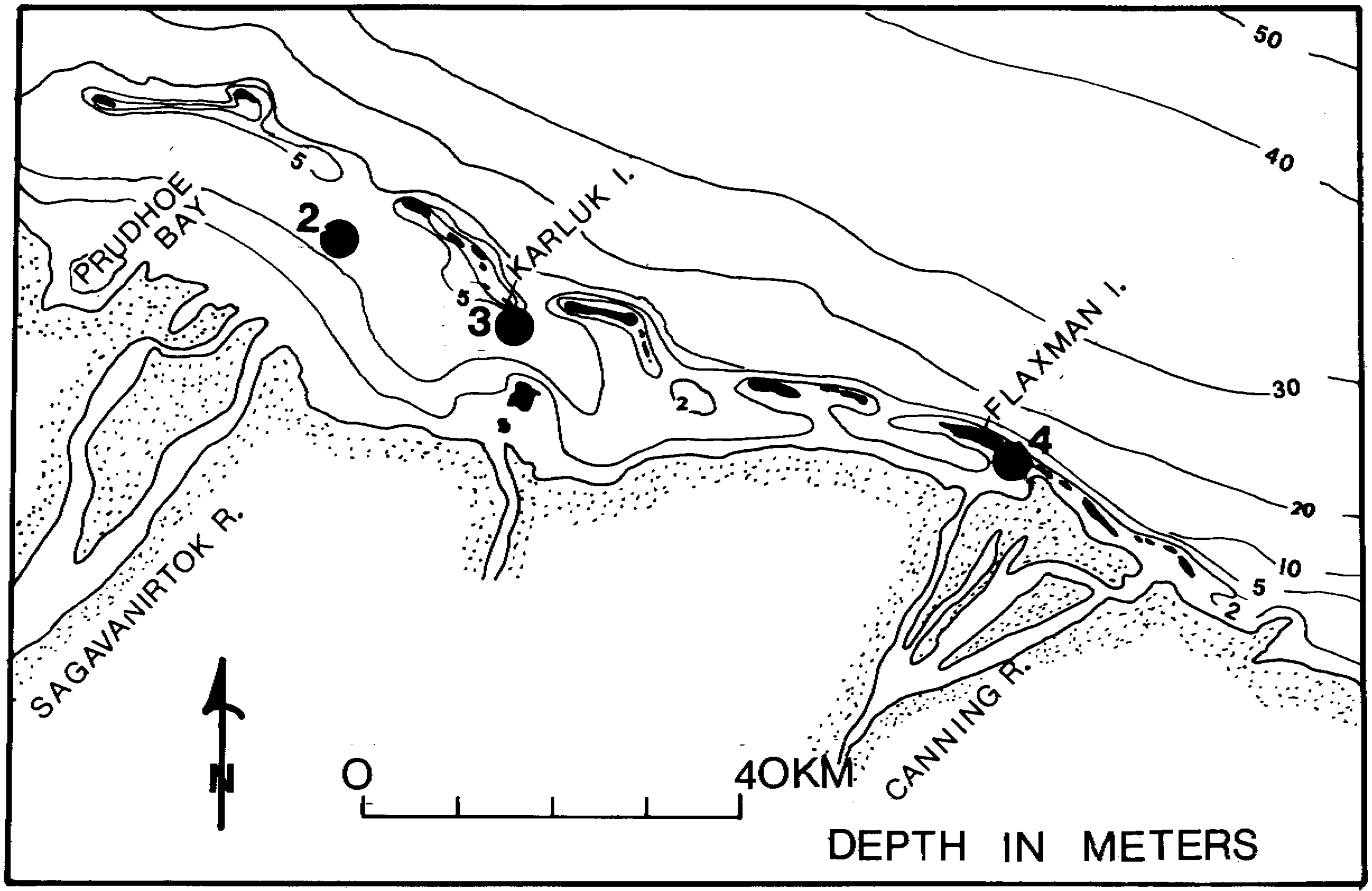


Figure 1. Index map showing the location of dive sites discussed in text and depicted in Figures 2a-d, 3a-d, and 4a-f.

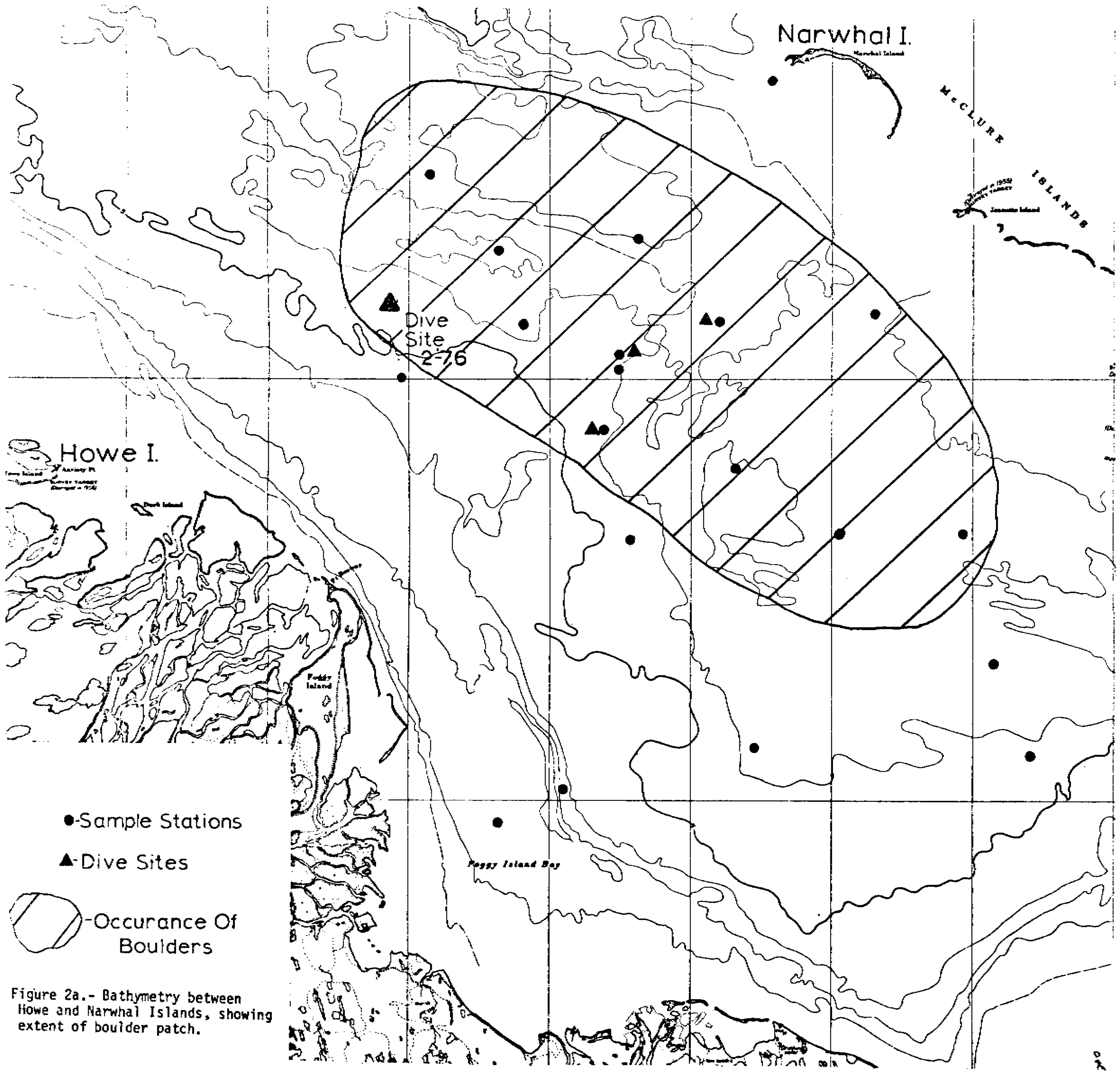


Figure 2a.- Bathymetry between Howe and Narwhal Islands, showing extent of boulder patch.

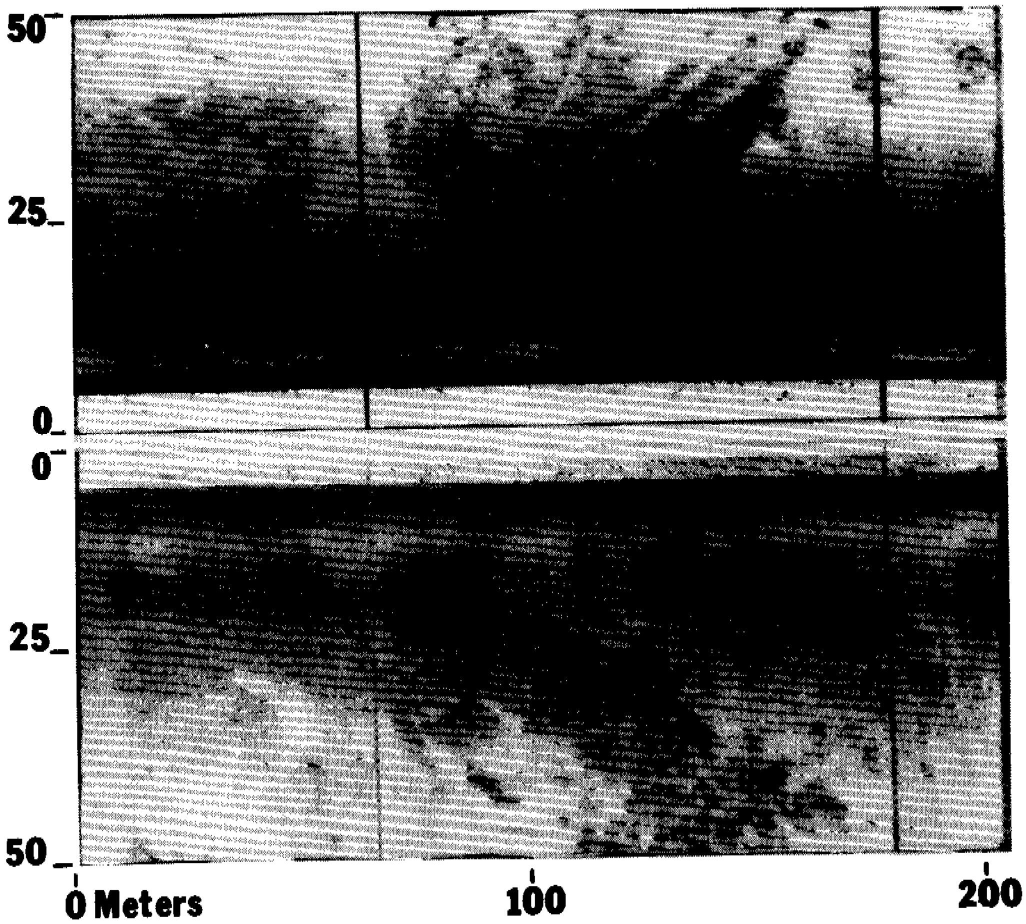


Figure 2b. Sonograph obtained west of Karluk Island (dive site 2 in Fig. 1) across boulder littered sea bed. The presence of numerous, fully-exposed boulders, some exceeding 1 meter in diameter, is indicated only by subtle changes in the acoustic reflectivity of the sea bed over broad zones (dark areas of central portion of record). The lack of strong point reflectors or acoustic shadows normally expected from objects,such as boulders on the sea bed, apparently is due to abundant marine growth (figures 2c and d).

signals on the Simrad recorder. Over one such zone (dive site 2 of Fig. 1) the boat was anchored and a diving traverse of the sea bed carried out in a Westerly direction.

Bottom Observations

Bottom Morphology

Boulders between 80 and 100 cm in diameter were observed immediately upon reaching the sea floor. The boulders together with numerous cobble size fragments lie exposed on a flat bottom devoid of noticable relief except pits and mounds attributed to the worm Arenicula and at several points along the traverse low outcropping ledges composed of compacted organic materials. These outcrops have a relief of between 5 and 7 cm. When split by hand the ledges seperate along bedding planes about 2 cm in thickness. Although not specifically determined it was the divers impression that the organic materials composing the ledges consisted of decayed and accumulated algal debris rather than tundra. A sample was obtained for further study. The ledges were found to dip in various directions so that their general strike could not be determined. It also appeared in many cases that the boulders and cobbles of the surrounding sea bed rested atop the compacted organic unit forming the outcrops.

Nature of Sediments

Surficial sediments consist of a 5 to 6 cm thick blanket of highly bioturbated soft gray mud easily thrown into suspension when disturbed by the divers motions. The mud is underlain by compacted more granular materials which could not be penetrated by hand. Many cobbles could be felt buried within the mud veneer. Both boulders and cobbles showed a high degree of angularity which was masked by a thick attachment of marine growth. The boulders appeared randomly distributed and generally seperated by distances of more than 3 m. Slight depressions of the mud veneer were visible around many of the boulders having attachments of long kelp fronds. Frequently these depressions contained accumulations of decaying organic debris (Fig. 2d). The depressions seem the result of scouring by rotation of the long kelp fronds along the sea bed around their points of attachment.

Aside from the slight scour depressions described above no evidence of recent current activity was noted. No ripple marks were encountered and there was a thin (about 1 mm) covering of soupy light brown mud on many of the exposed clasts and kelp fronds indicating a rather quiet depositional environment. Neither was there an indication of recent ice gouging along the traverse. Overturning of a number of cobbles revealed many burrowing organisms, but, their undersides were free of the remnants of holdfasts or barnacles found on exposed surfaces.

Benthic Organisms

The diversity of benthic organisms observed on many of the exposed boulders was striking. Large anenomes 10 cm in diameter, cupp-shapped red sponges, impressive soft bodied corals (?)(attached to right hand side of boulder seen in Fig. 2c), and five legged starfish 10-12 cm in diameter were encountered commonly during the traverse. The various forms of algae depicted in Figures 2c&d, including the brown kelp are typical of those observed. Common to the muddy substrate were polychaete worm tubes, isopods, small shrimp, and the brown, thick-shelled,clam- Astarte (?).

General Comments

The presence of boulders exposed on the sea bed is often characterized on sonographs by strong individual point reflectors associated with well defined acoustic shadows. As is apparent (Fig. 2b) no such unique characteristics appear in the sonographs obtained within the boulder patch. Rather the sonographs are more charastic of subtle changes in textural grain sizes. We attribute this, together

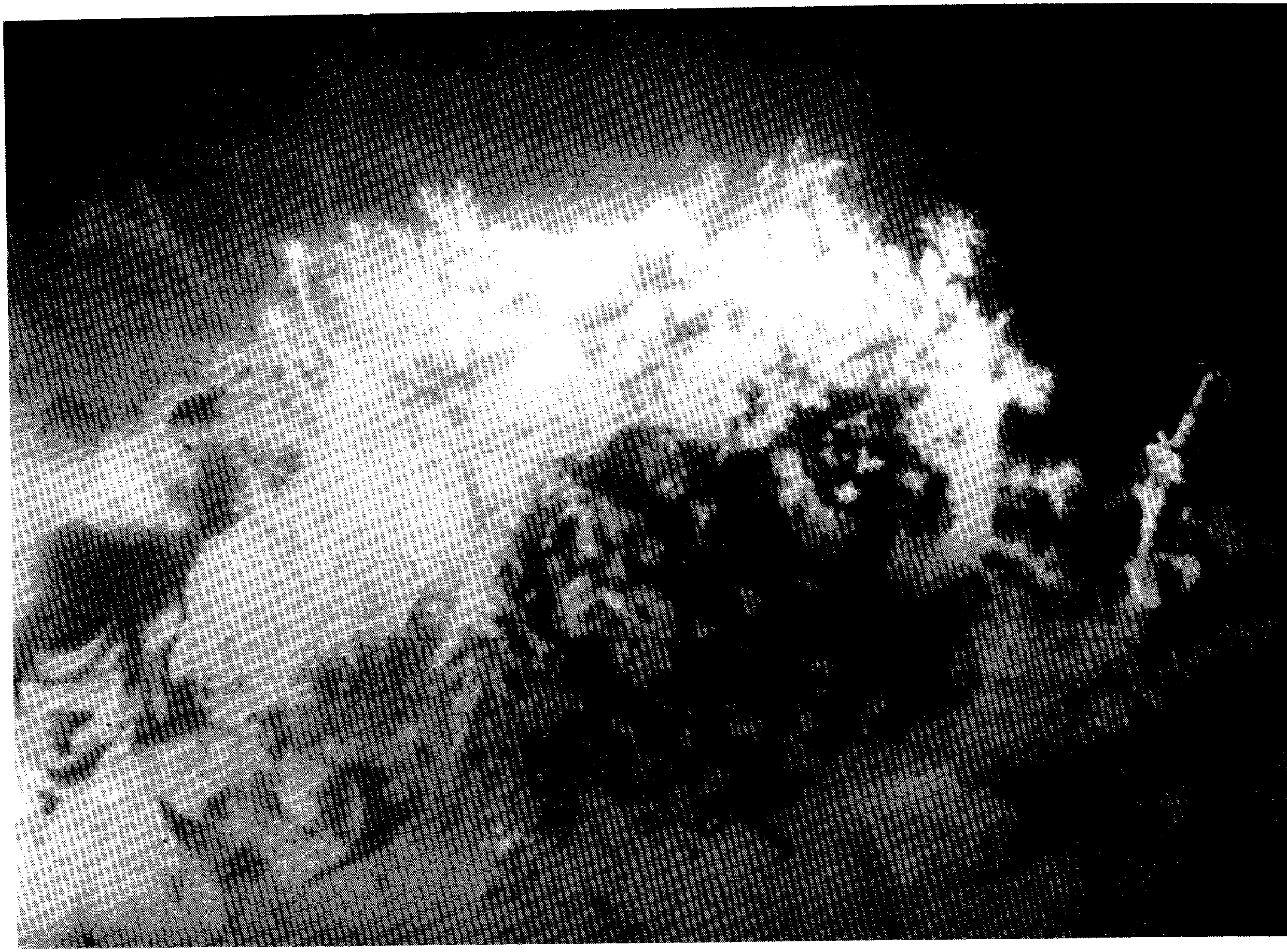


Figure 2c- Underwater photograph taken at dive site 2 at a depth of 7 meters. The sub-angular boulder seen in center of photo is 50 to 60 cm in diameter.It rests on a substrate of highly bioturbated soft,gray mud. The wide diversity of marine growth covering the boulder is typical of all boulders seen during the dive.

Figure 2d- Underwater photograph taken at dive site 2 of accumulated organic materials found at the base of exposed boulders. The stalk-like polychate worm tubes projecting from the substrate are between 2 and 4 cm in length.

with the elongation of return signals seen on the Simrad to masking (signal diffusion) by the abundent marine growth,particularly kelp. This masking makes accurate mapping of the boulder patch difficult without further direct observations of the sea bed.Sightings of boulders incorperated within the Gubic Formation along the coast have been recorded by Leffingwell(1919) and MacCarthy(1958). It is generally agreed that the boulders are of ice-rafted origin. It is of interest,therefore, that besides the boulder patch we have strewn boulders in smaller concentrations within the lagoon south of Flaxman Island and eslewhere along the coast.We have tentatively classified these as representing lag deposits resulting from erosion of small islands of the Gubic.Present day examples of such islands would include Flaxman,Tigvariak and Howe Islands. Although no ice gouges were encountered during the traverse described,ice gouges have been observed during previous dive boulders having been displaced along the gouge flanks. Such actions might explain the occurrence of boulders atop what appears to be a compacted unit of marine debris.

Dive Site No. 3

Date: Sept. 8, 1976
Depth: 6 m
Sonographs or Fathograms: Yes
Visibility: 2-3 m
Photography: Yes

Location: $70^{0}18.2'N$, $147^{0}18.7'W$
Divers: Reimnitz & Toimil
Length of bottom traverse: 300 m
Currents: Very weak

Introduction

This dive site is located in Newport Entrance of Stefansson Sound, between the south tip of Karluk Island and a small exposed shoal (Figs. 1 & 3a). The small shoal has migrated a considerable distance since first charted about 25 years ago (Fig. 3a). A side scan sonar survey in the general area showed a highly mottled bottom, not easily assignable to one of the bottom types we already knew. Seismic reflection records indicated that Holocene marine sediments are on the order of 1-5 meters thick. We therefore speculated that pre-Holocene materials cropping out on the sea floor may be responsible for the "funny bottom"

The bottom in this area was studied by divers on Sept. 8, 1976. In selecting the specific dive site, side scan sonar was operated from 1230 to 1237 hours, and a bouy dropped to mark the spot. Figure 3b shows the side scan sonar record for the last 200 meters prior to the bouy drop. We swam along the bottom in a westerly direction from the bouy, as indicated by the arrow in Fig. 3a.

Bottom Observations

Bottom Morphology

The bottom is characterized by about 20 cm of vertical relief. The high areas, from 2 to 10 meters in diameter, are generally bounded by distinct bluffs. Their surfaces are relatively smooth, marked by a dense growth of worm tubes (Polychaetes Fig. 3c) protruding by about 4 to 5 cm. Small mounds and craters, some apparently from the worm Arenicula, and a few pebbles to small cobbles (left foreground in Fig. 3c), form micro-relief on the high areas. The low areas are characterized by smooth, flat lying bottom, generally bare of polychaetes, and lacking any wave or current produced bedforms (Fig. 3d). Micro-relief in the low ground is formed by a large variety of bottom dwellers and burrowers, producing tracks, burrows, and craters and mounds with heights up to 5 cm. Accumulations of pebbles and shells in small patches, and occasional small rounded cobbles are other forms of micro-relief. From the linearity of some of the low ground traversed, it is obviously related to ice gouging.

Nature of sediments

The high ground is covered by soft mud that adheres to the diver gloves and has to be rubbed off before taking pictures, as it makes the water cloudy. The divers' hand can penetrate up to his wrist. Using a diver-held shearvane, the surficial shear strength was measured to be from too weak to register, ranging up to 0.34 PSI (2.34 KN/M^2).

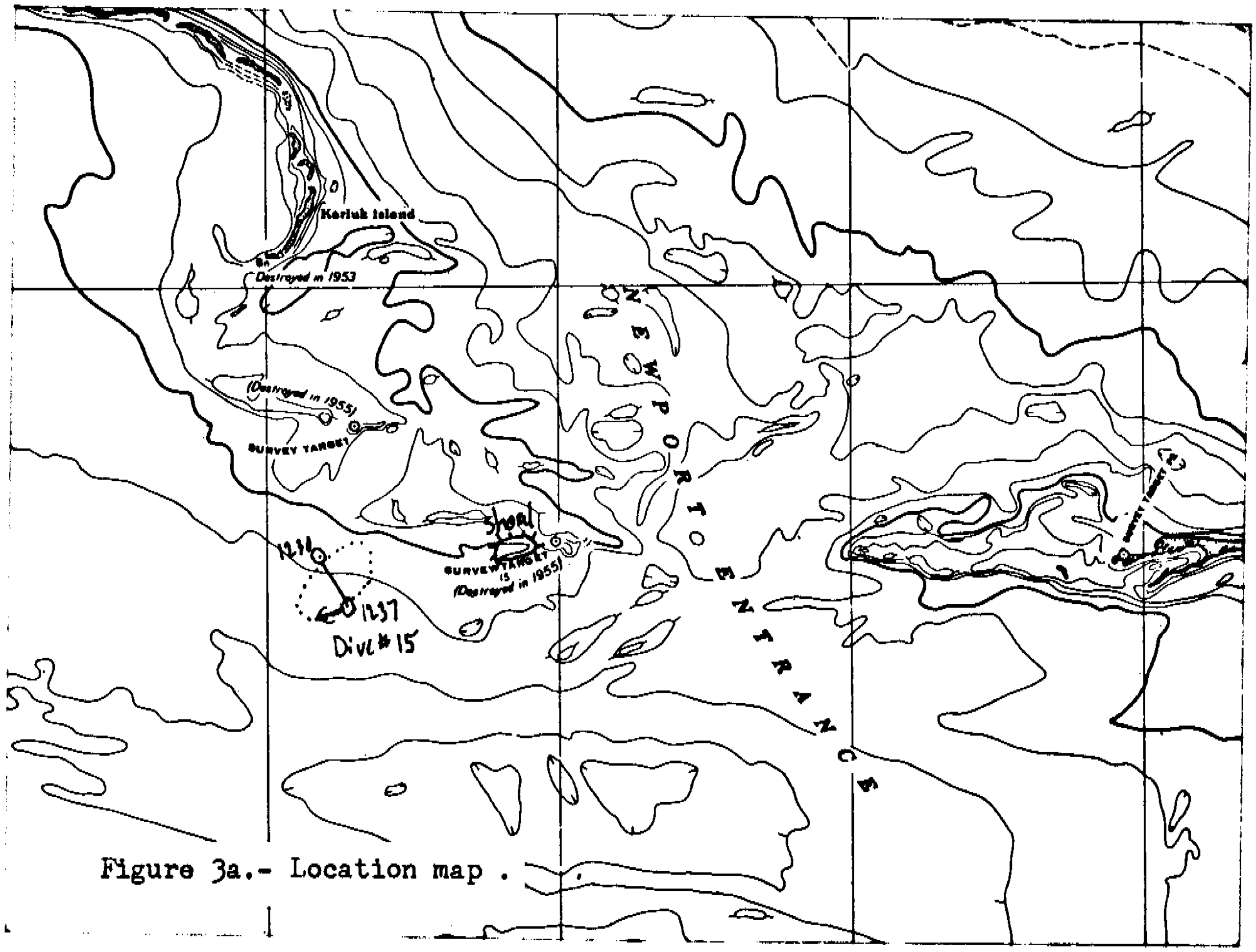


Figure 3a.- Location map .

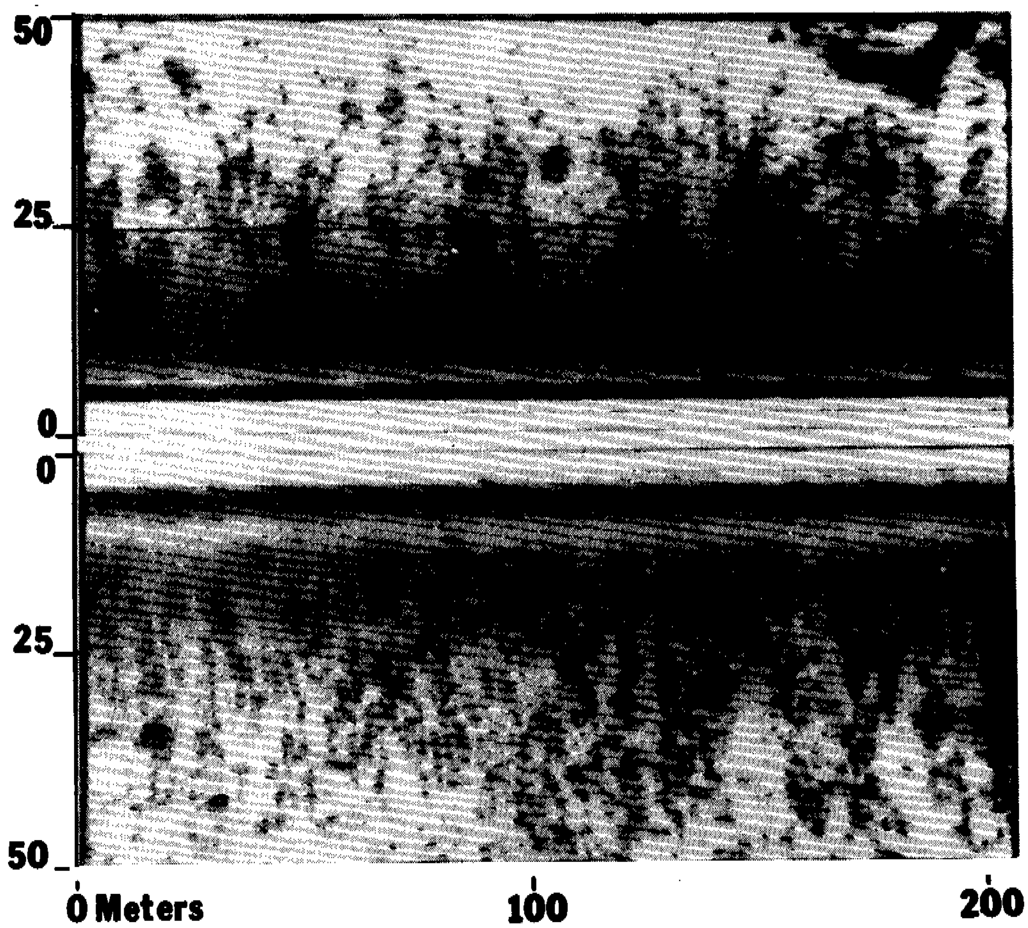


Figure 3b.- Sonograph of the sea bed south of Karluk Island (dive site 3 in fig. 1). Blotches of relatively strong acoustic signal return from a flat sea bed similar to those seen in the record (dark patches) are often the result of textural variation of surficial sea bed sediments. Here, however, they are attributed to the distribution of polychaete worm tubes projecting above the sea floor (Figs. 3c. and d.).

Figure 3c.- Underwater photograph taken of the sea bed at dive site 3 at a depth of 6 meters. The sea bed relief is between 20 and 30 cm. The density of protruding agglutinated worm tubes to the right of the 15 cm high anenome (center of photo) is typical of topographic highs.

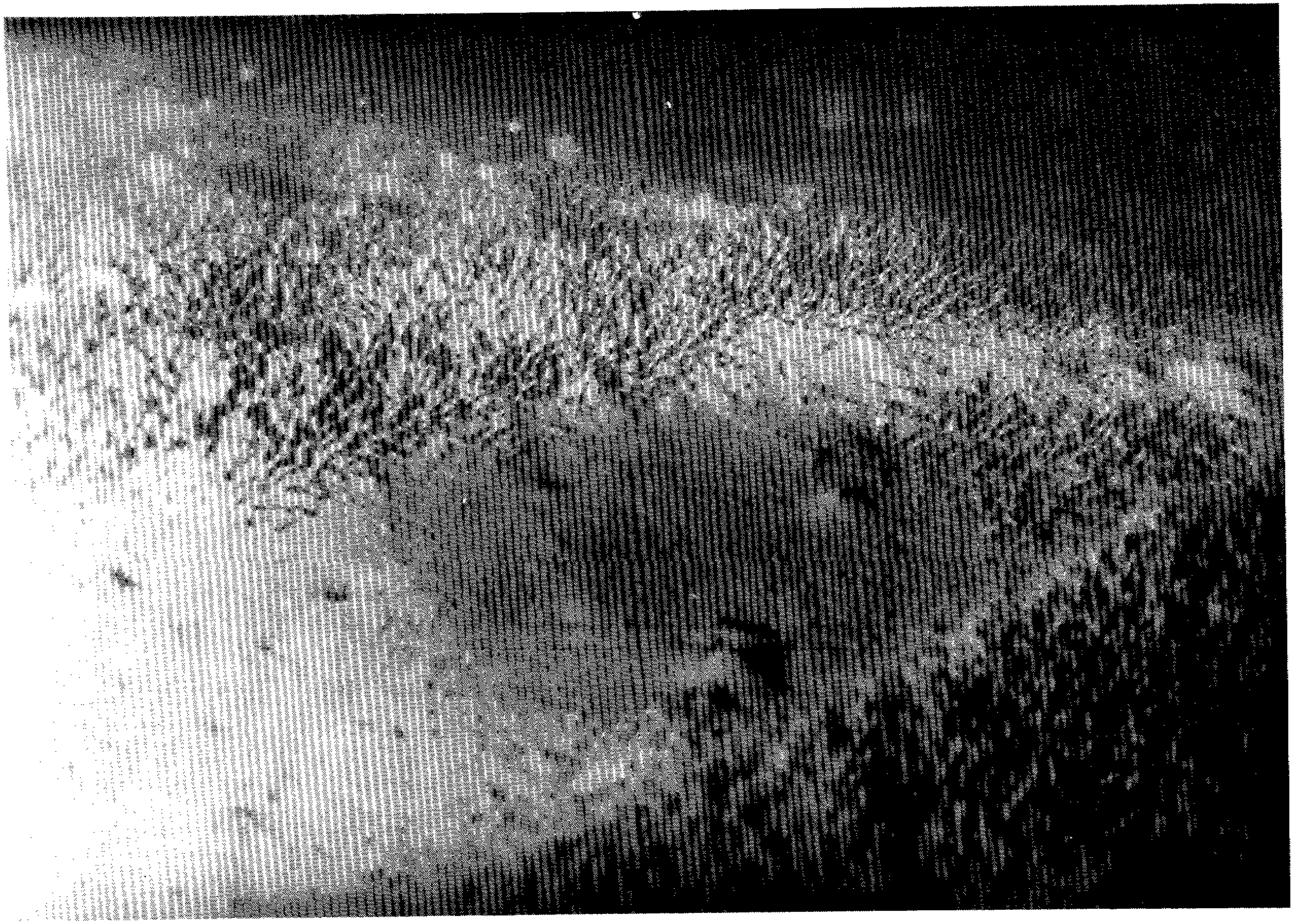


Figure 3d.- Underwater photograph taken at dive site 3 of linear, one meter wide ice gouge. The floor of the gouge is highly bioturbated and criss-crossed by the tracks of isopods. However, the polychaete community has not nad sufficient time to become re-established.

Bottom Organisms

The most abundant by far are the polychaete tubes, appearing like closely cropped lawns. We estimate that 60% of the bottom in the area traversed was covered by polychaete fields, with tubes spaced 1-2 cm apart. A few of these were obviously alive, as the organism withdrew into the tube when approached. Most of them may have been dead. A few Sea Anenomaes (Fig. 3c) were seen in the polychaete fields, and small, spherical Coelenterates. The presence of Arenicula was suggested by 5 cm high mounds and similar sized craters occuring in pairs. There are many other types of bottom dwelling and burrowing critters, judging from the microrelief seen in the low areas. Several pale pink soft bodied, bush-like organisms (soft corals,?), up to 20 cm high, and similar to those described under dive site 2 in the boulder patch, were observed. There also are what appear to be small hydroids, protruding by several centimeters from the surface. Several fronds of the large brown kelp were also seen. These apparently were not attached but in transit. The soft corals (?) and hydroids seem to be attached to buried rock fragments. Several pebbles had overgrowths of a brownish, filimentous algae, 1 to 3 cm long. Only a few of the otherwise so abundant large isopods were observed, leaving their characteristic tracks on the sediment surface.

General Comments

The mottled nature of the side scan sonar records (Fig. 3b) obviously is related to the patchy distribution of polychaete fields in this area. It seems to us that the cumulative effects of echoes from worm tubes produce the dark patches on the record. Their boundaries sometimes are marked by more intense reflections originating from small bluffs. The vertical relief in this area is due to preferential sediment accumulation in polychaete fields, providing a sheltered micro-environment. These fields occasionally are disrupted by ice gouging, killing most of the worms. After such events, currents and waves retard deposition in the bare spots. But the dominant activity in the bare spots is that of reworking by organisms. At the time of the dive, and commonly during summers there is much ice moving through Newport Entrance. Diving was possible on this date, because winds and currents moving the ice were weak, and some ice was grounded. Because of the common occurence of drifting pack ice in this area, where it accumulates under easterly winds, we were surprised to find this type of bottom fauna. The presence of polychaete communities is known in a number of localities from our sampling operations. Several diving traverses off Reindeer Island (in a 4-m deep between the beach and the first longshore bar) went through Polychaete fields of similar density (Reimnitz and Barnes, 1974). Here protection from ice was provided by the bar.

Dive Site No. 4

Date: Sept. 6, 1976
Depth: 2 - 10.5 m
Sonographs or Fathograms: Yes
Visibility: 2 m
Photography: Yes

Location: 70°13'N, 145°57'W
Divers: Reimnitz & Toimil
Length of bottom traverse: 200 m
Currents: surface 100-150 cm/sec into lagoon, bottom appr. 10-15 cm/sec

Introduction

In 1973, a high resolution seismic reflection and side scan sonar survey line running from Leffingwell Lagoon through Leffingwell Entrance (east of Flaxman Island, Figure 1) seaward to the open shelf showed anomalous, mottled bottom on the seaward facing slope of Flaxman Island. Insepction of the bottom with closed circuit television revealed the presence of numerous, sub-rounded to angular coarse pebbles and cobbles with brown algae and other marine growth. A similar bottom was found seaward of the western end of Flaxman Island. This fact, and the presence within the lagoon of "Flaxman Boulders" (Leffingwell, 1919), a lag deposit formed at sea level during coastal erosion and winnowing of the Gubic Formation, led us to believe that the deepest part of the tidal inlet should be covered by a similar lag deposit. This closed depression (Fig. 4a), in fact, should hold the coarsest materials contained in the upper part of Flaxman Island.

On Sept. 6, 1976, we made a brief inspection of the deepest part of Leffingwell Entrance. The setting of this tidal inlet, with the deep channel hugging the west side, is similar to that of nearly all the inlets along this coast. In this case the westward migrating inlet is cutting into 7 to 8 m high bluffs. The original bathymetric survey of the channel, done in 1950 (Boat Sheet H-7852) and contoured in Figure 4a, shows a maximum depth of 7 m close to the small spit extending into the laggon. From close to this small spit, composed of rounded coarse gravel, cobbles, and small boulders, we ran several bathymetric profiles southwest and southeast across the channel. One of these profiles is shown in Figure 4b. In this crossection, which is not deeper than the others, the maximum depth is 10.5 m. A marker bouy was dropped at the deepest part of the crossing to mark the dive site. However, due to a 1 to 1.5 knot (100 to 150 cm/sec) surface flow carrying much ice into the lagoon, our marker bouys were snagged and dragged away by ice within minutes. Still, our diving traverse starting at point 'c' in Figure 4b took us closely along the profile shown.

Bottom Observations The steep sides

At the beginning of the traverse in 3 m water depths the bottom was slightly undulating, medium grained sand, shaped into lingoidal current ripples (dark parts in Figure 4c), facing into the lagoon and recording lagoonward currents, commonly were marked by small concentrations of brown fiberous organic matter. Firmly grounded ice in this area did not have ice gouges leading to the ice/bottom contact, but a slight current scour depression and lingoidal ripples fields surrounded the ice.(Fig. 4c). At a depth of about 4 m we found one small boulder, covered with short, brown, filiamentous algae. From this depth down to a depth of about 7 m several low-relief ledges (up to 8 or 10 cm high) of grey, current-eroded mud, aligned roughly parallel to the channel axis, were traversed (Fig. 4d). The thinly bedded mud was gently dipping westward. These ledges lacked any evidence for bioturbation or burrowing, seen on older outcrops of this material elsewhere, indicating modern erosion by currents. Between the ledges, the thin sand cover was marked by lingoidal ripples as encountered at the start of the dive. Two depressions, about 10 cm deep and 30 cm in diameter, surrounded by an irregular 5 cm high rim of grey mud, were seen in this sand cover. These may have been formed by ice loading in a small area, squeezing out the underlying mud. From 7 to 10 m depth our traverse took us across three 1 to 1.5 m high, vertical to overhanging walls. Exposed in these walls were up to 10 cm thick beds of almost pure, brown, fiberous orgainc matter, interbedded with thinner medimum grained sand layers (Fig. 4e). The fiberous organic matter also contains small branches of wood, and a fairly large bone with fur (from a Caribou ?), containing fresh, undecayed appearance. The interbedded sand layers show current ripple bedding. These ripple structures, observed in five different locations and elevations, all indicate lagoonward currents. Figure 4e shows a vertical wall encountered at about 10 m depth, which along the diving traverse had a corresponding wall on the west-side of the channel axis. Below these two bluffs, the channel floor is sand-starved, exposing grey, cohesive, stiff, mud. This mud is bedded, and locally current- shaped into very small legdes and linear scour depressions

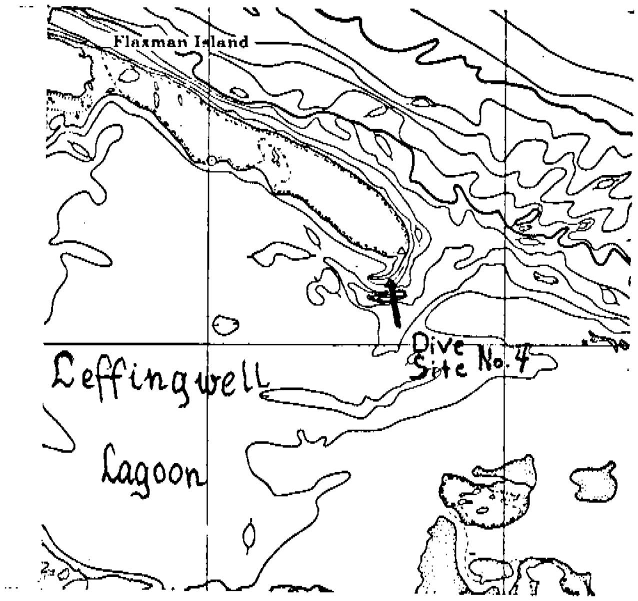


Figure 4a.- Dive site 4.

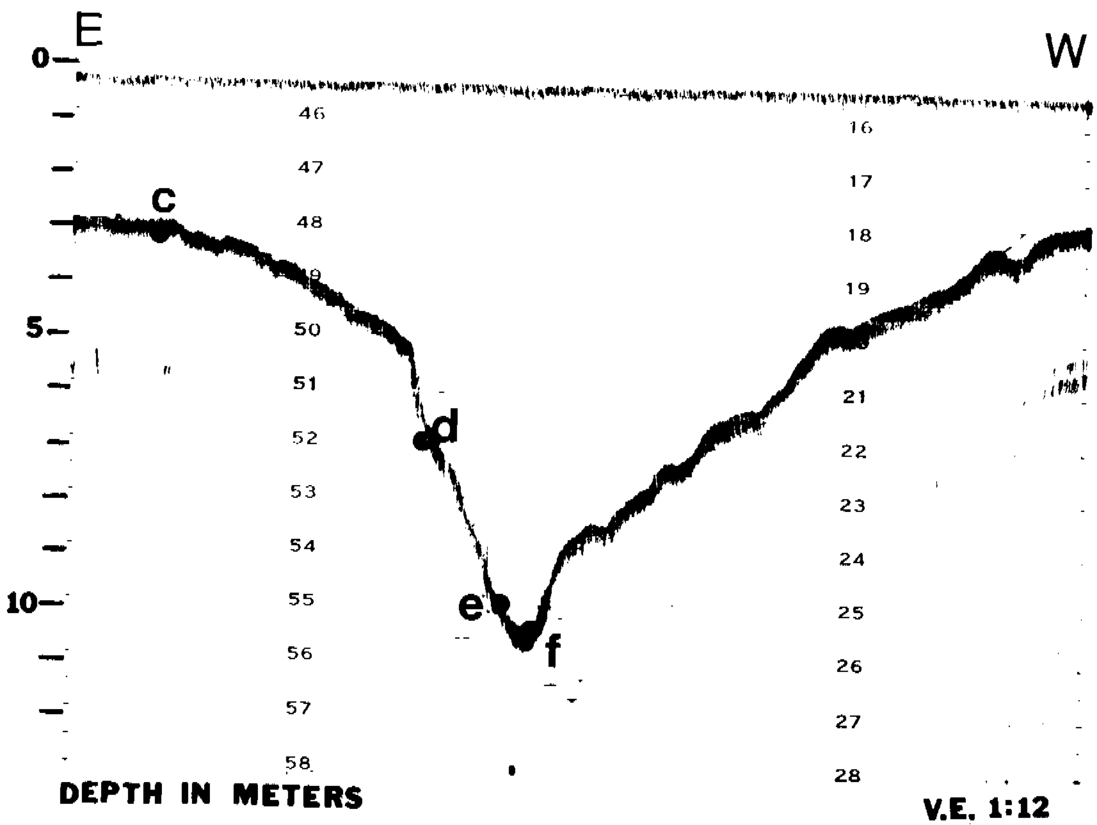


Figure 4b.- Depth profile of Leffingwell Entrance.

Figure 4c. Underwater photograph taken at a depth of 3 meters on the southeastern flank of the entrance channel (c in Figure 4b). The linguoidal current ripples surrounding the grounded ice keel have wavelengths of 20-30 cm and face into the lagoon. The sparkled appearance of the under-surface of the ice is due to numerous small shrimp.

Figure 4d. Underwater photograph taken at a depth of 7 meters (d in Figure 4b) of low outcropping ledges 10 cm high. The ledges are composed of gray, current-eroded, silty clay and are aligned parallel to the channel axis.

Figure 4e. Underwater photograph taken at a depth of 10 meters (e in Figure 4b) of vertical wall 1-1.5 meters high. Exposed beds consist of up to 10 cm thick fibrous organics separated by clean, sometimes cross-bedded sands.

Figure 4f. Underwater photograph of the floor of Leffingwell Entrance channel. The starved linguoidal ripples face into the lagoon and overlay gray, cohesive stiff mud which has been scoured by both ice and currents.

paralleling the channel axis. But even the channel floor at this point, was affected by ice gouging and rip-up by ice, as seen in Figure 4f. Where the mud is blanketed by thin patches of medium grained sand, this again is formed into lingoidal ripples as before, with traces of fiberous organic matter on the lee sides of the ripples. However, this material was not being moved by currents at the time. Several small patches of sub-angular gravel were observed near the channel axis, and a few scattered pebbles and water-logged drift wood on the channel floor. Swimming up the west flank of the channel we found only one pronounced vertical wall at 9 - 10 m depth, and generally rippled, medium grained sand lying on a rather steep slope. At a depth of about 4 to 6 meters on the slope leading up to the cobble spit, we traversed a temporary accumulation of very loose, brown, fiberous organic material, 1 to 2 m thick. This material was so loosely packed that our entire arm could easily penetrate it. Still further up the slope, at a depth of about 2 m, much ice was grounded in sandy, rippled bottom fringing the cobble spit. Some of the grounded ice was sitting in closed scour depressions, one fragment had a gouge leading to the ice/bottom contact.

Bottom Organisms

Among the few benthic organisms observed in this dive were the ubiquitous large isopod, several spherical 1-2 cm diameter soft-bodied coelenterates, a few of the now common cones and craters produced by the worm Arenicula, and numerous small shrimp found around the under surfaces of the ice.

General Comments

We were surprised by several findings of this investigation:

1) The lack of Flaxman Boulders in the closed depression of the tidal channel.

2) Evidence for recent strong currents shaping the channel crossection.Calculated current speeds necessary to form the lingoidal ripples observed in medium sand of the channel floor are about 1.5 knot (150 cm/sec); but the current shaped ledges in cohesive, stiff mud indicate much higher velocities.

3) Presence of bedded mud on both sides of the channel in the lower 5 meters, while channel deposition normally is characterized by coarser material. We are wondering whether these bedded muds are actually underlying and pre-date Flaxman Island.

4) The lack of a thick sequence of offlapping deposits on the east side of the channel. According to Leffingwell (1919) and Lewellen (1977) Flaxman Island is eroded at a rate of 9 m/year. The westward migration of the channel would have to proceed at the same rate, and erosional cutbanks therefore would have to be restricted to the west side.

5) Sir John Franklin reported difficulty with shoal water in the entrance in 1826 (Leffingwell, 1919). During the period from 1906-1914, Leffingwell's (1919) observations implied a channel depth of about 5.5 m (3 Fm.). During the hydrographic surveys of 1950, the maximum depth in this channel was 7 m (23 ft.). Today the channel is 10.5 m deep.

6) Ice gouging takes place in the closed channel depression. Deep draft ice is either formed in place, or formed temporarily by up-ending of floes.

7) Past currents recorded by the presence of lingoidal ripples and internal sedimentary structures within the channel fill indicate lagoonward flow. The largevolumes of organic matter probably originate from the active part of the Canning River, and therefore probably were transported into the channel from the open shelf. Yet, optimum conditions we envision for producing the strong currents through the inlet (westerly storms piling water in the eastern part of Leffingwell Lagoon and river flooding) would result in seaward flow.

Some of the puzzling findings listed here suggest that Leffingwell Entrance, the tidal inlet of Leffingwell Lagoon, is not in equilibrium with todays flow regime.

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ANNUAL REPORT

Contract #RK6-6074
Research Unit #206
Reporting Period -
May, 1976 - April, 1977

Areas of Faulting and Potentially Unstable Sediments in the St. George Basin Region, Southern Bering Sea

Principal Investigators: J. V. Gardner
T. L. Vallier

I. SUMMARY OF OBJECTIVES, CONCLUSIONS, AND IMPLICATIONS

The objectives of this project are to map the distribution and types of faults and to outline areas of potentially unstable sediment masses in the St. George Basin region of the southern Bering Sea continental margin. Data are from four U. S. Geological Survey cruises from 1969 through 1976. Abundant faults, classified as major, minor, and surface faults, cut the subsurface strata and are particularly concentrated over the St. George Basin and the peripheral Pribilof Ridge. Some of the major faults outline the borders of the St. George Basin and Pribilof Ridge and displace the seafloor. Minor faults cut Pleistocene sediments in most places and some break the sediment surface. Zones of potentially unstable sediment masses occur along the entire upper part of the continental slope and the walls of the large submarine canyons.

The St. George Basin region is adjacent to a major lithospheric plate boundary that is an area of high seismicity. Although earthquake epicenter data show a few events located in the southern Beringian continental margin, the seismic activity at the plate boundary is much greater and clearly affects the whole region. The presence of surface and near-surface faults indicates that the region is tectonically active. Wherever there is a significant bathymetric gradient, such as along the continental slope and walls of the major canyons, there is a potential for downslope sediment movement.

II. INTRODUCTION

Most of the text that follows is a preliminary version of a U. S. Geological Survey Open-File Report that is in preparation. It will be available from Mr. Tom Chase, Marine Technical Data Center, Pacific-Arctic Branch of Marine Geology, U. S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025.

The relevance of this project to petroleum development is in the realm of geological environmental problems (faults and potentially unstable sediment masses) that should be considered for the safe exploitation and development of resources in the region.

III. CURRENT STATE OF KNOWLEDGE

Previous geologic studies in the St. George Basin region have concentrated mainly on the structural evolution of the Beringian continental margin and the origin of the St. George Basin (Scholl and others, 1966; Scholl and others, 1968; Scholl and Hopkins, 1969; Scholl and others, 1970; Pratt and others, 1972; Moore, 1973; Nelson and others, 1974; Scholl and others, 1975; Cooper and others, 1976; Marlow and others, 1976; Marlow and others, in press). This study focuses on faulting and potential sediment instability by describing the types and distribution of faults and by outlining areas where potentially unstable sediment masses occur.

IV. STUDY AREA

The St. George Basin area can be broadly subdivided into four major physiographical provinces: outer continental shelf, continental slope, Pribilof Ridge, and the Bering and Pribilof Canyons (Fig. 1). The outer continental shelf is a broad, flat region that has a gradient of 1:2000 (0.03°) between the 100 m isobath and the shelf break at 170 m. The shelf break persists at about 170 ± 2 m depth along those parts of the margin that are not cut by the large submarine canyons. The Pribilof Ridge is a prominent northwest-southeast-trending topographic high that is capped by the Pribilof Islands. It has a relatively smooth surface with at least one terrace that may represent a Pleistocene wave-cut terrace. It plunges into the subsurface at about 56°31'N, 168°35'W, but can be followed in the subsurface on seismic data to 56°N, 165°40'W. The continental slope abruptly drops away from the shelf break in the northwestern part of the area where gradients are about 1:20 (3°). Towards the southeast, however, the gradient decreases to about 1:40 (1.4°). The continental slope is characterized by hummocky topography, scarps, and canyons on almost all scales. The prominent submarine canyons, the Bering and Pribilof Canyons (Scholl and others, 1968: Scholl and others, 1970), will be discussed in a subsequent report.

The geology of the southeastern segment of the Beringian continental margin was briefly described by Scholl and others (1968) who distinguished two major acoustic units that overlie a seaward-thinning crust. An upper low-velocity, semi-consolidated unit, the "main layered sequence", unconformably overlies a lithified second unit that corresponds to acoustic basement on low frequency, seismic-reflection profiles. The essentially flat-lying upper unit ranges in thickness from 500 m to several thousand meters and probably is mostly of Cenozoic age (Creager, Scholl, and others, 1973; Scholl and others, in press). The lower unit, which is tightly folded beneath the outer continental shelf, is probably Upper Cretaceous sediments (Scholl and others, 1966; 1968).

The St. George Basin is a deep subsurface graben whose long axis is parallel to the present continental margin. The St. George Basin, according to Marlow and others (1976), has an area of approximately 1000 km^2 (300 km long and in places up to 50 km wide) and a volume of at least 56,000 km^3. Marlow and others (in press) speculate that after subduction jumped from the Bering Sea to the south, forming the Aleutian ridge, tectonic deactivation occurred along the Beringian continental margin. Since then, the outer shelf has undergone extensional rifting and regional subsidence. Differential rifting and subsidence have resulted in the formation of a series of basement ridges and basins in the area; the basins subsequently have been filled with sediment.

V. SOURCES, METHODS AND RATIONALE OF DATA COLLECTION

The data used to map the distribution of faults and areas of potentially unstable sediment masses are from the following seismic-reflection equipment:

(1) 3.5 kHz; (2) 2.5 kHz (Uniboom source); (3) single-channel seismic reflection (60 KJ and 160 KJ sparker and up to 1300 in^3 airgun sources); and (4) 24-channel multichannel equipment using a 1300 in^3 airgun array. The various types of data and the cruises are shown in Table 1 and Figure 2 shows the appropriate tracklines. Approximately 7,000 km each of 3.5 kHz, Uniboom, and single-channel seismic-reflection data and about 700 km of multichannel seismic-reflection profiles were studied.

Table 1. Cruises and types of seismic reflection data.

Ship	Cruise	Data Type: High Resolution		Low Resolution		
		3.5 kHz	Uniboom 2.5 kHz	single channel airgun	single channel sparker	multi-channel
R/V SEA SOUNDER	S4-76	X	X		X	
R/V LEE	L5-76	X	X	X	X	
R/V LEE	BERS-75-XA	X	X			X
R/V STORIS	ST-69				X	

Navigation was by integrated Loran C and satellite for cruises of the R/V SEA SOUNDER and R/V LEE and by satellite for R/V STORIS. In addition, the R/V LEE utilizes doppler sonar integrated into the navigation system. The integrated navigation systems have nominal position accuracies of ± 200 m or better, whereas the satellite system of the R/V STORIS has position accuracies of ± 500 m or better.

The distribution of faults and potentially unstable sediment masses was compiled by studying the profiles in order of low to high frequency (increasing resolution). First, features found on the multichannel data were plotted, followed by data from single channel, then 2.5 kHz Uniboom, and finally 3.5 kHz profiles. The major advantage of this technique is that large-scale features are initially pin-pointed and, subsequently, their geometries and effects are refined at increasingly smaller scales.

In general, the quality of the 3.5 kHz data is only fair, but the 2.5 kHz Uniboom data are fair to good and the low resolution seismic-reflection data are fair to excellent. The 3.5 kHz system generally penetrated only to the first subbottom reflector (0.005 sec; approximately 4 m), but in a few places it penetrated to 0.05 sec (approximately

35 m). The 2.5 kHz Uniboom system typically penetrated to 0.05 sec or less. The low-resolution, single channel seismic-reflection profiling systems penetrated to a maximum of about 2.0 sec in deep water and the multi-channel system was able to penetrate as much as 5.5 sec over the St. George Basin.

Factors which affect the quality of the seismic data can be grouped in two broad categories: (1) the types of seismic systems used and their environments, and (2) the surface and subsurface geology. The environment of the seismic system includes the sea-state at the time of recording, ambient acoustic interference generated by the vessel, depth of water, and the watchstander overseeing the system. The first two factors affect the high-resolution systems much more than the low-resolution systems. Sea-state conditions during which most data were collected ranged between calm and Force 8, but were typically between Forces 1 and 4. Rough sea-states resulted in the decoupling of hydrophones and/or transducers from the water column, thus seriously reducing the quality of high-resolution records. Ambient acoustic interference generated by the vessel adds further to the noise level on all the data. The depth of water affects the high- and low-resolution systems in opposite ways. On the low-resolution single channel sytems, shallow water depths influence the records by producing a first harmonic (multiple) that on many records obliterates the signals beneath it. As the water depth increases, the interference by the first harmonic is at deeper levels on the records, thus allowing more signals to be recorded. The high-resolution systems, performed well in shallow water because of the high repetition rates of the outgoing signals (generally 1/4 to 1 sec), but they did not perform well in deep water because of their relatively low power output. Reverberations create a "ringing" that also tends to mask out some signals.

Despite the weaknesses of the various systems and because of the extensive coverage of the area and the large amount of good quality data collected, we feel that the data are more than adequate to interpret the surface and near-surface geology of the region.

VI. RESULTS OF THE PAST YEAR

FAULTS

Classification

In this study, we classify faults by the seismic system that resolved the feature. The resolutions of the seismic systems (Table 2) were calculated using the velocity of sound in water and by following the procedure of Moore (1972) who showed that the resolution of seismic reflection systems is between 0.25 and 0.75 the wavelength of the source.

Table 2. Ranges of Resolution for Seismic systems.

Approximate Peak Frequency	Range of Minimum Resolution (m)
100 Hz	3.2 to 11.2
2.5 kHz	0.15 to 0.5
3.5 kHz	0.1 to 0.3

However, as we noted above, the actual resolution of a feature is not only a function of the outgoing frequencies but also is affected by the environments of the systems (e.g., sea-state, depth of water, acoustic interference, watchstander) and the surface and subsurface geology. There is a gap in the resolving range of our systems between about 0.5 m and 4 m which suggests that features with thicknesses or offsets in that range would not necessarily be resolved on our systems.

Our studies have concentrated on faults within the main-layered sequence. The faults are classified as surface, minor, and major faults. Surface faults are those that offset the surface of the sea floor regardless of which seismic system recorded them. They generally offset the sea floor no more than 1 or 2 meters. A minor fault is one observed on Uniboom and/or 3.5 kHz records, but not on low frequency single or multichannel seismic- reflection profiles. This class of fault typically has displacements of less than 0.006 sec (5 m), and most are near-surface but do not break the sea floor. In places, sediment can be seen draping over what was a Pleistocene surface fault. Major faults are those seen on low frequency multichannel and single-channel seismic-reflection profiles. They generally show growth features (increasing offsets with depth) and in places they offset acoustic basement. Boundary faults are a subclass of major faults that mark boundaries of the major structural elements.

Distribution of Faults

The distribution of the faults is given in Figures 3, 4, and 5. The symbols used in these figures are squares, triangles, and circles and the sense of displacement is indicated by shading on either side of a horizontal line within the symbols. No fault trends should be interpreted from the symbols themselves.

Boundary faults clearly delineate the St. George Basin and the Pribilof Ridge that bifurcates the basin in the subsurface (Fig. 1). These boundary faults typically are normal faults, occur in groups, show growth features with depth, in many places cut nearly all of the sediment section, at places offset acoustic basement, and in rare places offset the sea floor. Offsets greater than 0.08 sec (60 m) occur in the central region of the St. George Basin. These faults are connected in Figures 3 and 4 to form linear fault zones because they clearly define major structural features.

Major faults (those that are not boundary faults) occur principally within the confines of the St. George Basin with a few scattered in the Amak Basin that lies to the southwest (Fig. 4). They seem to decrease in number near the Pribilof Islands. These faults show displacements that generally are less than the larger boundary faults. They do not always show the same sense of offset as the adjacent boundary faults, which suggests that the tectonics involved are more complicated than just simple subsidence. Faults found on NE-SW ship tracks (perpendicular to the long axis of the basin) greatly outnumber those observed on NW-SE tracks, which indicates that the vast majority of major faults have a NW-SE trend probably paralleling the axis of the St. George Basin. However, because of the large number of faults and the 30 to 50 km trackline spacing, we have not connected any of these faults into trends or zones.

Surface faults tend to be more abundant along the outer margins of the St. George Basin and along the Pribilof Ridge (Fig. 4). Most can be traced from high-resolution to low-resolution profiles, thereby indicating that most surface faults are tied to major faults and boundary faults. Only one surface fault was observed in the Amak Basin.

Minor faults occur throughout the region, but similar to the other classes of faults, are concentrated in the mid-St. George Basin area (Fig.5). They are more common in the St. George Basin away from the Pribilof Ridge and occur with greater frequency south of the ridge than north. Few minor faults occur over the Amak Basin, suggesting that the basin is a flexure rather than fault controlled. Just as with major faults, many more minor faults were encountered on NE-SW tracklines than on NW-SE lines, which suggests that the most minor faults trend NW-SE, roughly parallel to the boundary faults and to the axis of the St. George Basin. Again, no attempt was made to correlate minor faults between tracks because of the track spacing. Most minor faults have offsets of less than 0.006 sec (5 m) and almost all affect the top 0.005 sec (approximately 4 m) of sediment section. Preliminary results, from studies of diatoms in 50 gravity cores that range up to 2 m in length, show that none of the sediment recovered is older than 260,000 yrs (all are within the _Denticula Seminae_ Zone; John Barron, pers. commun., 1976). If we assume that in 2 m core just penetrated the entire _Denticulina Seminae_ Zone, then there is a minimum sediment accumulation rate of about 0.83 cm/10^3 yrs. If we further assume that this minimum sediment accumulation rate occurred throughout the top 4 m of sediment, (the thickness typically affected by minor faults) then the maximum age of the sediment, calculated at 0.8 cm/10^3 yr, is 500,000 yrs. B.P. This suggests that the minor faults are at least Pleistocene in age. If the accumulation rate is much greater, like 10 cm/10^3 yrs., as is suggested by C^{14} dates from comparable areas farther north (Askren, 1972), then the minor faults could cut sediment as young as 40,000 yrs. B. P.

POTENTIALLY UNSTABLE SEDIMENTS

Areas of potentially unstable sediment masses were determined from the seismic records by using one or more of the following criteria: 1) surface faults with steep scarps and rotated surfaces; 2) deformed bedding and/or discontinuous reflectors; 3) hummocky topography; 4) anomalously thick accumulations of sediment; and 5) acoustically transparent masses of sediment. Regions that show unstable sediments (e.g., gravity slides, slumps, creep, scarps, etc.) are confined to the continental slope and rise and the Pribilof and Bering Canyons (Fig. 3). Zones of creep, as shown by irregular, hummocky topography, begin near the shelf break at depth of about 170 ± 2 m. Hummocky topography occurs on the continental slope on a large scale and mass movement is a common feature. Individual slumps were not mapped because of our wide line spacings, but we regard the entire continental slope and the walls of the major submarine canyons to be zones of potentially unstable sediment.

VII and VIII. DISCUSSION AND CONCLUSIONS

Abundant faults cut the St. George Basin area. Many faults cut upper Pleistocene sediments and a few reach the surface of the sea floor, thereby indicating that the area is tectonically active. Zones of slumping along the continental slope and steep walls of the submarine canyons show that sediment instability and mass movement of sediment are common occurrences.

The southern Beringian continental shelf and margin are located within 500 km of the Aleutian trench, which marks a subduction zone between the Pacific and North American plates. Several intermediate- to deep-focus (71 to 300 km) and many shallow-focus ($<$ 71 km) earthquakes were recorded in the area from 1962 to 1969 (Department of Commerce, 1970). Seismicity in the area during that time interval is shown in Figure 6. The shelf of the St. George Basin area has been subject to earthquakes with intensities as high as VIII (modified Mercalli scale), which corresponds to a magnitude 5.7 earthquake (Meyer and others, 1976).

Recurrence rates of earthquakes for the area bounded by latitudes 50° and 60°N and longitudes 160° to 175°W have been as high as 6.4 earthquakes per year from 1963 to 1974 for magnitudes of 4.0 to 8.4, and 0.013 earthquakes per year of magnitude 8.5 to 8.9 (1 every 130 yrs) , from 1899 to 1974 (Meyers and others, 1976).

The effects of earthquakes on faulting and sediment stability in the area are not well understood (see Page, 1975). We believe, however, that some faults are active and that they probably respond to earthquake-induced energies and possibly to sediment loading over the St. George Basin. Regimes of active sediment movement could respond to a variety of energy sources including earthquakes, storm waves, internal waves, gravity, etc.

IX. NEEDS FOR FURTHER STUDY

Preliminary analyses of seismic and sediment data collected during the 1976 field year indicate that the large submarine canyons in the region, the Pribilof and Bering Canyons, exert a profound influence on the sediment distribution and dynamics of the adjacent outer continental shelf region, including St. George and Amak Basins. In addition, our data show that the upper continental slope and shelf break are areas of mass movement of sediment (creeping, slumping, and catastrophic movement as shown by steep scarps).

The effects of the canyons on the distribution of sediment and the near-bottom dynamics must be known before man-made structures, whether they be offshore rigs, underwater completion systems, storage facilities, or pipelines, are placed in this area. An investigation of slumping along the continental margin should allow us to estimate the present rate of sediment flux over the outer continental shelf region and what it has been in the past. Hopefully, by understanding the masses of unstable sediment, we can better estimate the effects of seismicity in the region.

It should be emphasized that the vast majority of the data collected during the 1976 field season have not been analyzed and put into perspective. As this process continues, new insights into the shallow geology of the Beringian shelf margin will emerge.

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X. SUMMARY OF FOURTH QUARTER OPERATIONS

A. No field work was performed during the fourth quarter.

B. Data analyzed - seismic

Approximately 7000 km each of single-channel seismic-reflection profiles, 2.5 kHz Uniboom data, and 3.5 kHz data and approximately 700 km of 24- channel channel seismic-reflection profiles we re analyzed for the presence of faults and potentially unstable sediment masses.

Data analyzed - sediments

Analyses of total carbon were run on 202 samples, which, including replicate runs for statistics, accounts for 1129 analyses. Grain-size analyses were run on 295 samples. The range of grain size recorded is from 2 μm to 4 μm. This represents three types of analyses: sieving for > 2 mm, rapid sediment analyzer (settling tubes) for 2 mm to 63 μm and hydrophotometer determinations for 63 μm to 4 μm. Replicate analyses were run at random intervals to check the precision. Analytical procedures followed standard techniques and calibrated standards were run every few hours to ensure accuracy. These data will be reported in a subsequent report.

Walter E. Dean of the Regional Geochemistry Branch, U.S.G.S., Denver, Colorado, a shipboard scientist on the U.S.G.S. cruise S4-76, is analyzing 180 samples for 30 elements by a combination of atomic absorption, optical emission spectroscopy, x-ray fluorescence, and neutron activation analysis. These data and their interpretations will be published in a U.S.G.S. Open-File Report.

Keith Kvenvolden of the Pacific-Arctic Branch of Marine Geology, U.S. G.S., Menlo Park, California, also a shipboard scientist on cruise S4-76, is in the process of analyzing, by gas chromatography, 80 samples for low molecular-weight hydrocarbons. These data and their interpretations will be published in a U.S.G.S. Open-file Report.

Table 3 is a summary of the data analyzed during the Fourth Quarter.

Table 3. Summary of Analyses Performed during Fourth Quarter

DATA TYPE	Number of ANALYSES	Number of SAMPLES
SEISMIC PROFILES	28,000 km	
TOTAL CARBON	1,129	202
GRAIN SIZE	885	295
INORGANIC GEOCHEMISTRY	5,400	180
ORGANIC GEOCHEMISTRY	80	80

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FIGURES

Figure 1. Physiographic map of the St. George Basin region, southern Bering Sea.

Figure 2. Tracklines of cruises over the St. George Basin region.

Figure 3. Map showing distribution of faults and areas of potentially unstable sediments.

Figure 4. Map showing the distribution of major and surface faults.

Figure 5. Map showing the distribution of minor faults.

Figure 6. Seismicity of the St. George Basin region (after U. S. Dept. of Commerce, 1970). Symbols show earthquake magnitudes: +, none given; △, <6.0; ◇, 6.0-6.9; ○, 7.0-7.9.

ANNUAL REPORT

Title: Earthquake Activity and Ground Shaking
in and along the Eastern Gulf of Alaska

Report by: Christopher D. Stephens and John C. Lahr

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Research Unit: 210

Reporting Period: April 1, 1976 through March 31, 1977

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ILLUSTRATIONS

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I. Summary of objectives, conclusions and implications with respect to OCS oil and gas development.

The objective of this research is to evaluate the hazards associated with earthquake activity in the eastern Gulf of Alaska and adjacent onshore areas. These hazards may pose a threat to the safety of petroleum development.

Seismic activity in and adjacent to the eastern Gulf of Alaska for the past two years has been correlated with known geologic structures. The area around Icy Bay has been one of the most active along the eastern Gulf during this time. A well-defined trend in the epicenters in the bay is aligned along strike with an offshore fault and an inferred onshore thrust fault, and may represent an offshore continuation of the fault. A composite focal mechanism for these recent, locally-recorded earthquakes, and four focal mechanisms (J. Davies, personnel communication, 1977) for teleseismically-recorded events in the same area all indicate shallow thrusting resulting from northwesterly compression.

Continued seismic monitoring will no doubt reveal other areas of activity and delineate other active geologic structures. While the locally recorded earthquake data obtained since September, 1974 provides evidence of active faulting in the Icy Bay region, the general absence of earthquakes elsewhere in the eastern Gulf of Alaska cannot indicate in itself the absence of faults capable of generating potentially damaging earthquakes. For some mapped surface faults, however, sufficient geological and geophysical information may be available or attainable to conclude that the fault is inactive because of the lack of fault movement over a suitably long interval of time.

A recent re-evaluation of a series of three great (M>8) earthquakes (W. Thatcher and G. Plafker, personal communication, 1977; see Appendix I) which occurred in the vicinity of Yakutat Bay at the turn of the last century has confirmed earlier estimates that they were indeed magnitude class 8 events. Another onshore earthquake such as one of these, or a great earthquake associated with low-angle oblique underthrusting of the sea floor beneath the continental shelf (Page, 1975) would be accompanied by strong ground shaking throughout much of the eastern Gulf of Alaska, possibly from Cross Sound to Kayak Island, and could trigger tsunamis, seiches, and submarine slumping, any of which could be hazardous to offshore and coastal structures (Meyers, 1976).

II. Introduction

A. General nature and scope of study.

The purpose of this research is to investigate potential earthquake hazards in the eastern Gulf of Alaska and adjacent onshore areas. This will be accomplished by assessing the historical seismic record as well as by collecting new and more detailed information on both the distribution of current seismicity and the nature of strong ground motion resulting from large earthquakes.

B. Specific Objectives

The major aim of this research is to develop an understanding of what geologic structures in the eastern Gulf of Alaska have generated or are capable of generating damaging earthquakes.

A second aim of the proposed research is to obtain recordings of strong ground motion close to the zone of energy release in a major earthquake. Currently no such records have ever been obtained within 40 km of a magnitude 8 earthquake. Without such information, there is a disturbing uncertainty in regard to the nature of the ground shaking that causes significant damage in major earthquakes.

C. Relevance to problem of petroleum development.

It is crucial that the potential seismic hazards in the eastern Gulf of Alaska be carefully analyzed and that the results be incorporated into the plans for future petroleum development. This information should be considered in the selection of tracts for lease sales, in choosing the localities for landbased operations, and in setting minimum design specifications for both coastal and offshore structures.

III. Current state of knowledge

The eastern Gulf of Alaska and the adjacent onshore areas are undergoing compressional deformation caused by north-northwestward migration of the Pacific plate with respect to the North American plate (Figure 1). Direct evidence for this convergent motion comes from studies of large earthquakes along portions of the Pacific-North American plate boundary adjacent to the eastern Gulf of Alaska.

The 1958 earthquake on the Fairweather fault in southeast Alaska was accompanied by right lateral slip of as much as 6.5 m (Tocher, 1960). The 1964 Alaska earthquake resulted from dip slip motion of about 12 m (Hastie and Savage, 1970) on a fault plane dipping northwestward beneath the continent from the Aleutian Trench and extending from eastern Prince William Sound to southern Kodiak Island. In the intervening region between these earthquakes, from approximately Yakutat Bay to Kayak Island, the precise manner in which this convergent motion is accommodated is not known. There are some indications that a broad region is involved, extending from the continental shelf inland to the Totschunda and Denali faults. Slip on these faults has been right lateral during Quaternary time as would be expected if the southern margin of Alaska were partially coupled to the Pacific plate (Richter and Matson, 1971). The eastern Gulf of Alaska is bounded by the young Chugach and St. Elais mountain ranges (Figure 2, upper).

The historic record of instrumentally located earthquakes in the vicinity of the eastern Gulf is probably complete only for events larger than magnitude 7-3/4 since 1899, earthquakes larger than 6 since the early 1930's and larger than 5 since 1964. The events contained in the N.O.A.A. Earthquake Data File for 1899 through February, 1975 are plotted in Figure 2, lower. Each number corresponds to the decade in which the event occurred. The coordinates of epicenters prior to about 1960 were often rounded to the nearest tenth of a degree. To avoid plotting epicenters on top of one another, the second and subsequent epicenters to be plotted at a given point have been randomly scattered by up to 4 km. The apparent increase in seismicity in the 1960's and

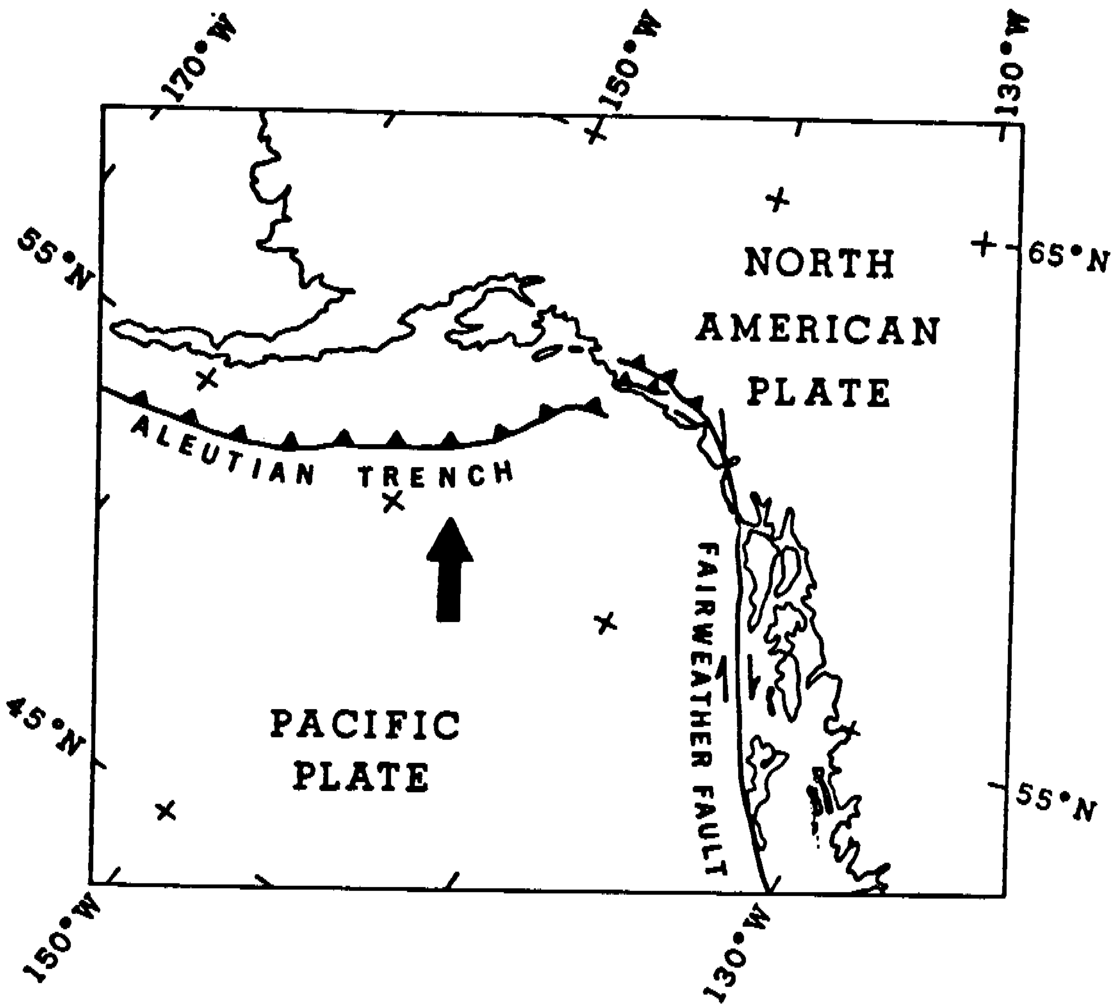


Figure 1. Plate tectonic relationships in the northeast Pacific. Large arrow indicates motion of the Pacific plate relative to a stationary North American plate. Small arrows indicate sense of horizontal slip on faults; barbs are on upper edge of thrust fault.

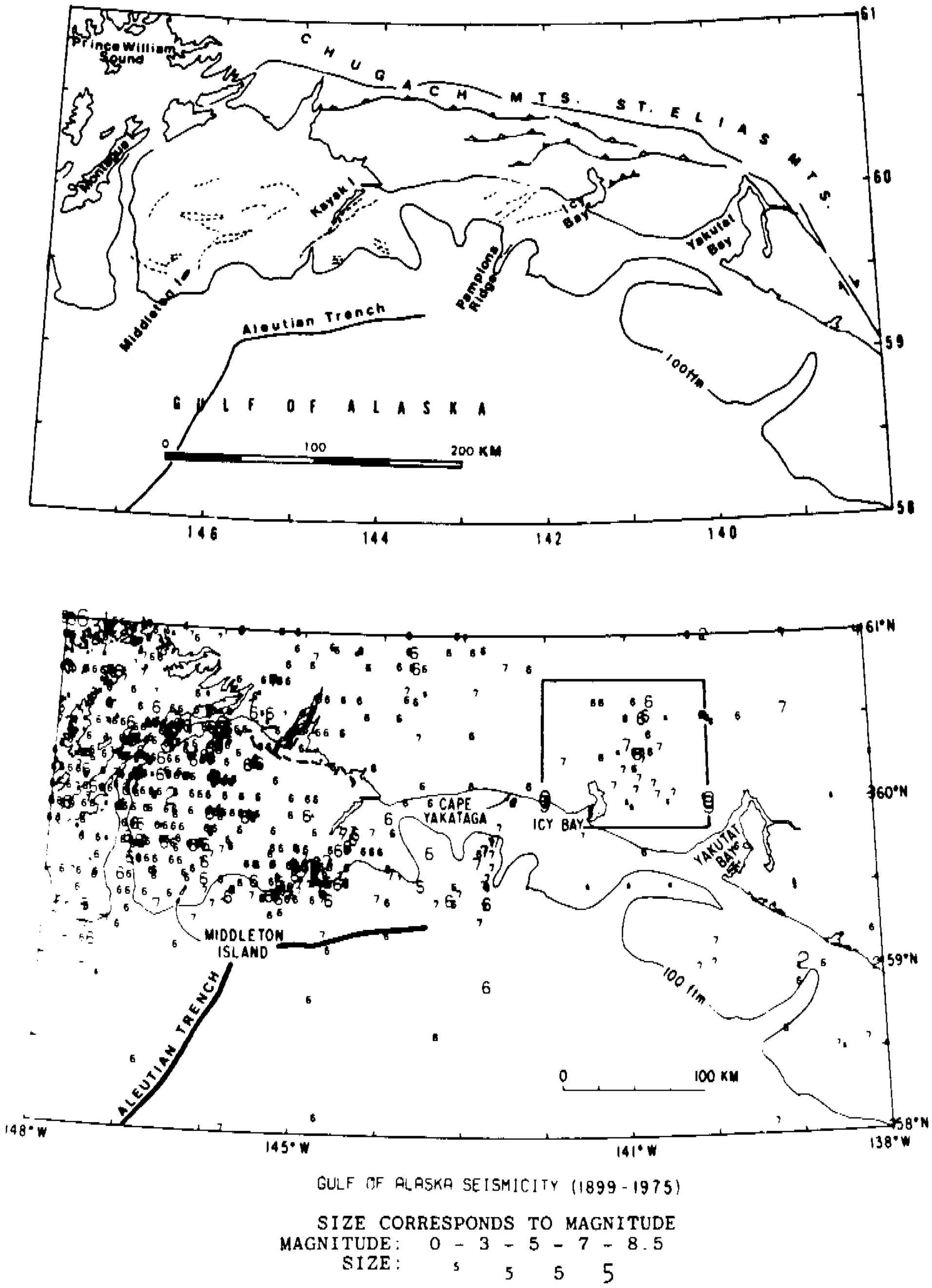


Figure 2. The upper map of the eastern Gulf of Alaska region shows offshore faults and selected onshore faults (from Carlson, 1976). The lower map is a plot of earthquake epicenters in the same area from 1899-1975. Numbers indicate the decade in which the earthquake occurred, for example, 7 indicates 1970's.

1970's is due in part to aftershocks of the 1964 Prince William Sound earthquake and in part to establishment of seismograph networks in southern Alaska in 1967 by N.O.A.A. (Palmer Observatory) and the Geophysical Institute of the University of Alaska. The seismograph stations closest to the region of study prior to 1972 were located on Middleton and Kodiak Islands and near Palmer. Prior to 1967 the closest permanent stations were at Sitka and College.

The largest historic earthquakes in the vicinity of the eastern Gulf of Alaska were three magnitude 8 earthquakes in the Yakutat area in 1899 and 1900 (Tarr and Martin, 1912; Richter, 1958), the magnitude 8 Prince William Sound earthquake of 1964 and the magnitude 7.9 earthquake on the Fairweather fault in 1958. Shorelines were uplifted as much as 14 meters in the Yakutat Bay area and about 1 meter at Cape Yakataga during the 1899-1900 earthquakes (Tarr and Martin, 1912). Coastal uplift during the 1964 earthquake ranged from 10 meters at Montague Island to less than 3 meters at Kayak Island (Plafker, 1969). The region between the 1958 and 1964 earthquakes (Figure 3) lies on the Pacific-North American plate boundary and has been identified as a likely location for a magnitude 7 or 8 shock in the next few decades (Kelleher, 1970; Sykes, 1971; Page, 1975).

The Chugach and St. Elias Mountains are bounded on the south and southwest by the Gulf of Alaska Tertiary province. Many north-dipping thrust faults have been mapped in this Tertiary province (Plafker, 1967), but it is not known which are currently active. A few of these faults are indicated on Figure 2, upper.

Available information on the offshore structure has been summarized by Bruns and Plafker (1975) Molnia et. al. (1976) and Carlson (1976). The location of near-surface offshore faults, interpreted largely from minisparker records, are shown in Figure 2, upper. None of these faults was found to offset Holocene sediments at the sea floor with great certainty, so their current state of activity may best be determined by earthquake investigations.

IV. Study area.

This project is concerned with seismic hazards within and adjacent to the eastern Gulf of Alaska continental shelf area. This is the southern coastal and adjacent continental shelf region of Alaska between Montague Island and Yakutat Bay (Figure 2).

V. Data collected.

The short-period seismograph stations installed along the eastern Gulf of Alaska under the outer Continental Shelf Environmental Assessment Program as well as the other stations operated by the USGS in southern Alaska are shown in Figure 4. Single-component stations record the vertical component of the ground motion, while three-component stations have instruments to measure north-south and east-west motion as well. Data from these instruments are used to determine the parameters of earthquakes as small as magnitude 1. The parameters of interest are epicenter, depth, magnitude, and focal mechanism. These data are required to further our understanding of the regional tectonics and to identify active faults.

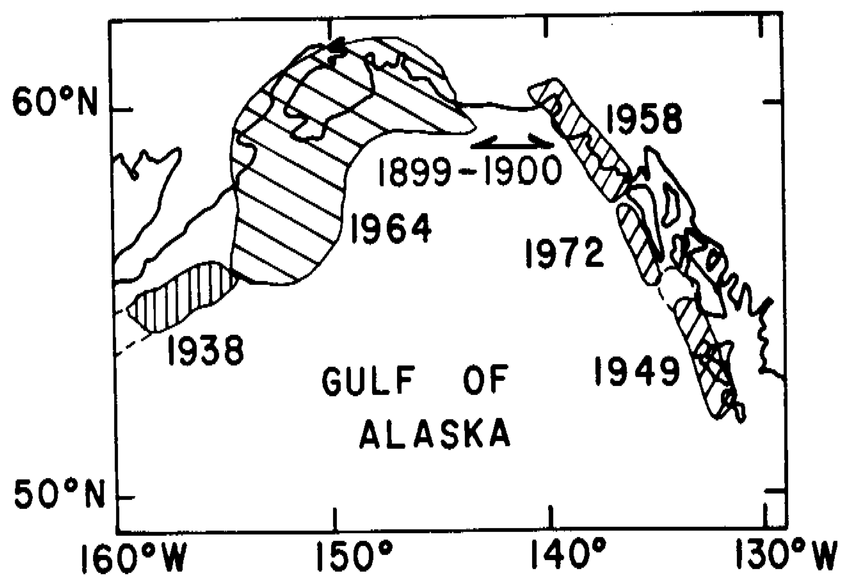


Figure 3. Map showing the aftershock zones for earthquakes of magnitude 7.3 or greater in the eastern Gulf of Alaska since 1938. No large earthquakes have occurred between the rupture zones of the 1958 Fairweather earthquake and the 1964 Prince William Sound earthquake since the 1899-1900 series of great earthquakes near Yakutat Bay, which makes this a likely site for another large earthquake. Modified from Sykes (1971).

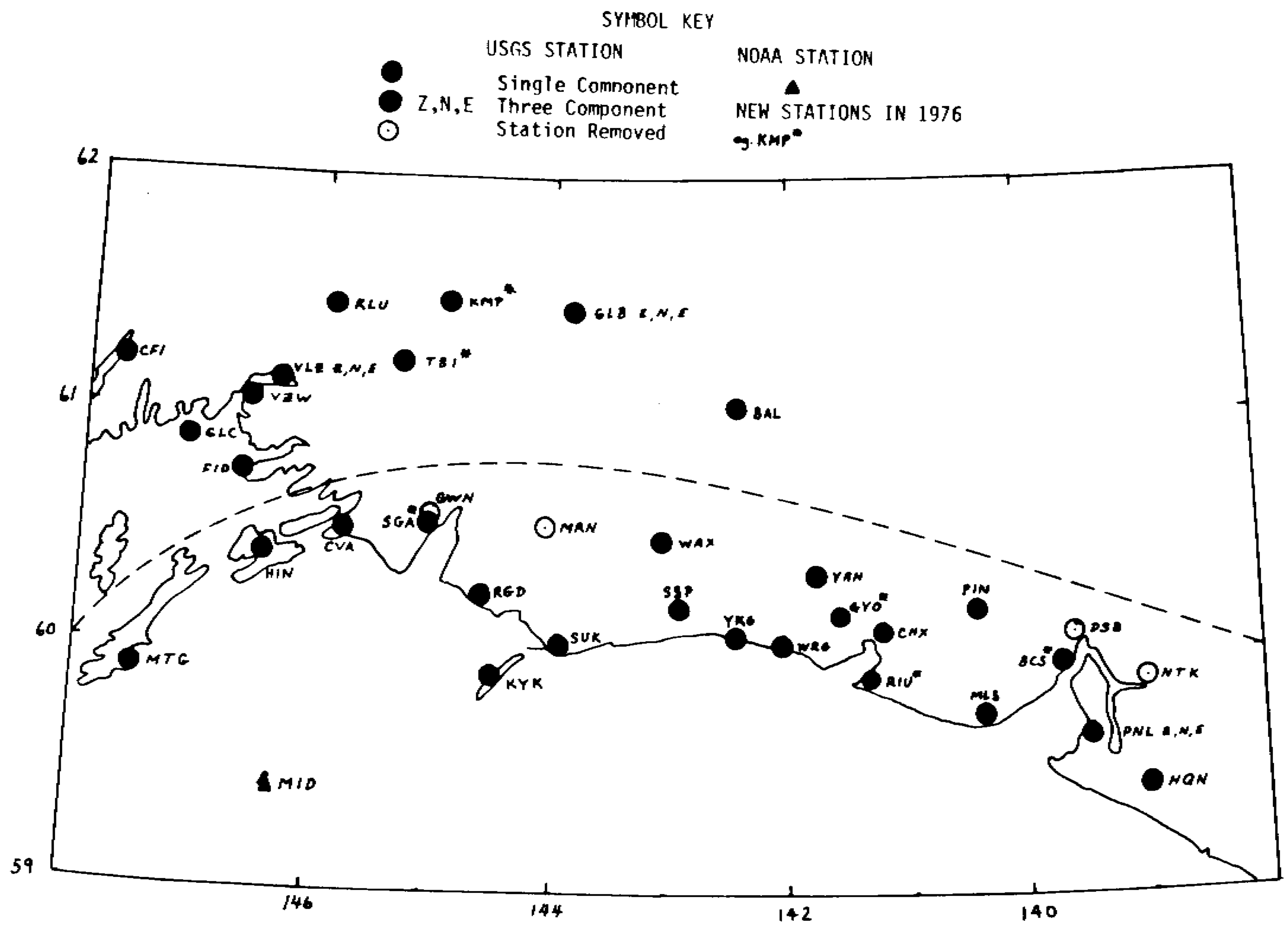


Figure 4. Seismic stations located in the eastern Gulf of Alaska region. Stations south of the dashed line are supported by OCSEAP.

A network of strong motion instruments is also operated by the Seismic Engineering Branch (Figure 5). These devices are designed to trigger during large earthquakes and give high-quality records of large ground motions which are necessary for engineering design purposes.

VI. Results

Preliminary earthquake epicenters in the eastern Gulf of Alaska region are plotted in Figures 6 through 8. All events for which at least four arrivals at three or more stations could be read are included in the figures. A catalog of the events is listed in Appendix IV.

As six previous quarters of data indicated, the data for the first three quarters of 1976 also show that we are locating very few offshore seismic events east of about Kayak Island. The most notable exception among the better located events is a small cluster of events located about 60 km south of Kayak Island (Figure 8) which occurred during the third quarter of 1976. There have also been earthquakes off of the Copper River delta, and and a few just SE of Montague Island. This pattern of seismic activity with close spatial and temporal clustering of earthquakes, appears to be characteristic of the low-magnitude activity in the eastern Gulf of Alaska.

On land there is a diffuse zone of seismic activity that closely parallels the Chugach- St. Elias fault zone, although none of the earthquakes has been clearly associated with any of the known or inferred faults in the area. In the first quarter of 1976, a number of earthquakes occurred in the Prince William Sound area southwest of Valdez. These events suggest a linear northwest trend that closely parallels other structures and faults near this area, although again there are no mapped or inferred faults clearly associated with the activity.

Over the past two years the Icy Bay area has been almost continually active. A well-defined, northeast trend in the epicenters of the earthquakes which have occurred since September of 1974 closely parallels the strike of both an offshore anticline and an inferred onshore thrust. This area will be discussed in more detail in the following section.

Data from some station supported by NOAA were used in a study of the seismicity of the Prince William Sound area (see Appendix III).

VII. & VIII. Discussion and Conclusions.

A. Icy Bay Region.

During the past two years, the Icy Bay area has been one of the most active along the eastern Gulf of Alaska. A plot of the better located events in this region (Figure 9) indicates a clear zone of seismicity which extends northeast from the mouth of Icy Bay for about 50 km until it intersects several major faults, at which point the trend becomes more diffuse. A composite focal mechanism (Figure 10) of only the best located events within this trend suggests thrust faulting resulting from northwestward compression, a result consistent with convergence between the Pacific and North American plates. Focal depths in this region are generally less than about 30 km. A cross-section view of this zone (Figure 11, top) looking along the strike of the trend does not show a simple planar earthquake distribution. This may be a

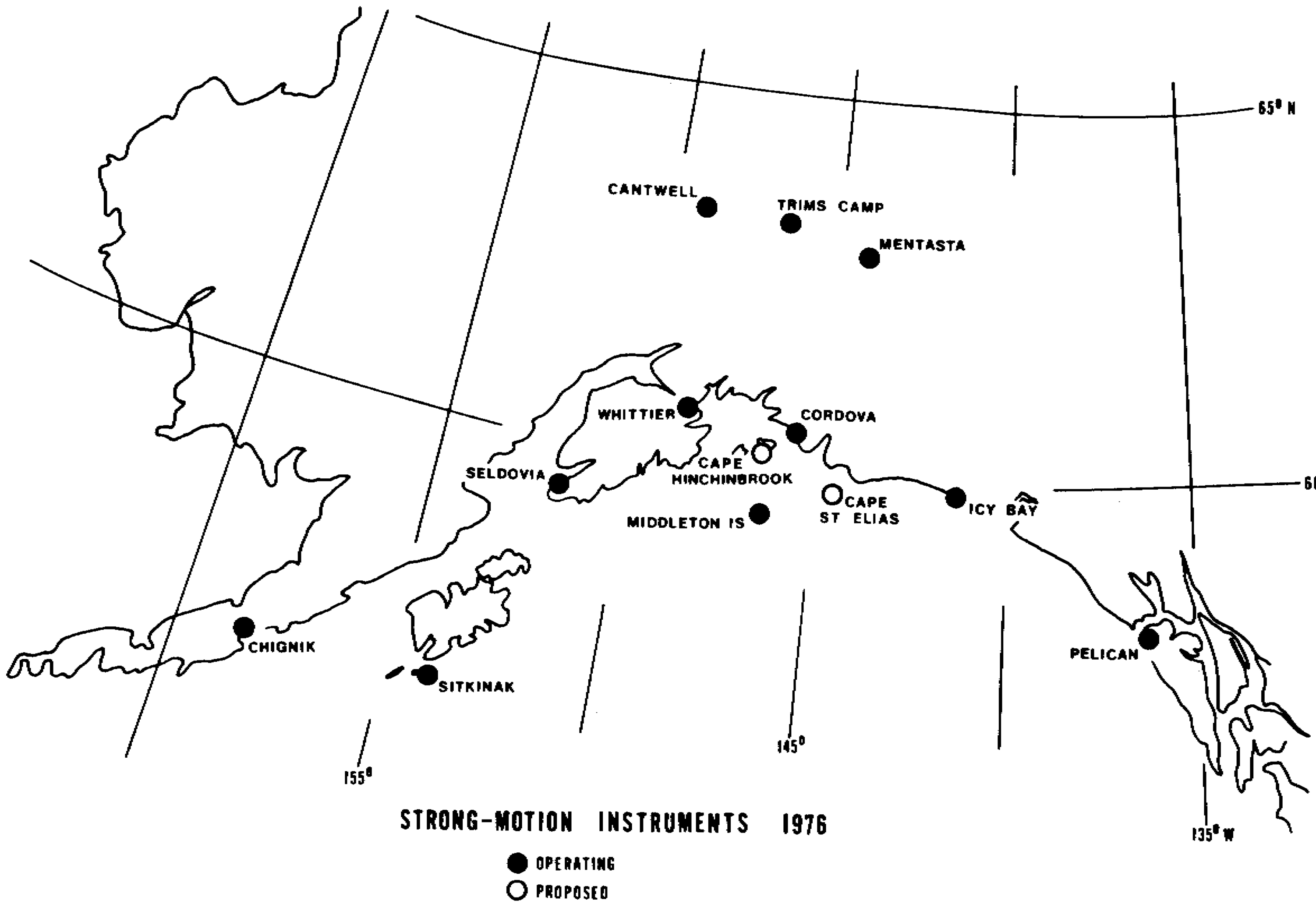


Figure 5. Map showing the locations of USGS operated strong-motion instruments in the eastern Gulf of Alaska and supported by OSCEAP.

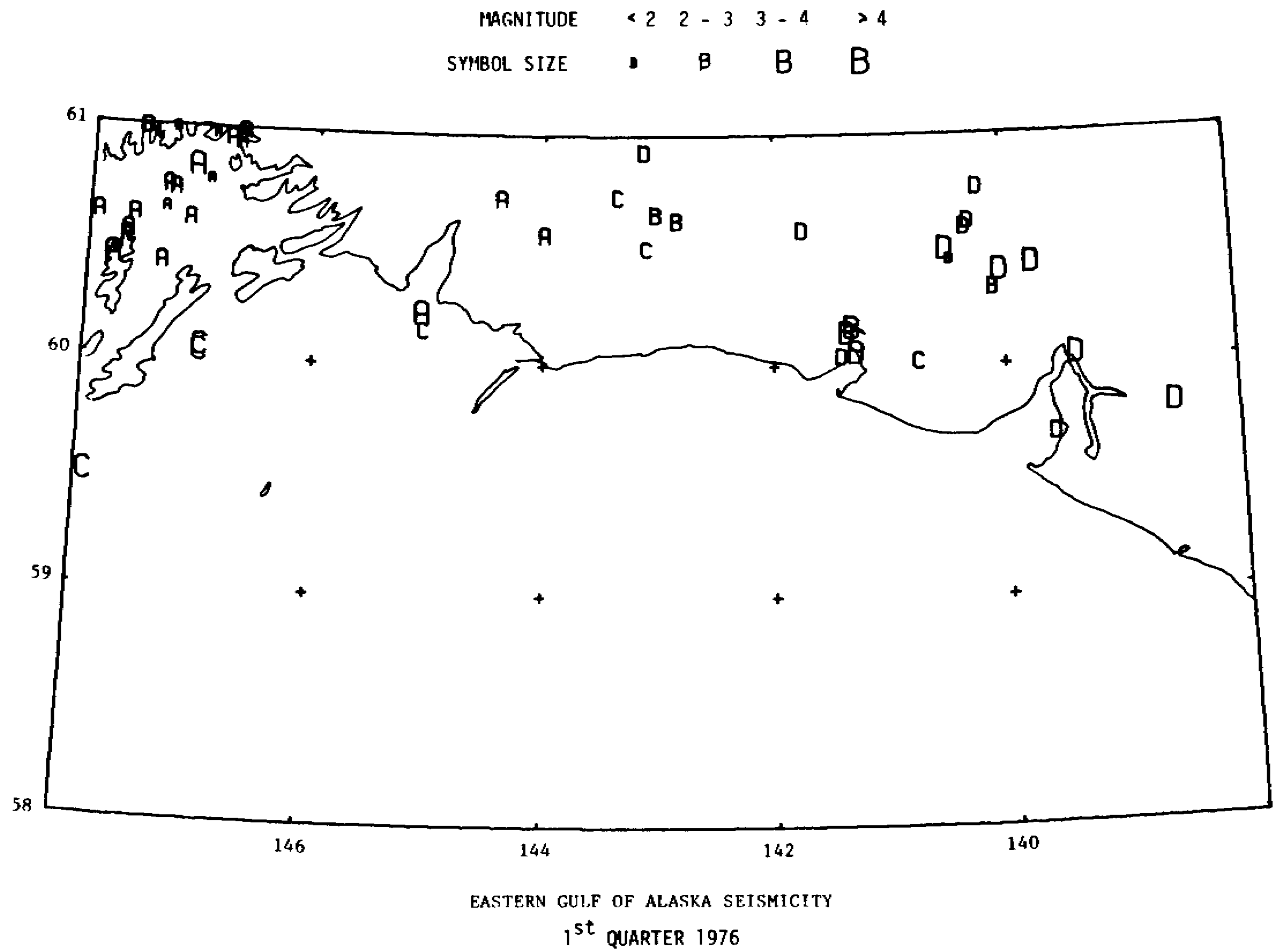


Figure 6. Map of earthquake epicenters from data from the USGS regional seismograph network, January-March, 1976

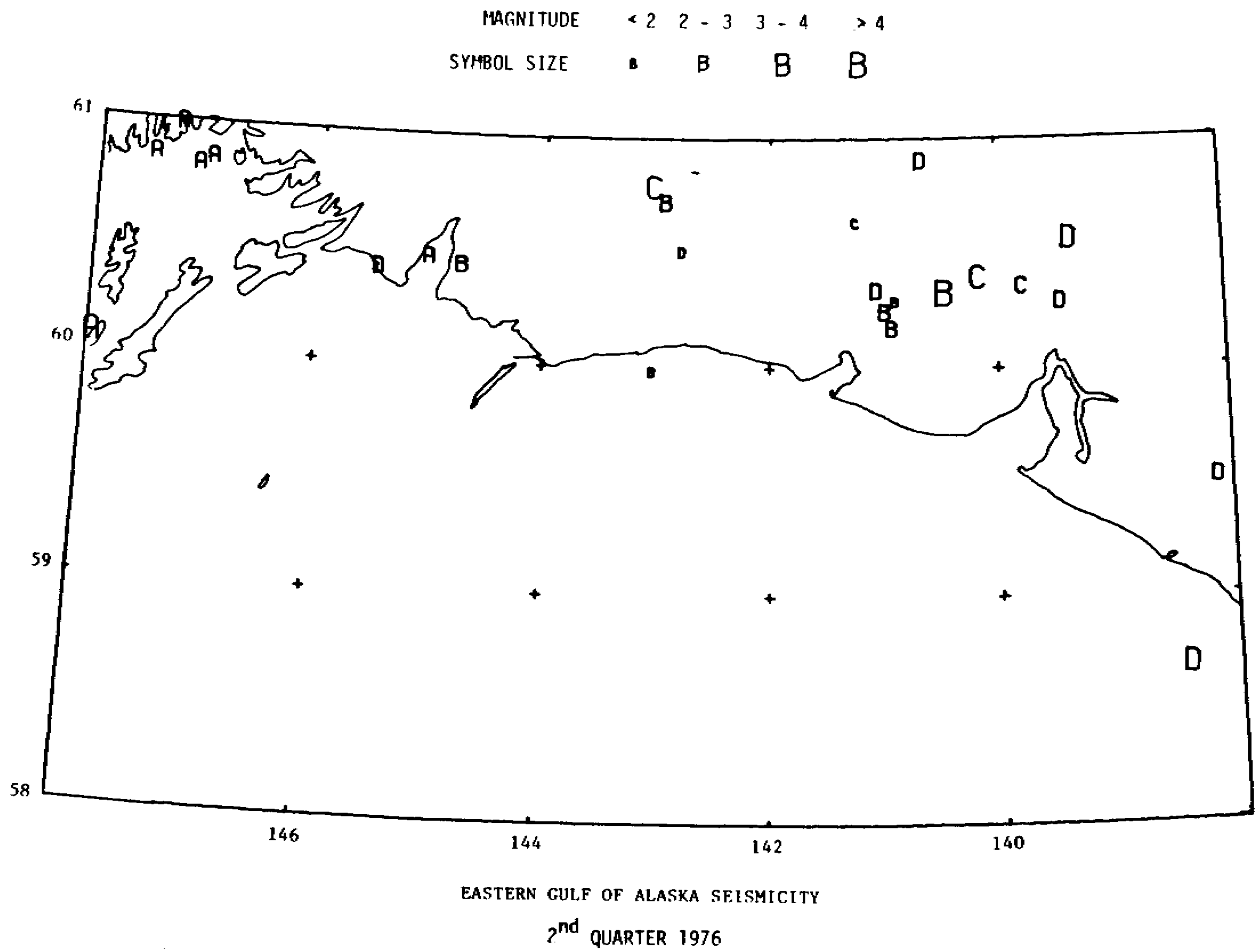
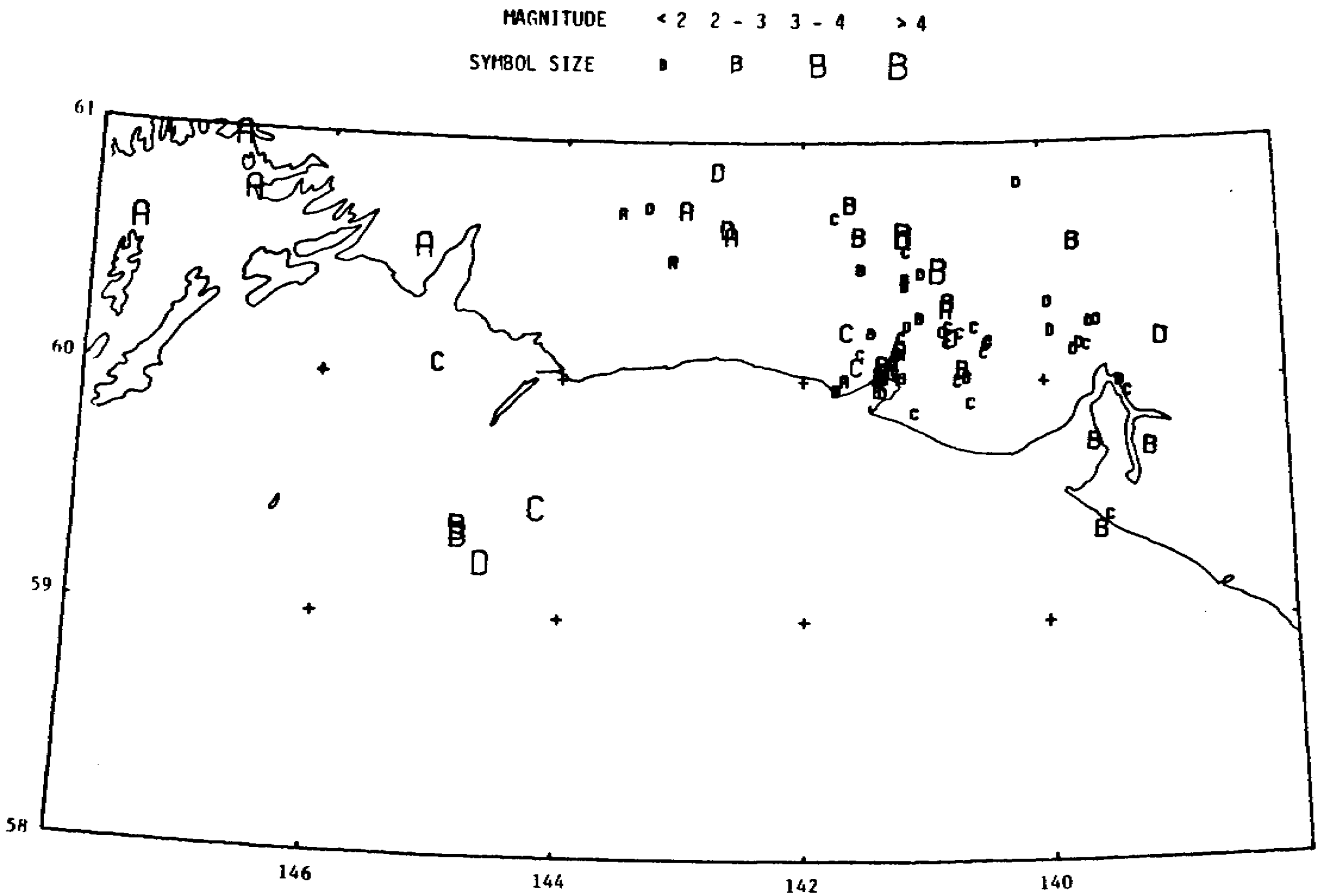


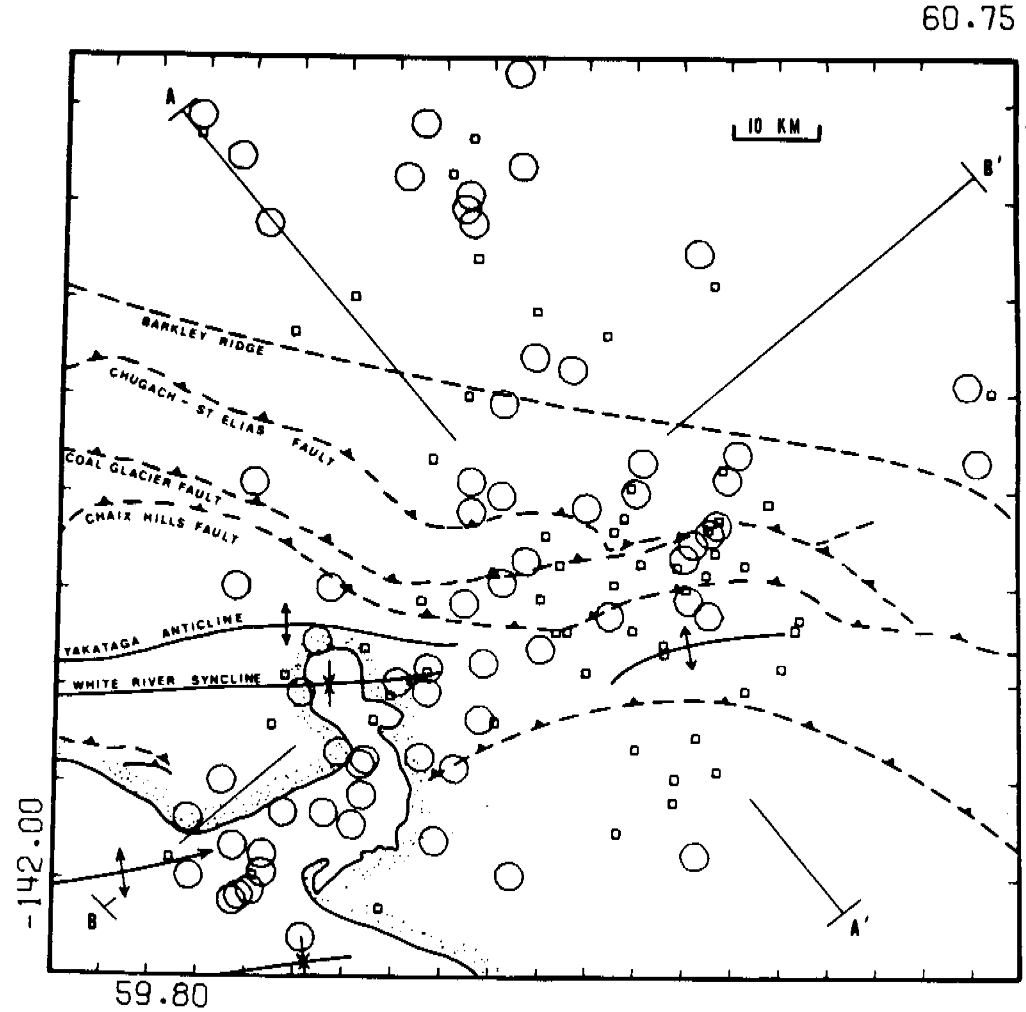
Figure 7. Map of earthquake epicenters from data from the USGS regional seismograph network, April-June, 1976.



EASTERN GULF OF ALASKA SEISMICITY

3rd QUARTER 1976

Figure 8. Map of earthquake epicenters from data from the USGS regional seismograph network, July-September, 1976.



ICY BAY 74Q3-76Q3

Figure 9. Map of earthquake epicenters near Icy Bay for the period September, 1974 through September, 1976. The main geologic structures and faults in the area are also shown (Brunes and Plafker, 1976; Miller, 1971). The locations of sections A-A' and B-B' of Figure 11 are indicated. The large circles represent the epicenters of locations with a standard error in the vertical direction of less than 2.5 km, while the small squares represent hypocentral locations having greater vertical errors.

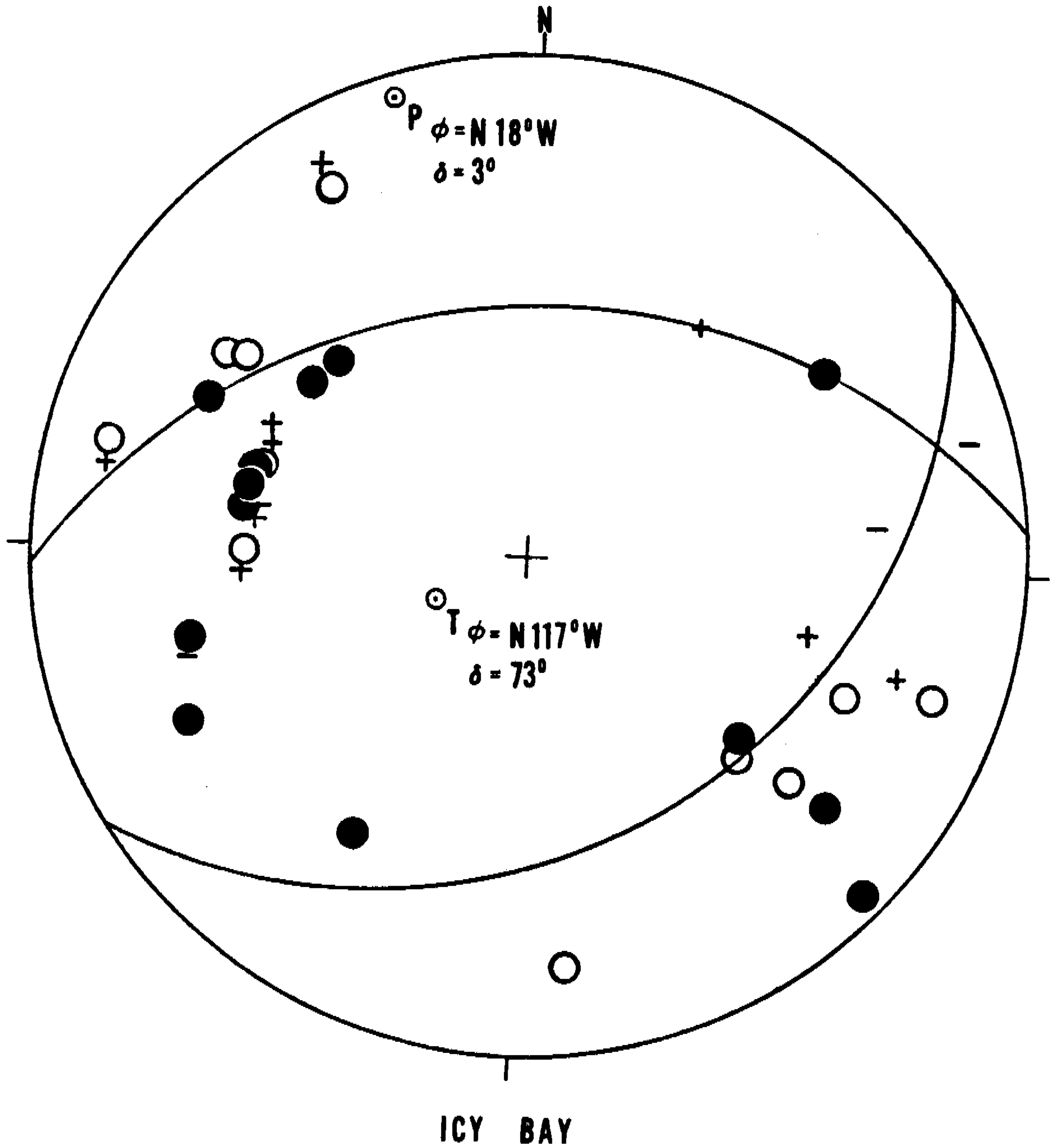


Figure 10. Composite first motion plot of the best located (quality A) earthquakes beneath Icy Bay. This is a lower hemisphere equal area projection. The mechanism is compatible with thrusting on a northwest dipping plane.

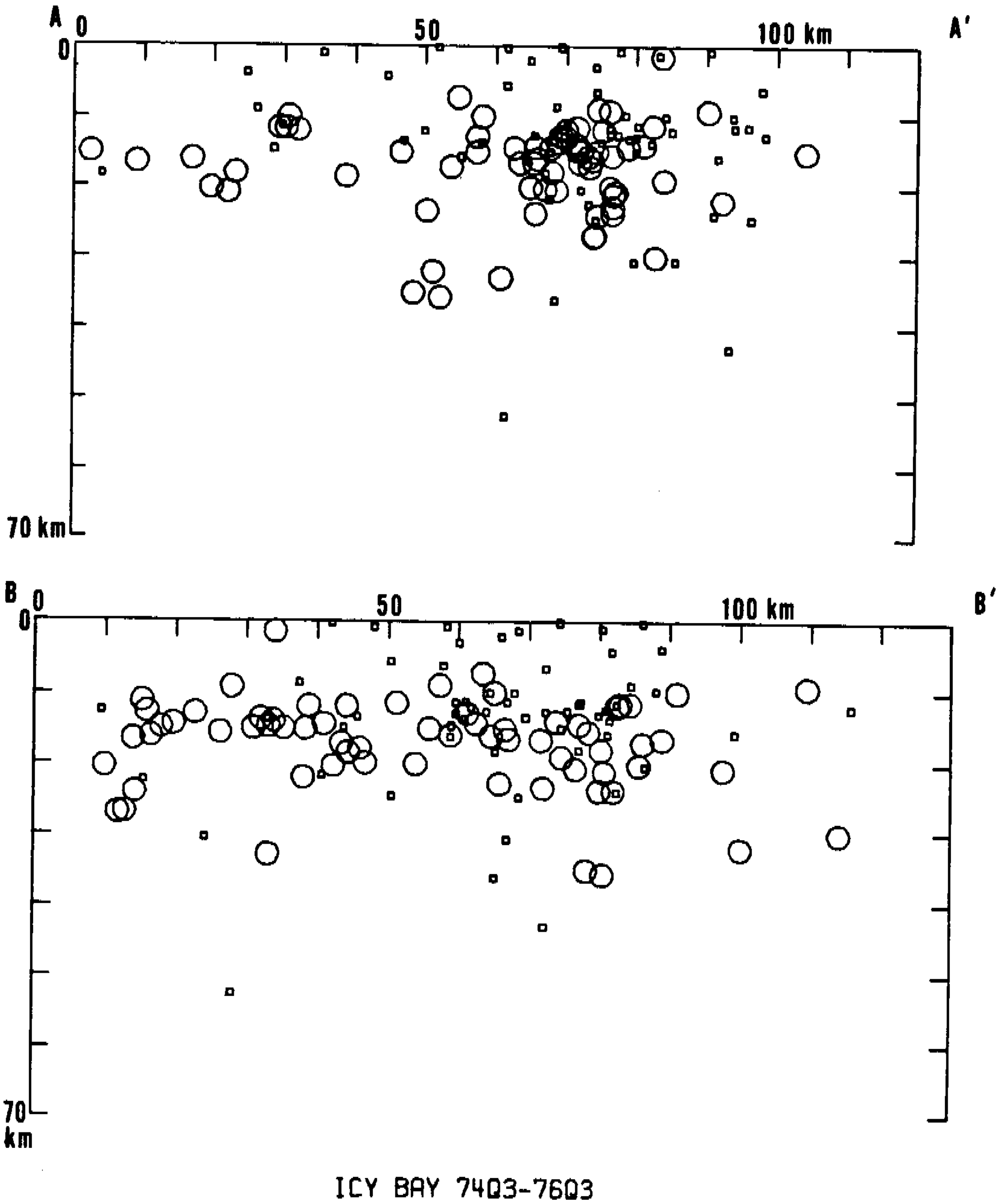


Figure 11. Cross-sections showing the hypocenters of Figure 9 projected onto the planes indicated in Figure 9. Circles represent hypocenters with good depth control.

result of a combination of structural complexity in the region, as illustrated in Figure 9, and location errors. The most striking feature of the trend in seismicity is the alignment with a mapped offshore fault and an inferred onshore thrust fault.

The trend of the seismicity near Icy Bay, when extended offshore, intersects the Pamplona Ridge, the site of a series of large earthquakes in 1970. A broader view of the seismicity around Icy Bay shows that the area southwest of Icy Bay, including Pamplona Ridge, has been quiet seismically for at least the past two years. Although the distribution of seismic stations is not ideal for locating earthquakes accurately in the offshore area, it is still capable of recording events of magnitude 2 and above. It is still possible that earthquakes of smaller magnitude do occur in the area southwest of Icy Bay, and detection of these events is important in order to interpret the apparent continuity of the onshore and offshore structures in this area.

B. The 1899 Yakutat Bay Earthquakes and Their Relation to Recurrence Intervals of Great Earthquakes in the Eastern Gulf of Alaska

A recent study (Thatcher and Plafker, 1977) of the three great earthquakes which occurred in the Eastern Gulf of Alaska in about a one-year period between 1899 and 1900 showed that these earthquakes have seismic moments on the order of 10^{28} dyne-cm (Figure 12).

One of these events (10 Sept. 1899) occurred in the vicinity of Yakutat Bay, and the raised beaches there may be accounted for by this event alone. Thus, the slip during the equally large 04 Sept., 1899 event must be accommodated elsewhere. Its large seismic moment and its location 150 km west of Yakutat Bay, as well as the absence of a tsunami from this earthquake and the 1 m uplift observed at Cape Yakataga all argue for thrusting on the east-trending Chugash-St. Elias zone during this earthquake. Distributing this seismic slip uniformly over a fault 150 km long and 50 km wide gives 5 m of plate convergence during the 04 Sept. event.

Geological evidence for slip along the Fairweather Fault (Plafker, 1976), geophysical evidence from deep sea paleomagnetic data (LePichon, 1968), and indirect evidence from seismic moment determination of the 1958 Fairweather earthquake (M. Ando, personal communication, 1977; see Appendix II), suggest that the convergence rate between the Pacific and North American plates in the region is about 5 cm/year. If significant creep is not taking place, so that strain is accumulating at a rate of 5 cm/yr, then the long-term average recurrence interval for earthquakes with 5 m of displacement is about 100 years. Considering the discrepancies often found between calculated and observed recurrence intervals (Plafker, 1972), the regional complexity, and the fact that three great earthquakes struck this area within about a one-year time period, the actual interval until the next great earthquake is not known.

IX. Needs for further study

The continuing high level of seismic activity near the mouth of Icy Bay and the possibility that this activity represents the offshore continuation of an inferred thrust fault is an important concern to offshore petroleum development. Presently, no clear relationship exists between the sudden apparent cutoff of the seismic activity immediately southwest of Icy Bay and a northeast trending submarine fault to the southwest which does not extend as far north as the zone of seismic

1899-1900 GREAT EARTHQUAKES

	LAT N	LON W	M_S (20-SEC)	M_M (100-SEC)	M_0 (10^{28} dyne-cm)
04 SEPT 1899	60°	142°	8.5	8.3	1.8
10 SEPT 1899 (17:04)	60°	140°	(7.8)	–	–
10 SEPT 1899 (21:41)	60°	140°	8.4	8.2	1.5
09 OCT 1900	60°	142°	8.1	7.7	~0.5
[18 APRIL 1906 SAN FRANCISCO			8.3	7.6	0.4]

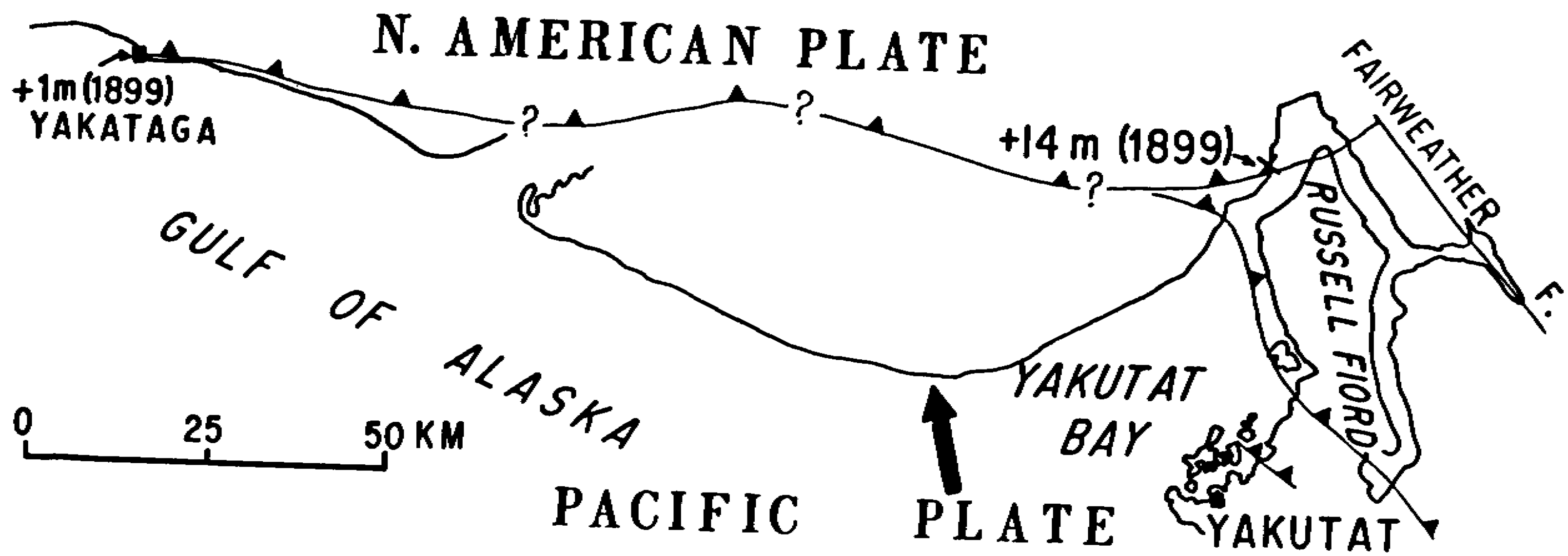


Figure 12. Summary of the magnitudes and moments of the 1899-1900 series of great earthquakes near Yakutat Bay. The 10 September, 1899 earthquake alone was large enough to account for the observed uplift of 14 meters at Yakutat Bay.

activity (T. Bruns, personal communication, 1977). Further work is necessary to investigate the seismicity of this region in more detail. A network of ocean bottom seismometers located in the area between Icy Bay and the Pamplona Ridge, similar to the one proposed for the 1977 field season, could contribute valuable data bearing on this problem. The network would aid in detecting much smaller magnitude earthquakes inthe offshore area, if they do occur, than is presently possible with solely land based stations, and would allow for more accurate location of the earthquakes that do occur in this area.

To date, little marine profiling has been done in Icy Bay. The bay may have been completely glaciated within the past 100 years, and thick deposits of glacial till will make it difficult to locate surface faults. This summer, P. Carlson and B. Molnia will be operating a mini-sparker from a 40' boat, and the data they collect may be able to establish whether there are any faults outcropping below Icy Bay.

A more detailed study of the earthquakes that have occurred along the eastern Gulf of Alaska is also necessary. This work includes relocations using a master event technique to search for possible fault-related structures in the hypocenters, and determination of focal mechanisms to aid in understanding the nature of faulting in the area. We also plan to develop a more accurate velocity model for the eastern Gulf of Alaska to help improve the quality of earthquake locations in this area.

X. Summary of fourth quarter operations

A. Field and Laboratory Activities

The operations during the fourth quarter were primarily centered around laboratory activities. The main efforts were concerned with improving the data reduction process, reorganizing the earthquake data base to facilitate in-depth studies of particular areas of interest, and developing more reliable components for field instruments. Each of these will be discussed below. In addition, limited station maintenance was conducted. A cooperative exchange with the Canadian government was also established wherein data from the Canadian seismic station WHC (Whitehorse) will be used to improve earthquake locations in the eastern Gulf of Alaska region.

1. Laboratory Activities

One of the most time-consuming steps in the routine processing of seismic data from the eastern Gulf of Alaska is manually scanning the films from the network. The same data is also recorded on magnetic tape at Palmer. A procedure is being developed to automatically scan the magnetic tapes for earthquakes with the aid of a minicomputer facility at the USGS/OES.

The algorithm used to scan the tapes yields approximate times of first arrivals, the number of stations recording the event, and approximate "size" indicators. The advantage of this method of processing the data is that up to 32 channels of information covering a 24-hour time period can be processed in about 3 hours, whereas the present method of manual scanning requires about 2-1/2 hours to scan a film with only 18 stations recorded. The particular algorithm currently used was developed for the California seismic network with relatively close spacing (about 10 km), and is not well "tuned" to the network in the eastern Gulf of Alaska where the stations are about 50 km apart. We are now running tests to improve the sensitivity of the processor to Alaskan data.

The USGS has recently installed a Honeywell Multics computing facility at the Menlo Park office. The interactive capability provided by this system will be a powerful tool to aid in the analysis and interpretation of seismic data. All of the seismic data from the Alaska network is now stored in the system, and we are in the process of developing programs to manipulate the data. These will include search and select programs, interactive locations, and graphical display.

A field test of the newly-designed seismic amplifier voltage-controlled oscillator (VCO) has been successfully completed. The instrument was operated alongside one of the standard VCO's in the USGS central California network, and its performance was very good. Some minor changes have been decided upon, and the final schematic drawings incorporating these changes are now being prepared. If everything goes as planned, we will have one or two prototype units installed in Alaska by this fall. If no problems arise during the winter we would then plan to replace all of the VCO's currently used in Alaska with the newly designed units in 1978.

2. Scientific Party

The Scientific Party included:

John Lahr, USGS, Project Scientist
Christopher Stephens, USGS, Geophysicist
Michael Blackford, USGS, Geophysicist (Mr. Blackford left the project in March, 1977)

The Technical and Field Party included:

Suzanne Conens, USGS, Physical Science Technician
John Rogers, USGS, Electronics Technician
Richard Brown, USGS, Technician
Tom Murray, USGS, Technician
Eric Fuglestad, Univ. Alaska, Geological Field Assistant.

3. Field Operations and Station Maintenance

Several of the stations in the network were visited during March 13-28. The actions taken at the various sites were as follows:

Palmer - automatic gain control devices were installed on all of the phone lines coming into the recording facility.

Cordova - a possible receiver site at the airport was investigated.

Boswell Bay - the receiving facilities at this site were closed down because no signals were being received.

Cape Yakataga - one battery and a preamplifier were replaced.

Yakutat - the power supply and one receiver were replaced, and all receivers were adjusted.

Moose Pass - a new amplifier-VCO unit was installed.

Portage - power supply was replaced.

Whittier - a dead receiver input was turned off, which had the effect of improving the signal received from Portage.

Seward - output was adjusted.

Diamond Ridge (Univ. of Alaska) RF transmitter was removed.

Nikishka - one battery was replaced.

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APPENDIX 1

THE 1899 YAKUTAT BAY, ALASKA EARTHQUAKES

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The following abstract was submitted for presentation at the IASPEI/IAVCEI Assembly, Durham, August 8-19, 1977.

A small number of early damped seismograms and vertical uplift data are used to constrain the fault slippage that occurred during the three magnitude 8+ earthquakes of 1899-1900. Magnitudes (M_S) of 8.5 (04 Sept.), 8.4 (21:41 GMT, 10 Sept.), and 8.1 (09 Oct. 1900) agree closely with those determined by Gutenberg from undamped Milne seismograms. Seismic moments determined from 50-sec. su·face wave amplitudes are 2×10^{28} dyne-cm for the two largest events, and a factor of 3 smaller for the third shock. Uplift determined from raised shorelines within Yakutat Bay can be accounted for by the 10 Sept. event alone, and these data can be fit by 10-20 m. of slippage on several local north and northeasterly dipping thrust faults. Faulting complexity is also shown by the S-wave seismogram of the 10 Sept. shock, which has a duration of 3 minutes and shows at least 3 distinct long-period pulses. The large seismic moment of the 04 Sept. event and uplift of 1 m. at Cape Yakataga (150 km west of Yakutat Bay) suggest a westward extension of faulting along the Chugash-St. Elias thrust zone. Estimates of the 1899 seismic slip across this zone depend upon its assumed width, but even taking an upper bound of 100 km gives 5 m. of plate convergence. Thus it seems likely that this seismic gap was in fact filled by the 1899 earthquakes.

APPENDIX II

SLIP RATES AND RECURRENCE TIMES FROM ANALYSIS OF MAJOR EARTHQUAKES ON PACIFIC-NORTH AMERICAN PLATE BOUNDARY IN WESTERN NORTH AMERICA

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The following is an abstract submitted for presentation at the 1977 Spring meeting of the AGU, May 30 - June 3 in Washington, D.C.

The southeast Alaska earthquake of July 10, 1958 (M =7.9) has been reanalyzed, mainly using seismograms from IGY stations. The mechanism of the earthquake is a right-lateral strike-slip fault with a strike N20 W. Using surface waves, a seismic moment of $4x10^{27}$ dyn. cm and an average dislocation of 4 m are obtained (fault area, 300x10 km). This seismic moment is almost the same as those of the 1857 Fort Tejon, the 1906 San Francisco, and possibly the 1949 Queen Charlotte earthquakes, all of which occurred on adjacent portions of the Pacific-North American plate boundary. If the remarkable damage marks dated 1853-1854 on trees in Lituya Bay are indeed due to a previous great 1958-type earthquake, an average slip rate along the plate boundary there amounts to 4 cm/yr. This is consistent with an estimation that the slip rate along the San Andreas fault is about half that estimated from oceanic magnetic anomalies in the northeast Pacific. Average recurrence intervals of 200 and 100 years are estimated for the 1857-1906 and the 1949-1958 segments, respectively. Therefore, the present may be a fairly dormant time in activity of large earthquakes along this plate boundary. Since evidence for strain accumulation associated with subduction of the Juan de Fuca plate in Washington and Oregon has not been found from geodetic and geomorphological data, this trench is probably currently inactive and large earthquakes are not anticipated there.

APPENDIX III

TECTONIC DEFORMATION IN NORTHERN PRINCE WILLIAM SOUND, ALASKA

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The following abstract was submitted for a talk presented at the 1976 Fall Annual Meeting of the American Geophysical Union, San Francisco.

Hypocentral data from the U.S. Geological Survey regional seismic network in south-central Alaska indicate the presence of a well-defined Benioff zone at depths of 50 to 175 km underlying the Cook Inlet-Aleutian Range area in the western part of the network. East of this area, beneath the Kenai Peninsula and Prince William Sound, the hypocenters suggest a complex zone of interaction between the American plate and the underthrusting Pacific plate. The uniform temporal and spatial characteristics of the seismic activity in the Benioff zone below 50 km depth grade into episodic activity beneath Prince William Sound. The data collected since 1972 in the Valdez region are of special interest owing to the location of the Alaska pipeline terminus nearby. Four earthquake sequences are examined in detail. Although fault plane solutions for these sequences are varied, the nodel axes for three of the four solutions are predominately oriented NE and have shallow dips. This is compatible with a zone of complex faulting controlled by regional stresses due to the underthrusting Pacific plate.

APPENDIX IV

Catalog of Earthquakes Located by the USGS
Regional Seismograph Network in the Eastern
Gulf of Alaska from January - September, 1976.

EASTERN GULF OF ALASKA EARTHQUAKES

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NP	NS	GAP DEG	D3 KM	RMS SEC	ERH KM	ERZ KM	Q
JAN	2	3	30	39.1	60	56.0	143	7.6	20.8	2.5	3	1	307	85	1.39	2.7	20.4	D
	4	18	25	34.3	61	.6	146	31.8	16.5	1.8	10	4	119	67	.52	3.4	2.5	B
	5	22	56	38.8	60	39.7	143	1.7	2.6	2.8	8	3	86	56	.76	1.2	2.9	B
	8	4	26	58.7	61	.6	146	34.9	15.0	2.2	14	7	91	30	.52	1.3	1.1	A
	8	10	27	8.7	60	44.9	147	19.0	15.2	2.4	15	5	134	57	.44	1.7	1.1	A
	9	19	42	13.4	60	37.5	147	55.3	14.0	2.5	18	6	155	66	.35	1.5	1.3	A
	14	5	43	48.5	60	43.9	144	22.9	12.6	2.5	16	4	66	78	.57	.8	1.3	A
	14	14	20	4.0	61	.9	147	4.3	25.0	2.2	14	7	83	42	.56	1.2	1.2	A
	14	19	51	7.1	60	13.8	145	3.3	7.2	3.3	21	2	115	67	.48	1.9	1.5	A
	15	0	0	9.3	60	8.9	145	2.8	8.3	2.2	4	3	233	121	.13	8.0	3.7	C
	15	6	27	41.6	61	.9	147	.6	25.0	1.9	12	7	113	39	.65	1.5	1.2	A
	15	12	5	12.0	60	36.5	147	6.3	15.0	2.4	18	4	139	65	.52	1.6	1.3	A
	17	14	20	23.2	60	59.5	146	40.2	15.1	2.0	11	4	92	30	.41	1.6	1.6	A
	17	22	51	18.0	61	29.8	146	38.4	17.7	2.5	13	5	72	71	.35	1.1	1.3	A
	19	22	52	49.5	61	23.5	145	28.2	16.0	2.9	15	4	112	89	.39	1.2	1.9	A
	20	15	40	23.1	60	8.4	141	21.5	.4	3.6	11	2	210	114	.73	4.2	3.4	B
	22	4	42	39.9	60	26.3	147	46.7	14.8	3.2	20	4	171	83	.42	1.6	2.1	A
	26	23	34	15.1	60	44.3	143	21.9	4.0	2.1	11	3	106	82	.53	2.8	6.1	C
	27	21	6	5.1	60	30.7	143	6.4	6.2	2.2	5	2	182	79	.22	2.1	7.0	C
	28	0	27	6.2	60	46.7	146	56.9	14.7	1.9	10	4	145	46	.38	1.8	1.0	A
	29	1	36	3.3	61	1.2	147	11.5	15.0	2.4	15	4	80	48	.48	1.3	1.2	A
	29	8	18	53.3	60	50.2	147	4.4	20.3	3.2	16	3	124	48	.36	1.4	1.9	A
FEB	1	22	29	57.9	61	31.2	146	26.1	18.1	2.5	11	4	82	67	.43	1.1	1.3	A
	7	13	58	1.3	59	41.4	139	35.2	15.0	2.2	4	1	169	214	.34	88.8	34.0	D
	9	6	7	22.3	61	21.7	146	51.1	18.4	2.5	13	5	63	58	.31	1.0	1.5	A
	10	7	37	11.7	60	6.4	141	15.7	15.0	3.9	14	1	148	153	.65	5.3	4.8	C
	10	8	36	31.0	60	35.7	140	19.4	2.4	2.9	3	2	211	211	.10	19.2	3.6	D
	10	9	0	44.5	60	37.3	140	17.5	3.0	2.4	3	2	213	211	.12	16.1	3.7	D
	10	16	53	58.0	60	44.3	147	15.2	15.0	2.3	14	6	135	85	.46	1.4	1.5	A
	10	17	28	10.1	60	59.9	147	16.7	20.8	1.9	9	4	107	78	.35	1.6	2.0	A
	10	23	1	22.3	60	30.2	140	29.7	4.9	3.2	4	2	202	148	.18	11.6	4.3	D
	11	1	44	39.8	60	9.9	141	18.9	3.8	3.0	5	3	192	158	.82	3.7	2.2	B
	11	5	20	38.6	61	9.4	147	16.5	12.4	2.0	9	6	82	69	.55	1.2	1.6	A
	12	18	41	25.0	60	34.2	143	59.7	.4	2.8	11	3	155	98	.51	1.8	2.4	A
	12	20	21	36.4	61	1.0	146	39.6	13.1	2.3	11	5	101	72	.58	1.4	1.2	A
	12	23	13	57.2	61	2.0	147	.7	25.0	2.3	9	6	86	88	.60	1.3	1.4	A
	14	5	16	42.2	60	35.2	141	44.6	11.3	2.5	4	2	174	147	.21	18.6	5.8	D
	14	16	14	17.4	60	.9	140	44.8	20.8	2.6	5	1	184	144	.52	7.4	5.8	C
	14	16	16	7.3	60	19.8	140	5.1	9.2	2.5	4	4	203	146	.72	4.4	3.7	B
	15	21	16	3.6	59	48.2	138	33.1	15.6	3.4	4	0	262	250	.13	67.8	72.3	D
	16	10	52	13.5	61	37.2	146	17.2	25.0	2.5	11	3	92	64	.39	1.2	1.9	A
	16	21	10	20.2	61	18.8	147	5.9	21.8	2.3	15	6	56	59	.34	1.1	1.8	A
	19	21	43	27.4	61	20.7	147	12.1	16.6	2.4	12	5	59	59	.31	.9	1.1	A
	20	5	26	7.5	60	56.8	146	41.9	20.8	2.3	12	6	107	29	.57	1.3	1.3	A
	22	0	19	49.3	60	31.4	147	39.9	10.7	2.9	15	5	156	83	.44	1.3	1.2	A

EASTERN GULF OF ALASKA EARTHQUAKES (CONTINUED)

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NP	NS	GAP DEG	D3 KM	RMS SEC	ERH KM	ERZ KM	Q
FEB	22	8	0	8.6	60	32.8	147	38.9	16.2	2.3	12	7	154	83	.34	1.4	1.6	A
	22	16	4	54.9	60	3.5	141	16.8	.0	3.0	3	1	202	207	.24	14.2	7.5	D
	22	18	31	19.3	61	23.5	147	22.5	14.1	2.2	12	5	86	69	.40	1.1	1.2	A
	22	22	43	37.7	59	29.7	147	54.2	19.4	3.6	14	3	213	137	.51	6.0	8.0	C
	25	9	22	40.7	60	2.4	141	24.6	23.3	2.5	5	2	205	157	.34	10.1	6.0	D
	29	13	15	58.5	61	35.7	146	21.1	25.0	3.1	15	5	88	61	.56	1.1	1.8	A
	29	17	37	58.2	60	25.9	139	44.5	15.0	3.0	4	2	260	248	1.05	57.3	60.7	D
MAR	1	14	38	11.8	60	37.1	147	36.3	11.9	2.1	11	5	146	82	.39	2.3	2.3	A
	2	20	36	27.5	60	25.0	147	20.2	15.0	2.6	15	5	100	90	.46	1.7	1.7	A
	3	18	39	4.1	60	46.2	140	12.5	2.3	2.4	3	2	222	208	1.43	15.1	4.0	D
	6	4	59	44.9	57	48.3	139	30.3	9.2	3.6	3	1	325	398	.06	99.0	99.0	D
	6	18	33	55.4	60	57.8	146	46.7	25.0	2.4	13	5	107	73	.60	1.4	1.3	A
	9	13	16	3.7	61	1.2	146	31.7	12.9	2.6	13	8	97	68	.80	1.4	1.2	A
	9	13	26	57.3	61	22.6	146	46.4	16.5	1.8	12	7	117	59	.41	1.1	1.2	A
	11	6	8	54.8	60	58.5	145	55.2	20.8	1.9	10	6	94	80	.60	1.5	1.4	A
	13	1	0	41.0	61	13.3	145	57.7	6.3	2.6	13	8	125	100	.34	1.3	1.4	A
	14	5	56	35.2	61	23.3	147	1.2	15.7	2.1	11	8	106	56	.44	1.2	1.3	A
	15	5	26	27.9	61	24.0	141	15.4	16.0	2.7	3	1	180	137	.12	17.4	9.5	D
	15	21	41	.6	61	9.7	147	19.9	4.8	1.7	8	7	81	66	.50	.9	1.8	A
	16	1	26	22.6	60	39.0	147	19.7	15.0	1.7	10	8	145	87	.58	1.5	1.6	A
	18	16	47	40.1	61	23.1	147	17.2	25.0	2.1	10	6	91	59	.40	1.2	1.9	A
	19	0	24	17.3	60	59.6	147	32.5	3.3	2.0	12	5	112	67	.56	1.0	2.8	B
	19	3	2	40.5	61	18.6	146	50.4	17.0	2.6	10	4	121	48	.23	1.9	2.1	A
	19	5	37	42.5	61	2.5	146	45.6	15.0	1.7	13	9	90	25	.57	1.2	1.2	A
	20	0	29	30.5	61	14.4	146	58.3	10.9	1.8	12	8	98	69	.52	1.0	1.3	A
	20	16	55	25.5	60	24.3	140	1.0	9.2	3.0	3	2	247	236	.56	67.8	72.6	D
	21	1	56	31.5	60	1.8	139	23.1	15.0	3.2	4	0	211	198	.13	69.4	70.7	D
	23	9	13	23.4	61	11.1	147	17.5	.9	1.8	12	9	83	67	.45	.9	1.9	A
	26	3	46	21.4	60	38.1	142	50.7	15.4	2.4	3	3	217	155	.13	3.7	3.5	B
	27	0	58	41.0	61	38.3	144	57.2	22.8	2.6	11	8	161	83	.45	1.8	2.6	B
	29	20	6	17.0	60	2.1	146	58.2	24.9	3.5	12	5	207	138	.55	3.7	8.6	C
	29	20	36	46.7	60	3.3	146	58.0	15.7	3.1	18	4	203	138	.42	3.4	5.7	C

EASTERN GULF OF ALASKA EARTHQUAKES

1976	ORIGIN HR MN	TIME SEC	LAT N DEG MIN	LONG W DEG MIN	DEPTH KM	MAG	NP	NS	GAP DEG	D3 KM	RMS SEC	ERH KM	ERZ KM	Q
APR 2	20 51	55.0	61 18.2	146 47.2	15.3	3.0	20	8	81	95	.35	1.3	2.1	A
9	23 48	47.6	60 21.4	139 47.4	19.8	2.8	5	3	258	159	.69	7.2	2.4	C
12	14 29	1.3	60 20.4	141 4.1	15.0	2.1	4	0	168	104	.34	91.0	39.3	D
15	14 49	12.6	60 30.3	142 46.9	15.0	1.8	4	2	250	163	.51	70.5	69.5	D
20	13 39	31.0	61 34.1	146 29.5	25.0	3.1	13	6	80	53	.57	1.1	1.7	A
20	14 27	19.7	60 19.5	140 27.8	15.0	4.3	12	1	211	113	.57	2.0	3.4	B
20	14 38	37.8	60 23.6	140 9.9	14.7	3.3	9	3	229	139	.62	9.7	2.8	C
20	14 51	11.8	60 33.9	139 21.7	15.0	3.2	6	3	274	260	.66	63.0	61.2	D
22	17 23	24.1	60 47.6	143 2.0	10.4	3.1	10	2	134	84	1.03	4.4	5.1	C
24	16 46	45.9	60 54.7	140 39.9	3.8	2.9	10	3	234	159	1.57	15.5	3.4	D
27	4 27	8.4	58 41.3	138 25.6	20.8	3.4	3	2	355	429	.37	99.0	85.1	D
29	5 30	21.6	60 17.3	139 27.1	15.0	2.8	4	3	275	269	.53	70.0	70.1	D
MAY 2	14 27	50.3	60 24.7	145 28.1	22.7	2.1	3	3	246	146	.34	11.8	12.0	D
11	16 46	17.0	61 27.4	146 50.8	25.0	4.1	21	4	81	81	.53	1.4	2.2	A
15	17 39	47.8	61 36.8	146 33.4	19.1	3.6	17	2	147	58	.38	1.4	2.0	A
20	6 7	39.4	61 46.1	146 57.9	25.0	3.5	17	6	118	72	.74	1.4	1.7	A
23	17 30	10.0	61 17.8	146 54.5	25.0	3.5	19	4	83	84	.37	1.2	1.7	A
24	4 3	22.6	60 51.2	147 30.7	12.8	2.3	13	8	122	80	.43	1.1	1.4	A
25	10 28	49.1	61 2.1	147 10.1	16.8	2.3	17	12	105	89	.39	1.0	1.6	A
26	12 46	23.5	61 31.1	146 32.3	17.1	2.3	16	15	77	55	.50	.9	.9	A
26	16 24	8.8	60 50.9	146 59.9	15.8	2.3	17	11	122	76	.46	1.1	1.3	A
28	9 36	1.6	61 25.5	146 44.8	20.0	2.3	17	11	74	82	.47	1.0	2.0	A
29	5 7	36.3	61 4.9	146 27.5	19.7	2.5	14	8	89	96	.62	1.4	.9	A
29	5 21	9.0	61 3.1	146 31.3	16.6	2.1	12	9	105	97	.56	1.2	1.0	A
29	13 8	29.9	60 49.1	147 6.9	9.7	2.3	12	9	126	98	.30	1.2	1.3	A
30	2 1	11.5	60 59.6	147 17.7	17.2	2.7	20	6	109	94	.34	1.1	1.7	A
31	18 32	56.8	60 26.0	144 44.1	3.3	2.6	9	8	247	117	.48	2.5	1.4	B
JUN 1	14 7	26.2	61 18.0	146 47.5	19.7	2.4	13	6	81	66	.38	1.1	1.4	A
1	19 29	10.7	59 30.3	138 7.7	10.2	2.5	3	2	335	136	.24	13.4	4.0	D
6	22 1	27.6	62 19.5	147 19.8	25.0	3.7	26	4	82	78	.52	1.6	2.1	A
8	17 50	50.5	60 3.3	147 57.2	7.4	3.7	21	8	141	108	.39	1.4	1.5	A
21	23 30	28.6	60 28.0	145 1.1	14.9	2.6	11	7	113	91	.50	1.8	1.6	A
25	23 45	16.8	60 14.7	140 59.6	4.6	2.3	9	4	161	44	.36	2.1	3.1	B
28	10 5	47.2	60 38.2	141 15.4	17.8	1.7	5	3	269	82	.25	5.3	4.8	C
29	0 5	27.6	60 10.3	140 55.7	2.1	2.8	7	3	157	63	.35	2.0	2.5	B
29	11 20	42.2	60 43.5	142 55.5	.0	2.2	5	3	146	93	.24	4.7	2.5	B
29	16 38	51.3	60 17.2	140 54.1	15.0	1.8	5	3	197	47	.17	3.1	2.7	B
29	21 27	39.6	59 58.8	143 2.2	16.6	2.2	7	5	163	84	.44	2.7	1.7	B

EASTERN GULF OF ALASKA EARTHQUAKES

1976		ORIGIN HR	MN	TIME SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NP	NS	GAP DEG	D3 KM	RMS SEC	ERH KM	ERZ KM	Q
JUL	2	8	11	31.5	60	19.8	139	57.2	3.5	1.7	4	2	271	64	.83	7.4	44.6	D
	2	16	28	37.5	60	36.5	141	9.0	11.6	3.4	12	1	188	75	.31	3.6	2.8	B
	2	21	26	39.8	60	35.6	141	9.5	11.6	2.6	8	6	187	75	.36	2.4	2.1	A
	6	1	19	12.5	59	59.5	139	22.0	10.0	1.0	4	4	317	51	.57	3.0	3.4	B
	7	7	33	45.0	60	32.6	141	7.9	1.1	1.5	4	4	191	69	.24	3.0	5.8	C
	7	16	4	30.0	60	35.6	147	37.7	13.1	3.3	20	8	89	82	.64	1.4	1.3	A
	8	3	59	47.2	60	27.8	140	51.6	.2	3.5	7	4	185	97	.28	4.2	4.2	B
	10	5	10	55.8	60	13.6	140	34.3	13.8	1.5	4	2	206	57	.48	6.1	8.4	C
	11	7	23	44.0	60	38.2	142	38.3	5.1	2.0	4	4	198	110	.08	13.4	3.8	D
	14	17	55	33.1	61	39.0	146	25.4	20.0	3.7	17	0	85	58	.58	1.5	8.0	C
	15	1	42	42.7	59	42.9	139	7.6	8.9	2.1	5	4	322	76	.65	4.0	2.3	B
	17	13	20	35.7	60	10.9	141	11.1	14.4	1.4	3	3	157	53	.40	6.5	9.7	C
	17	14	42	37.0	60	10.9	140	45.6	7.7	2.0	5	2	178	58	.24	2.6	11.1	D
	18	12	54	43.5	60	13.7	140	47.3	6.6	1.9	6	4	166	55	.24	2.5	6.5	C
	19	9	43	8.9	60	45.0	146	40.4	19.3	3.3	14	2	103	121	.24	1.9	2.2	A
	19	10	43	47.1	60	1.2	141	21.9	14.7	2.2	9	4	152	62	.36	2.6	1.6	B
	19	11	13	53.0	60	1.5	141	21.4	13.9	2.8	9	4	151	62	.38	2.3	1.5	A
	19	12	23	41.0	59	57.4	141	22.9	9.2	1.8	7	4	159	65	.45	3.4	2.9	B
	21	3	15	42.8	60	12.4	140	50.6	24.7	1.5	4	2	181	53	.25	6.4	5.4	C
	22	2	59	48.8	60	8.6	139	38.0	9.8	1.2	4	3	273	51	.27	3.1	8.8	C
	24	0	12	4.7	59	59.3	140	38.5	15.0	2.4	7	5	134	57	.83	2.3	2.2	A
	24	7	23	36.2	60	12.7	139	56.1	9.9	1.2	3	2	253	68	.49	13.2	16.3	D
	25	18	10	25.5	60	7.2	140	29.7	11.5	1.3	5	3	169	44	.21	3.7	5.5	C
	25	20	4	16.6	59	23.2	137	37.0	10.0	2.9	4	4	347	211	.51	41.4	44.8	D
	25	22	37	45.0	60	13.8	141	7.9	20.0	1.7	4	4	154	51	.52	14.2	7.9	D
	26	19	45	1.4	60	9.6	140	48.2	30.7	1.2	3	3	169	57	.11	6.0	6.6	C
	27	7	39	16.7	60	50.2	140	10.7	15.0	1.9	3	2	312	104	.28	51.5	84.6	D
	30	13	54	32.2	61	19.8	147	17.9	18.0	3.8	22	0	55	63	.29	1.4	2.3	A
	31	7	17	29.0	60	12.1	140	41.7	15.0	1.0	4	2	238	58	.07	5.0	5.2	C
	31	10	27	60.0	59	56.9	139	18.1	10.0	1.4	4	3	319	56	.69	5.8	4.3	C
	31	20	55	25.3	57	47.9	137	7.5	68.4	4.4	2	1	352	100	0.00	99.0	98.5	D
AUG	3	2	17	24.9	60	14.9	139	32.5	5.0	1.8	4	2	270	64	.26	5.9	27.3	D
	4	17	27	27.1	60	3.6	141	33.0	52.5	2.3	5	5	150	85	.64	5.8	8.1	C
	4	23	4	9.5	59	26.1	139	28.4	20.8	2.2	4	3	315	86	.37	5.5	4.6	C
	5	21	14	16.5	61	28.4	140	44.3	9.2	2.8	6	4	251	158	.79	9.2	12.0	D
	5	22	2	1.2	61	28.6	140	30.8	9.2	2.2	5	3	266	161	1.05	9.4	9.8	C
	6	8	7	6.6	60	14.5	141	4.4	15.0	1.9	5	4	160	74	.42	7.2	5.0	C
	7	0	50	43.1	60	9.2	139	41.5	8.1	1.0	3	1	271	50	0.00	6.1	11.5	D
	7	1	43	32.6	60	3.9	141	20.4	8.6	2.0	6	2	202	60	.48	4.5	3.0	B
	10	2	48	22.5	60	7.5	139	44.3	1.5	1.3	5	4	239	46	.24	3.1	50.9	D
	11	21	54	16.4	60	14.7	139	36.0	3.0	1.5	4	1	265	62	.28	9.2	75.8	D
	14	5	35	59.5	61	22.3	147	32.3	19.7	3.6	19	4	84	70	.48	1.5	6.2	C
	15	22	8	24.0	60	26.9	141	.8	9.6	1.5	4	3	181	57	.14	3.9	21.2	D
	18	5	14	36.3	60	12.1	141	25.9	17.2	1.4	5	3	185	66	.31	3.2	1.7	B
	20	10	21	20.4	61	11.8	140	26.1	9.2	3.0	7	3	246	123	1.12	2.7	2.8	B

EASTERN GULF OF ALASKA EARTHQUAKES (CONTINUED)

1976	ORIGIN HR	TIME MN	SEC	LAT N DEG MIN	LONG W DEG MIN	DEPTH KM	MAG	NP	NS	GAP DEG	D3 KM	RMS SEC	EPH KM	ERZ KM	Q
AUG 20	15	7	43.4	60 28.0	141 30.8	14.6	1.7	4	2	253	81	.20	4.0	4.7	B
21	5	5	14.8	60 44.3	141 35.9	12.3	2.1	8	4	185	79	.50	3.6	3.0	B
24	9	47	48.8	60 10.2	140 27.4	24.0	1.0	3	3	234	48	.16	5.6	4.4	C
25	14	13	48.6	60 6.7	141 31.6	14.1	1.5	5	2	220	71	.10	6.7	4.6	C
26	4	44	16.2	60 43.5	143 18.7	15.0	2.4	5	2	140	141	.41	7.8	9.2	C
26	6	43	54.3	61 25.4	140 12.5	15.0	2.2	2	2	279	168	.11	71.4	69.0	D
27	8	40	45.4	60 30.1	143 6.1	9.2	1.9	8	5	130	72	.90	2.0	2.3	A
28	9	41	2.8	60 25.0	141 10.1	15.0	1.7	3	3	226	62	.16	4.0	11.7	D
30	21	59	1.4	60 36.3	141 31.5	10.8	2.1	7	6	196	77	.33	3.8	3.4	B
31	18	22	44.9	60 7.7	141 11.5	15.0	2.8	6	3	143	52	.79	2.4	1.7	A
31	21	36	32.8	60 40.9	141 43.8	15.9	1.3	5	3	304	104	.52	5.5	3.8	C
SEP 1	1	9	46.0	60 6.8	141 12.4	2.3	1.8	5	3	176	53	.41	4.6	12.5	D
1	1	30	23.4	60 4.2	141 15.1	.4	1.5	5	1	201	55	.36	11.4	55.0	D
1	2	32	24.5	59 22.4	139 33.0	20.8	2.4	5	4	315	90	.40	4.2	4.0	B
1	2	36	8.5	60 1.1	141 21.4	15.0	1.9	4	3	218	73	.47	4.4	4.2	B
1	2	36	57.7	59 57.2	141 20.6	11.8	1.5	3	1	259	63	.38	14.6	14.3	D
1	3	24	5.1	60 5.1	141 14.9	1.2	1.7	5	3	198	55	.39	5.6	17.2	D
2	1	48	52.6	59 44.5	139 35.1	12.9	2.2	6	4	279	55	.39	3.9	1.5	B
3	12	43	58.1	60 58.5	146 47.6	19.9	3.0	24	6	39	29	.53	.9	.9	A
6	22	12	34.5	60 43.0	142 59.6	9.2	2.2	15	6	106	79	.67	1.2	1.8	A
7	10	16	14.2	60 3.6	139 28.0	9.2	2.5	9	3	230	44	.39	5.4	3.9	C
9	23	5	25.6	60 7.2	141 13.7	17.9	1.0	5	4	148	39	.17	3.0	1.4	B
10	10	1	13.1	60 .1	141 39.2	14.4	1.8	9	5	168	41	.54	1.8	1.3	A
10	23	42	55.4	60 1.4	141 15.3	15.0	2.1	10	4	100	18	.75	1.7	1.3	A
11	13	43	14.0	60 2.9	140 40.4	10.0	2.1	8	5	117	36	.52	1.6	3.7	B
11	13	47	10.3	60 .2	140 43.1	10.0	1.7	7	3	123	32	.51	2.3	5.4	C
12	4	6	41.4	60 36.6	142 36.4	10.8	2.7	15	11	103	61	.63	1.6	1.5	A
12	12	47	21.0	60 34.9	139 43.2	20.0	2.6	7	6	240	96	.84	2.7	4.5	B
14	3	44	24.0	61 33.7	141 30.7	.7	2.8	8	4	233	134	.50	3.3	4.1	B
15	9	0	40.5	60 9.6	140 28.0	15.8	1.7	6	2	193	48	.68	5.1	3.1	C
16	14	11	15.1	60 19.9	140 47.3	23.5	2.3	7	5	179	43	.54	2.7	2.7	B
20	10	50	27.1	60 18.0	140 47.9	14.4	2.4	9	4	173	41	.48	2.1	1.7	A
20	13	20	33.6	60 .9	141 10.4	14.4	1.3	6	5	200	50	.21	3.6	1.8	B
20	23	17	39.5	59 48.1	141 4.1	15.0	2.2	4	2	231	56	.40	6.8	8.5	C
21	3	40	41.9	59 22.2	144 49.5	12.0	3.4	17	9	219	141	.37	4.2	2.2	B
21	6	28	49.3	60 12.2	141 37.7	15.0	2.2	3	3	222	138	.12	7.5	2.5	C
22	12	43	11.5	60 3.4	145 2.8	14.3	2.3	4	3	254	114	.10	5.7	2.5	C
23	19	31	10.5	59 54.5	140 36.7	15.0	1.4	5	3	177	33	.47	3.6	9.7	C
26	23	30	42.2	60 42.1	143 32.0	.2	1.9	11	5	92	105	.22	1.3	2.4	A
27	5	59	47.6	60 32.6	145 11.7	27.2	3.8	25	3	54	84	.92	1.4	1.9	A
27	23	38	36.8	59 57.7	141 43.2	15.0	1.5	7	4	235	36	.56	2.7	1.9	B
28	8	26	33.8	60 52.8	142 43.5	30.0	2.2	5	1	208	86	.60	27.8	27.8	D
28	9	2	37.5	59 27.6	144 11.2	19.7	3.2	8	4	274	195	.18	8.7	6.8	C
28	9	17	24.4	59 13.5	144 37.7	22.0	3.2	9	9	279	230	.77	32.6	49.4	D
28	14	52	34.3	59 20.5	144 49.3	13.6	3.4	19	6	216	158	.49	4.9	2.4	B

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FAULTING, INSTABILITY, EROSION, AND DEPOSITION OF SHELF SEDIMENTS, EASTERN GULF OF ALASKA

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I. Summary of objectives, conclusions and implications with respect to OCS oil and gas development.

FY 1977, we proposed to study in detail those areas and processes identified from FY 75-76 information to be of significant environmental concern to resource development, such as areas of rapid accumulation of unconsolidated sediment off the Copper River and Bering and Malaspina Glaciers, and areas of intense erosional activity on Tarr Bank, Kayak Platform, Middleton Island, Fairweather Ground and nearshore zones near Cape Yakataga and Malaspina Glacier. Areas of submarine sliding, erosion, and faulting that were studied in detail include the Copper River pro-delta, the Bering Trough, the Malaspina inner shelf, Icy Bay, Glacier Bay National Monument, and the shelf break off Kayak Island.

Our objectives in FY 1977 were to determine as precisely as possible the length, orientation, and displacement of shallow faults; the geometry and boundaries of major slumps; and the areas of present-day sediment erosion, deposition, and bypassing. The various sedimentary, structural and physiographic provinces will be characterized. In addition, elements of the Quaternary geologic history of the EGOA-OCS were reconstructed to more fully understand today's geologic setting.

The northeastern Gulf of Alaska is a region of active seismicity, intense storms, and rapid sediment accumulation. Therefore, instability of the sea floor is a serious hazard to development on the outer continental shelf (OCS).

Evidence of faulting at or near the sea floor has been found on Tarr Bank, around Middleton and Kayak Islands near structural highs south of Cape Yakataga, and adjacent to Pamplona Ridge. Along several faults, the sea floor was offset from 5 to 20 m. The relatively short lengths of the faults compared to amounts of displacement suggest episodic movement. Very few of these faults appear to cut thick Holocene sediments, but many reach the surface in areas where the Holocene sediment is lacking or extremely thin.

Seaward of the Copper River prodelta and Malaspina Glacier are areas that contain disrupted bedding and irregular topography commonly associated with submarine slides or slumps. The areas comprise 1700 and 1100 km^2 respectively of thick (> 150 m) Holocene sediments on slopes of about $1/2^o$. Additional areas of hummocky topography that suggest submarine sliding are present at the edge of the shelf and upper slope.

Other parts of the OCS that have thick accumulations of under-consolidated sediments (clayey silt and interbedded mud and sand: peak-vane shear strengths 0.01-0.09 kg/sq cm) and slopes steeper than 1^{o} are potentially hazardous: they are susceptible to ground failure when large earthquakes provide rapid ground acceleration or tsunami or storm waves disrupt the sea floor.

Four major sedimentary units occur on the sea floor of the continental shelf in the northern Gulf of Alaska. These units, defined on the basis of seismic and sedimentologic data, are: (1) Holocene sediments, (2) Holocene end moraines, (3) Quarternary glacial marine sediments, and (4) Tertiary and Pleistocene lithified deposits.

A wedge of Holocene fine sand to clayey silt covers most of the inner shelf, reaching maximum thicknesses of about 350 m seaward of the Copper River and about 200 m seaward of Icy Bay. Holocene end moraines are found at the mouth of Icy Bay, south of Bering Glacier, and at the mouth of Yakutat Bay. Quaternary glacial marine sediments are found in a narrow arc that borders on the north and west side of Tarr Bank and in a large arc 20 km or more offshore that parallels the shoreline between Kayak Island and Yakutat Bay. Tertiary or Pleistocene stratified sedimentary rocks, which in profile commonly are folded, faulted, and truncated, crop out on Tarr Bank, offshore of Montague Island, and in several localities southeast and southwest of Cape Yakataga. The lack of Holocene cover on Tarr Bank and Middleton, Kayak and Montague Island platforms may be due to the scouring action of swift bottom currents and large storm waves.

West of Kayak Island the Copper River is the primary source of Holocene sediment. East of Kayak Island the major sediment sources are streams draining the larger ice fields, notably the Malaspina and Bering Glaciers. Transport of bottom and suspended sediment is predominantly to the west.

If deglaciation of the shelf was completed by 10,000 years B. P., maximum rates of accumulation of Holocene sediment on the inner shelf may be as high as 10-35 m per 1000 years.

II. Introduction

A. This program is attempting to unravel the confused geologic history of the Eastern Gulf of Alaska OCS so that a clear understanding of normal and catastrophic processes can be obtained to aid in decision making related to safe OCS petroleum development.

B. The specific objectives of this project are three-fold. They are: (1) to determine the types and characteristics of bottom sediments; (2) to determine the types and extent of natural seafloor stability, and (3) to determine and map the distribution, mode of faulting, age of most recent movement, and magnitude of offset for major faults.

C. Relevance to problems of petroleum development.

The continental shelf of the eastern Gulf of Alaska is a very dynamic environment. Rivers and streams carry vast quantities of glacial silt and clay to this shelf, which is affected by strong, longshore currents, frequent periods of high energy storm waves, and occasional seismic sea waves (tsunamis). The stability and maintenance of drilling rigs, production platforms, pipelines, and shoreline based facilities are all affected by the erosional and depositional hazards of this high energy shelf.

Major earthquakes will occur that may damage installations on the shelf or along the coast. Hazards include ground shaking, fault displacement, and tectonic warping, and ground failure. Numerous onshore faults (several of which have been active in the past century) have been mapped to the shoreline of the Gulf of Alaska. It is not known now if these faults continue across the shelf. It is, therefore, imperative that offshore faults be mapped and a determination made regarding magnitude and age of offset. A related hazard is that of ground failure, such as submarine slumps or slides. The thick sequences of unconsolidated sediment which are being deposited off rivers (e.g., Copper River) and streams draining this glaciated region are susceptible to failure caused by earthquakes or by agitation related to storm waves, seismic sea waves (tsunamis), and internal waves. Ground failure can also result if these water saturated sediments are overloaded by continuing deposition or by improperly designed and overloaded man-made structures. In order to make environmentally safe decisions, knowledge is therefore needed about the distribution, thickness, and type of these unconsolidated sediments.

III. Current state of knowledge.

This is the third year that the U.S.G.S. has worked on the environmental hazards and geologic history of the Eastern Gulf of Alaska OCS. Prior to FY 75, the quantity of available knowledge was very limited (see Wright, 1972).

Preliminary work in FY 75-76 was designed to gather reconnaissance level information about the regional environmental geology of the EGOA, identifying general areas of active surface faulting, slope instability, and sediment erosion and deposition, as well as to classify the surface and near-surface sediment types. Attention was focused on OCS Lease Area No. 39. They have been reported on in detail in previous quarterly and year-end reports and in many scientific publications. (See Section XI - Bibliography for a complete listing.).

IV. Study Area.

The primary region examined in this study lies in the Gulf of Alaska, between the southern tip of Montague Island and the eastern entrance of Yakutat Bay (fig. 1). Data have also been collected from areas between Yakutat and Cape Spencer. Areas where concentrated efforts have taken place are Tarr Bank, Kayak Trough, Bering Trough, Pamplona Ridge, Seaward of Malaspina Glacier, Icy Bay, the Delta of the Copper River and the Gulf of Alaska shoreline in Glacier Bay National Monument.

V. Sources, methods and rationale of data collection.

All bottom sediment samples were collected by U.S.G.S. Suspended sediment samples were collected by Dick Feely of PMEL and furnished to U.S.G.S. for analysis. Air photographs used in shoreline erosion studies were obtained from U.S.G.S. Sioux Falls Data Center, NOAA, or from commercial suppliers. Funds for these were not included in the project budget.

State of the art high-resolution geophysical equipment (160 Kj sparker, uniboom, mini-sparker, 3.5 Khz, side-scan sonar), bottom samplers (piston corer, box corer, gravity corer, grab, dart corer), visual format instrumentation (underwater TV and still photography), and navigation (Sat. Nav) Miniranger and Loran A were used for our marine programs.

VI. Results and VII Discussion.

Two cruises to the north-eastern Gulf of Alaska, the R/V ACONA (4/76) and the R/V SEA SOUNDER (6/76) (fig. 2) have added 3,000 km of seismic lines, 144 bottom samples, and 25 seafloor television and bottom camera stations to our data base. These data and data collected the previous 1 1/2 years, have allowed us to make numerous observations about the seafloor environmental hazards in OCS lease area 39 and the adjacent shelf, both west and east.

The entire area has a high incidence of seismicity, which causes significant marine environmental hazards including: (1) surface and near-surface faulting; (2) tectonic uplift and subsidence; (3) generation of tsunamis; and (4) slumping and the potential for mobilization of thick unstable sedimentary deposits. Additional marine geologic hazards are: (5) rapid marine sedimentation; (6) thick unstable Holocene sediment, which makes man-made structure siting difficult; (7) gas charged sediment; (8) submarine moraines blocking bay mouths; (9) high rates of beach erosion and deposition; and (10) icebergs and potential for offshore buried ice. Many onshore geologic hazards that also have been investigated are related to Pleistocene and Holocene glaciations of the onshore area and the adjacent continental shelf.

Faults

The general trend of the near-surface faults in the study area is northeast-southwest to east-west (fig. 3), subparallel to major onshore structures (Plafker, 1967). These near-surface faults probably are related to the development of the deeper structures on the continental margin as shown by Bruns and Plafker (1975) and generalized by Plafker and others (1976).

In most cases, the near-surface faults cut strata which are probably of Tertiary age (fig. 4). Commonly these Tertiary strata are covered only by a thin veneer of Holocene sediment (fig. 5) and in many places crop out at the seafloor (fig. 4). A few of the faults appear to cut Holocene sediments (fig. 6), but none were found that unequivocally offset Holocene sediment at the seafloor.

The most prominent clearly fault-associated scarp is located on Tarr Bank and has a relief of about 20 m (fig. 4). This fault, which is upthrown on the north side, also has been recorded on 3 other high resolution seismic profiles (offsets of seafloor vary from 5-10 m) and appears to be 18 km long. Bonilla and Buchanan (1970) have plotted lengths of historic surface faults (from all parts of the world) versus surface displacements and their graph suggests that a fault with 20 m of displacement should be nearly 600 km long in order for that amount of displacement to have occurred as a single event. Five meters of displacement requires a fault length of over 100 km. Conversely, the amount of displacement expected along a 20 km fault is less than 1 m. It appears, therefore, that episodic movement is required to account for the 5-20 m of displacement. The fault illustrated in figure 4 is associated with several other faults branching from the Wessels Reef complex on Tarr Bank (fig. 3), extending the overall length to 35 km (maximum single event displacement $\sim$1.5 m). Three seismic events (all less than magnitude 4 earthquakes) recorded in the period September 1974 - May 1975, whose epicenters were plotted in the vicinity of the Wessels Reef fault complex, (John Lahr and Robert Page, oral commun., 1976) emphasize the currently active nature of these faults. These faults offset the seafloor, which appears to be folded truncated Tertiary rock. Samples collected from Wessels Reef in June 1975 (friable sandstone and granule conglomerate) are similar to rocks assigned by Plafker (1974) to Katalla-Poul Creek Formations (Gary Winkler, oral commun., 1975).

A series of east-west-trending faults of varying lengths cut the folded truncated Tertiary strata (probably Yakataga) west of Middleton Island (fig. 3). The southernmost of these faults is more than 30 km long, identified on six separate seismic profiles. The relative movement along these faults appears to be north side up.

Northeast of Middleton Island, a 50-km-long curving complex fault zone (fig. 3) cuts Tertiary strata. The middle part of this fault zone reaches the seafloor, but at each end the faulted strata are covered by a thin veneer (5-10 m) of Holocene sediment. The relative motion is up on the north side.

The longest near-surface faults in the study area are southeast of Kayak Island (fig. 3). The seaward side of this fault zone extends southwest of Cape Suckling and appears to cut Tertiary strata and perhaps the lower part of the overlying 10-20 m of Holocene sediment. Disrupted reflectors on minisparker profiles may indicate the presence of gas-charged Holocene sediment along part of the fault trace (fig. 7). Sediment samples contained methane plus other hydrocarbon gases of higher molecular weights (Kvenvolden and others, in press). The gas could be generated within the Holocene sediment or it could be gas that has migrated up the fault plane into the surficial sediment. This fault zone nearly parallels Kayak Island, probably includes Plafker's (1974) 10 Fathom fault and continues southwest along the Kayak platform. The total length of this near-surface fault zone is approximately 70 km. This fault also appears to have a sense of motion of up on the northwest.

High resolution seismic profiles show numerous small scarps (fig. 8) cutting well-lithified strata near the edge of the continental shelf south of Kayak Island (fig. 3). Based on this seismic control (3-5 km line spacings), we have not been able to correlate indivdual scarps from line to line. The scarps are found in two small clusters having areas of about 100 and 125 km^2 in water depths of 150-225 m. The relief of individual scarps varies from 2-5 m and the average distance between scarps on individual seismic lines is about 0.5 km.

Some of the blocks show evidence of backward rotation; however, the seismic records do not show outward (seaward) curvature of the normal fault or slip planes. The slip or glide planes can be traced to a maximum depth of about 150 m in the Tertiary strata. Along some of the seismic lines that continue seaward over the continental slope, masses of what appear to be slumped sediment are seen on the records. Both areas of these discontinuous scarps overlie complex anticlines that are oriented sub-parallel to the shelf edge (Bruns and Plafker, 1975).

The Gulf of Alaska is seismically active; numerous earthquakes of magnitude 6-7 have occurred between 1899-1975 that have epicenters near the shelf edge south of Kayak Island (Lahr and Page, 1976). Thus, the scarps can be readily accounted for by faulting, either associated with step faults formed by uplift and growth of the underlying anticlinal structures, or with gravity slumping at the shelf edge.

The age of the faulted strata is almost certainly no older than late Pliocene and may be no older than Pleistocene, based on seismic stratigraphy of the Gulf of Alaska (Bruns and Plafker, 1975; Carlson and Molnia, 1975; and Molnia and Carlson, 1975). However, it is not known when the most recent movement has occurred or if the faults are currently active.

Regardless of the age or origin of the scarps, they represent a potential environmental hazard to petroleum exploration and development of the underlying anticlinal structures. Movement of the individual blocks could occur during seismically induced ground shaking, as a result of wave action, or other natural or man-induced activity.

Several near-surface faults trend northeast-southwest parallel to the Icy Bay major structural trends (Bruns and Plafker, 1975) south of Cape Yakataga. The two longest of these faults can be traced for about 30 km (fig. 3). Sense of motion is up on the northwest. Most of these faults are covered by 5-10 m of Holocene sediments (fig. 4) and in one of the profiles one of the faults may continue upward into the Holocene sediments, but does not appear to break the surface.

Submarine slides and slumps

Seismic profiles seaward of the Copper River and of Icy Bay (fig. 3) show disrupted bedding and irregular topographic expression commonly associated with submarine slides and slumps. Some of the disrupted reflectors visible on a few of the profiles (fig. 9) perhaps are due to the presence of gas-charged sediment and are similar to those off Kayak Island (fig. 7). However, all along the Copper River prodelta, which has a gradual slope of less than one-half degree, the seismic profiles show a second type of disrupted or discontinuous reflector in the Holocene sediments (fig. 9). The Copper River prodelta was investigated with seismic profiling equipment by Reimnitz (1972) shortly after the 1964 Alaskan earthquake. He attributed slump structures seen on high-resolution seismic records to this earthquake. These structures are similar in size and shape to the structures visible on our profiles over this same area. We conclude that these slump structures, which show progressive failure due to lateral extension of a sedimentary unit at the base of the slump blocks, were probably created by the intense ground shaking that accompanied the 1964 Alaskan earthquake. These structures are present in an area of about 1,730 km^2 that extends about 20 km offshore between Hinchinbrook Island and Kayak Island (fig. 3).

The Copper River is a major source of Holocene sediment in this region, annually supplying 107 x 10^6 tonnes of detritus (Reimnitz, 1966). Much of this sediment has accumulated on the prodelta, reaching a maximum thickness of 355 m southeast of the main channel and averaging about 150 m thick across the entire prodelta (fig. 10). In regions with high rates of sedimentation such as the Copper River delta, the lag between accumulation and consolidation gives rise to excess pore pressure, and the sediment is prone to sliding.

The most spectacular example of mass movement in this study area is a large submarine slide located at the eastern edge of the Copper River (fig. 11). This slide has a length of 18 km, a maximum width of 15 km and a maximum thickness of about 115 m. The estimated volume of material affected by this slide is approximately 5.9 x 10^{11} m^3. In addition to very irregular surface morphology and disrupted internal reflectors, this slide has a fairly well preserved pull-apart scarp with a relief of about 10 m and a well-developed toe that is 20 m thick about 2 km from the distal end (fig. 12). The toe of the slide is partly buried, suggesting erosion of the underlying sediment as the slide moved down the one-degree slope into Kayak Trough although post-slide deposition may account for some of the sediment cover. Apparently there was enough momentum at the toe of the slide to carry it past the thalweg of the trough, imparting to the surface a very slight upward concavity.

Sediment samples collected with a box corer from the upper 50 cm of the surface of this slide consisted of gray clayey silt that is seemingly structureless. However, X-radiographs of slabs of the sediment reveal contorted disturbed bedding, some crossbedding, and chaotic mixtures of irregular fragments of various shapes. The sediment is extremely weak as shown by laboratory tests with a vane shear apparatus that yielded a peak shear strength of 0.02 kg/cm^2. These tests were run about two months after the cruise, and the samples could have been weakened by possible remolding due to jostling in transit. However, the extremely-weak nature of some of the samples was underscored by sediment flowage when the box cores were opened on board ship to permit description and subsampling.

The age of the slide is unknown, but its fresh surface with apparently no overlying undeformed sediment, especially in an area of such high sedimentation, suggests that it must be quite youthful. Samples which were radiographed failed to show undisturbed layering overlying the contorted bedding. None of the seismic profiles show any undisturbed bedding at the surface, but the high resolution seismic method used has a resolution of 1-2 m at the water-sediment interface which would obscure bedding in that interval if present. To generate a possible maximum age for the slide assume that the modern sedimentation rate is the minimum calculated for post-glacial time (7.5m/1000 y). Also assume that there is a 2 m thick undisturbed sedimentary section covering the slide mass and not seen in seismic profile. The computed age for the slide in this case would be about 270 years. The thinner the undisturbed layer, or the greater the sedimentation rate, the younger the age of the slide. If in fact, there is no undisturbed sediment covering the slide mass (as the radiographed samples suggest), then the age of the slide could be considerably younger.

Possible triggering mechanisms for the slide include seismic disturbances and agitation by storm waves. Numerous earthquakes of magnitude 8 and greater have affected the slide area in the past and can be expected in the future (Plafker and others, 1975). If earthquakes are the triggering mechanism, then the most likely historic times for the generation of the slide would be the 1964 Alaska earthquake or the 1899-1900 Yakatat series of earthquakes (Tarr and Martin 1912). An attempt was made to locate pre-1964 bathymetry in the Kayak Trough, but only a few soundings were found, all by lead line, and it was concluded that no meaningful pre-and post 1964 earthquake comparison could be made. The 1964 earthquake did generate many landslides in the Gulf of Alaska. Among these were slides at Cordova, Whittier, Valdez, Seward, Homer and Anchorage (Hansen and others, 1966).

If agitation by storm waves is the triggering mechanism it would be very difficult to pin-point a particular storm event as the cause. Storms with waves whose heights approach 10 m are common (Searby, 1960) and larger storms with wave heights of 15 m and greater occur less frequently. (Pierson and others, 1955).

A second large area of disrupted reflectors and irregular topography connoting slides or slumps is located seaward of Icy Bay and encompasses about 1,100 km^2 of the seafloor (fig. 3). Slump blocks that make up this disrupted sediment occur in water depths of 70-150 m on a slope of less than 0.5°. Individual "blocks" are about 0.5 km wide (front to back), have a relief of 2-5 m, and consists of low-strength, poorly sorted, clayey silt. These slump blocks appear to show progressive failure due to lateral extension or stretching of a sedimentary unit at the base of the slump blocks. This slump mass lies at a depth of 15-40 m within Holocene sediment that reaches a thickness of more than 150 m (fig. 10). The sources of much of the sediment are probably the nearby coastal glaciers including the Malaspina Glacier from which sediment-laden meltwater flows into the Gulf of Alaska and is moved westward by the dominating counter-clockwise flow of the Alaskan Gyre (Reimnitz and Carlson, 1974).

These slump features seaward of Icy Bay cannot be related to a specific earthquake. However, the active seismicity near the mouth of Icy Bay and recent seismicity associated with nearby Pamplona Ridge (three magnitude 6 shocks in 1970-Lahr and Page, 1976) indicate that prolonged ground shaking is common and of sufficient intensity to cause the mass movement.

Possible buried ice

Analysis of high resolution seismic profiles and fathograms from Bering Trough, a glacially carved sea valley south of the Bering Glacier, indicates an area of approximately 15 km^2 in water depths between 180 m and 230 m which appears to be underlain by ice (fig. 13). This possible ice-cored area is located at the head of the Bering Trough, surrounded on the upvalley sides by thick parallel-bedded sequences of gently dipping Holocene sediment. In seismic profiles these layers become broken and chaotic where they underlie the ice-cored region, but no scarps indicative of slumping have been found. Sea floor morphology of the ice-cored area consists of hummocky ridges and basins reminiscent of subaerial "kame and kettle topography" of Pleistocene continental ice sheets and of active ice-cored moraines of modern glaciers such as the Malaspina, the Bering, the Fairweather, the Muldrow, and others.

Individual submarine "kettles" are semi-circular in cross section and are as much as 15 m in depth and 200 m wide, although the majority are smaller.

This area has an extremely high sedimentation rate (as much as 10m/ 1000 years). The presence of the irregular sea floor morphology suggests active melting of buried ice to maintain relief and prevent sediment from smoothing the area.

Alternative explanations have been considered but none deal as adequately with the sea floor morphology as the buried ice hypothesis. The date of the advance responsible for this buried ice is unknown but dating of local moraines and the regional glacial chronology suggest that the buried ice may be a remnant of the latest Pleistocene ice sheet.

Distribution of sedimentary units

Analyses of high resolution seismic data and seafloor sediment samples indicate that Holocene sediment covers much of the continental shelf in the northern Gulf of Alaska in thickness varying from less than 5 to more than 300 m. The wedge of Holocene fine sand to silty clay of the Copper River prodelta, the thickest of all the modern sediments measured, is about 350 m thick just southeast of the main channel of the Copper River. Other thick sequences of sediment are seaward of Icy Bay near Malaspina Glacier (260 m), south of the Bery Glacier (200 m), between Hinchinbrook and Montague Island (250 m), and at the southwest end of Kayak Trough (155 m) (fig. 10).

Holocene sediment blankets the entire near-shore area between Hinchinbrook Island and the south end of Kayak Island. And Holocene sediment forms the surface fill in the Hinchinbrook Seavalley and covers the area south of Tarr Bank and north of Middleton Island. East of Kayak Island, Holocene sediment blankets the nearshore area except for Holocene morainal areas at Icy Bay and the Bering Glacier, and an area of Tertiary and Pleistocene bedrock that crops out southwest of Cape Yakataga between Cape Suckling and Icy Bay. Holocene sediment occurs in a series of isolated pods toward the outer edge of the continental shelf. Characteristically, Holocene sediment is well stratified with continuous reflectors extending for many kilometres (fig. 14).

Holocene end Moraines are found at the mouth of Icy Bay and south of Bering Glacier and may lie south of the Malaspina Glacier and at the mouth of Yakutat Bay. In seismic profile, end moraines have very irregular surfaces with hummocky lobes exhibiting rapid changes in depth; they typically show discontinuous subbottom reflectors (fig. 15). Pockets of flat-lying sediment are frequently found ponded behind morainal lobes.

Quaternary glacial marine sediments are found in a narrow area that borders the north and west sides of Tarr Bank and in a large area 20 km or more offshore that parallels the shoreline between Kayak Island and Yakutat Bay. In profile glacial marine pebbly muds show many hummocky discontinuous subbottom reflectors (fig. 16). In many places, glacial marine sediments have filled parts of glacially carved U-shaped bedrock valleys.

Tertiary or Pleistocene stratified sedimentary rocks, in profile commonly folded, faulted, and truncated (fig. 17), crop out on Tarr Bank, offshore of Montague Island, and in several localities southeast and southwest of Cape Yakataga.

The main sources of Holocene sediment in this region are the Copper River and two large piedmont glaciers (Bering and Malaspina). Much of the Copper River sediment is transported into Prince William Sound through passes east and west of Hinchinbrook Island. Sediment presently supplied from the two glaciers is primarily suspended matter, the plumes of which extend more than 30 km from shore. A secondary but significant source is the Copper River Plateau and Delta; fine sediment is carried by strong northerly winds which in fall and winter are funneled through the Copper River gorge with sufficient force to carry dark clouds of silt over 50 km into the northern Gulf of Alaska.

The sediment, whether supplied by river, glacial runoff, or wind, is subject to the coastal currents which, except for local eddies, move sediment in a westerly direction, as does the offshore Alaska Current.

The absence of sediment on Tarr Bank and on the Middleton Island platform may be due to the scouring action of swift bottom currents and the frequent storm waves that are particularly large and forceful during the winter season of intense low pressure activity in the Gulf of Alaska.

The four sedimentary units that crop out on the continental shelf are the key to the sequence of geologic events that contribute to the present form of the outer continental shelf. The deformed stratified unit predates the more recent major advances of the continental ice sheet in Quaternary time and owes its eroded and beveled nature to scour by major advances of continental shelf ice as well as to preglacial erosion. The Quaternary glacial marine unit is composed largely of lodgment and ablation tills deposited by advancing and wasting ice sheets on the shelf. It is too widespread in its distribution and too thick to represent isolated ice-rafted sediments. However, the bedrock troughs or valleys cut into the continental shelf (fig. 1) all possess glacially carved morphologies and generally shoal seaward, indicating the limit of bedrock scour by ice. The discovery of terminal moraines further seaward would help confirm this interpreted origin. The Holocene end moraine unit represents recent readvances of small segments of the ice sheet that previously blanketed the shelf.

Holocene sediment is actively accumulating. Satellite photographs and ship and aerial observations confirm the presence of plumes of new material entering the Gulf of Alaska from numerous sources. The Holocene sediment forms a wedge that thins seaward, as it overrides the Tertiary stratified unit and the Quaternary glacial marine unit. The absence of Holocene sediment cover on Tarr Bank and other bedrock outcrops may be due to intense bottom currents and reworking by storm waves. Bottom television and side-scan sonar coverage of Tarr Bank indicates the presence of boulders and large cobbles that probably represent lag deposits resulting from the removal of fine-grained Quaternary glacial marine and Holocene sediments.

No information on depositional rates has been confirmed, but if the deglaciation of the continental shelf paralleled that of other comparable medium-high-latitude regions, ice sheets retreat from the continental shelf was completed by 10,000 years B.P. Assuming this is true, then nearshore deposition rates of 10-35 m per 1000 years are indicated. If the time interval between deglaciation and the present were shorter, then the rates would be correspondingly higher.

VIII. Conclusions.

The northeastern Gulf of Alaska OCS is a region of frequent earthquakes, violent storms, and rapid accumulation of unconsolidated sediment. These phenomena create significant seafloor environmental hazards chief of which are: (1) surface and near-surface faulting, (2) rapid deposition and erosion, and (3) instability of the seafloor.

Surface and near-surface faults thus far detected are in four main parts of the OCS area: (1) south of Cape Yakataga, (2) on or adjacent to the Kayak Island platform (3) on Tarr Bank and (4) near Middleton Island. Most of the faults cut Tertiary strata that either crop out at the seafloor or are covered by a thin veneer of Holocene sediment.

Very few faults have been found that unequivocally cut Holocene sediments.

Along several of the faults that cut the Tertiary strata, seafloor offsets of 5 to 20 m were observed. The longest fault traces measured were about 50 km and 70 km, northeast of Middleton Island and southeast of Kayak Island respectively. Two near-surface faults up to 30 km in length are a part of the major Icy Bay structural trend. Of these faults where sense of motion could be determined, the north or northwest side was upthrown.

The areas of most rapid accumulation of Holocene unconsolidated sediments (10-35 m per 1000 yrs.) are the nearshore zones seaward of the Copper River and seaward of the Malaspina and Bering Glaciers. Additional areas of thick Holocene clayey silt are the glacially carved troughs that are incised in the continental shelf; they include Hinchinbrook Seavalley, Kayak Trough, Bering Trough, and Yakutat Seavalley.

Stratigraphically underlying the Holocene sediment is a glacial marine unit that consists where sampled, of unconsolidated, olive-gray pebbly mud.

Areas of erosion or non-deposition include the topographic and structural highs, Pamplona Ridge, Kayak and Middleton Island platforms and Tarr Bank. The absence of Holocene sediment on these positive relief features may be due to the erosive action of swift bottom currents and large storm waves.

Two large areas of seafloor in the OCS region, seaward of (1) the Copper River delta and (2) Icy Bay and the Malaspina Glacier, show evidence of submarine slides and slumps. Several other areas because of their relatively steep slopes and thick accumulations of holocene sediment are vulnerable to submarine sliding. Slides may occur if the sediment is disturbed by (1) prolonged ground shaking triggered by earthquakes, (2) oversteepening due to erosion of the seafloor by tsunamis or storm waves, or (3) overloading by seafloor construction activities.

IX. Needs for further study

1. Long piston cores (7-10 m) to study:

   a. Stratigraphic changes

   b. Geotechnical properties (shearstrength, Atterberg limits, moisture content, bulk density).

   c. Sediment variations in the 3rd dimension (size, sorting, mineralogy, carbon content-organic and carbonate, faunal changes).

   d. Variations in hydrocarbons

2. Seismic lines, samples and observations in the nearshore zone to: provide link between shelf and beach zones; extend or connect faults, sediment boundaries, and boundaries of unstable seafloor.

3. More detailed seismic profiling, sediment sampling, and direct observation of seafloor features with T.V. and bottom cameras. These data should be gathered for a better understanding of types and rates of seafloor processes such as slump, slide or other mass movement phenomena, and sediment transport with resultant erosion and deposition.

X. Summary of 4th quarter operations

A. Ship or laboratory activities

1. Ship or field trip schedule

   a. Jan. 15 - Feb. 3, 1977; U.S.C.G.C./CAMBELL

   b. Jan. 17 - Jan. 24, 1977; n.e. Gulf of Alaska winter beach observations.

   c. Mar. 13 - Mar. 23; NOAA DISCOVERER

   d. Mar. 21 - Mar. 24; U.S.G.S. R/V GROWLER

2. Scientific party

   a. William Levy, U.S.G.S., sedimentologist

   b. Bruce Molnia, U.S.G.S., marine geologist

   c. Jack Hampson, U.S.G.S., sedimentologist

   d. Paul Carlson, U.S.G.S.) co-Chief Scientists
      Bruce Molnia, U.S.G.S.)
      Jim Nicholson, U.S.G.S.) electronic techs.
      Harry Hill, U.S.G.S.)
      Austin Post, U.S.G.S. glacialogist
      Jim Yount, U.S.G.S. marine geologist

3. Methods

   a. Collected Van Veen grab samples of seafloor sediment

   b. Measured beach profiles

   c. Collected cores and grab samples of seafloor sediment

   d. Tested geophysical and sediment sampling gear to be used on small boat cruise next quarter.

4. Sample localities

   a. Eastern Gulf of Alaska continental shelf between Yakutat Bay and Dixon Entrance.

   b. Eastern Gulf of Alaska beach between Cape Fairweather and Lituya Bay.

   c. Northeastern Gulf of Alaska shelf between Prince William Sound and Yakutat Bay.

   d. Puget Sound near Tacoma, Wash.

5. Data collected during 4th quarter

   a. 12 sediment samples

   b. 6 beach samples, 6 beach profiles measured, and 7 days of observations made.

5. Data collected during 4th quarter (cont'd)

   c. Cores and grab samples will be collected whenever and wherever possible on this "ship of opportunity."

   d. Primary purpose of cruise is check-out of vessel and equipment - data will be collected when feasible.

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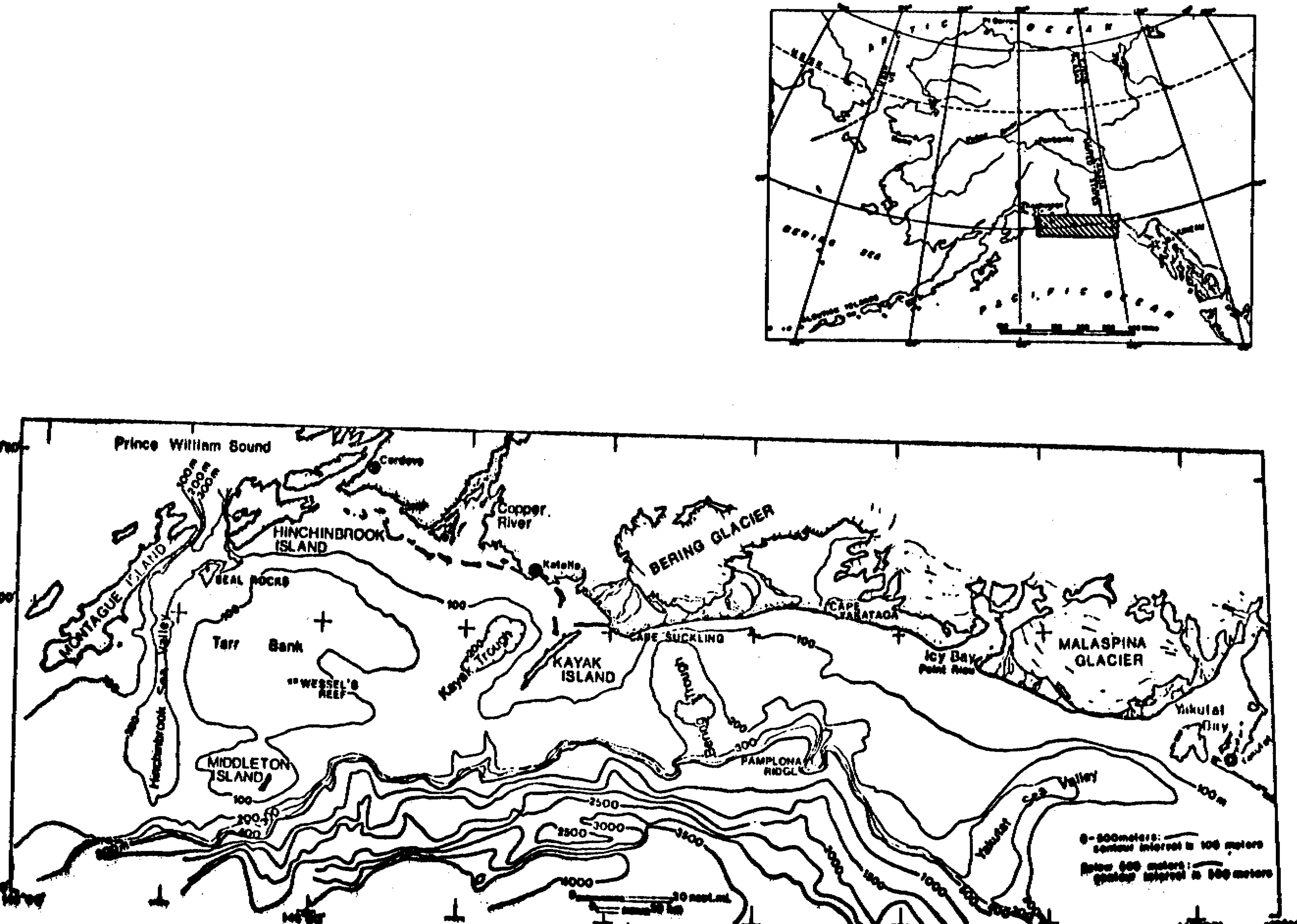

Figure 1. Location map of study area, after Molnia and Carlson (1975).

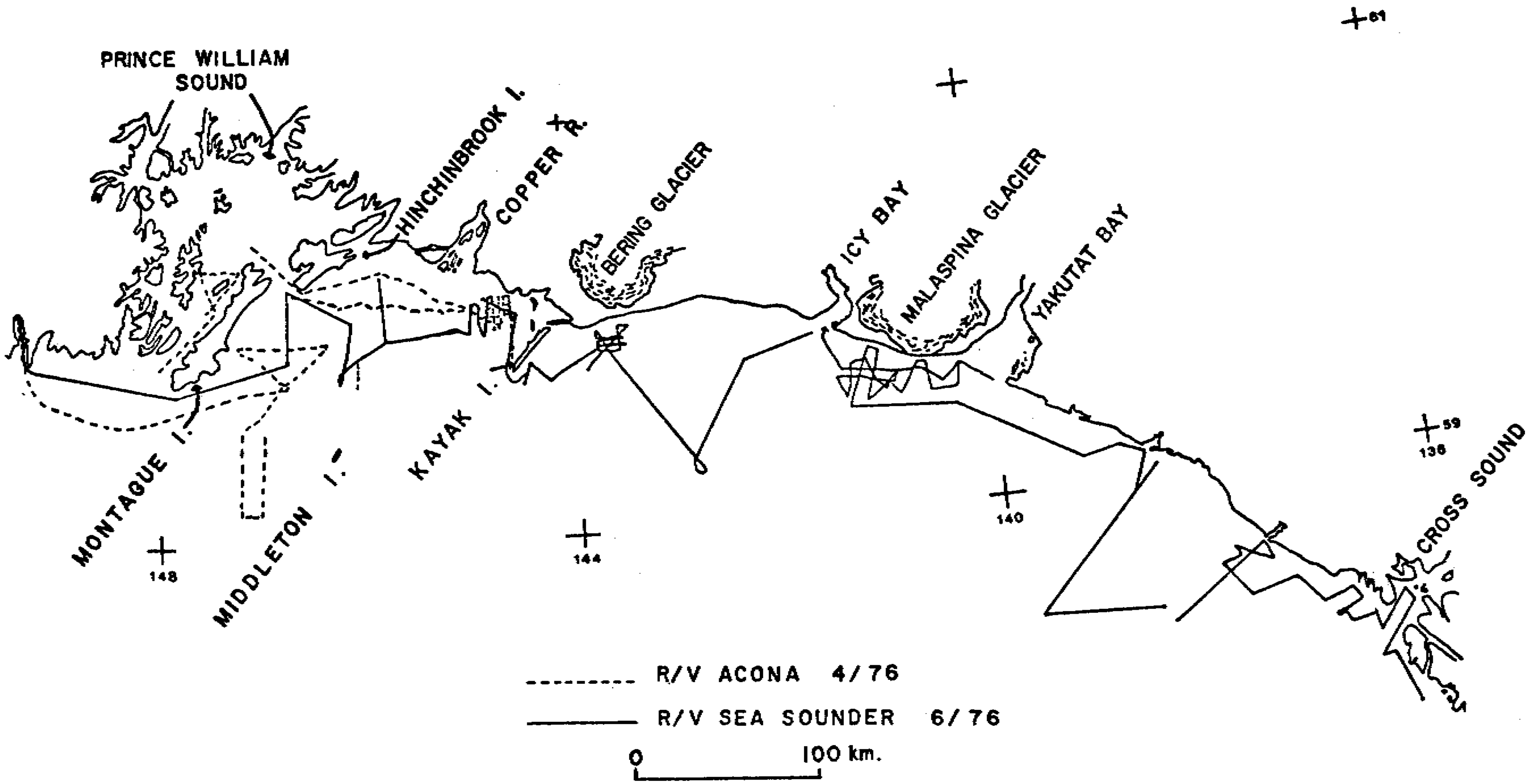

Figure 2. Tracklines of R/V ACONA (4/76) and R/V SEA SOUNDER (6/76).

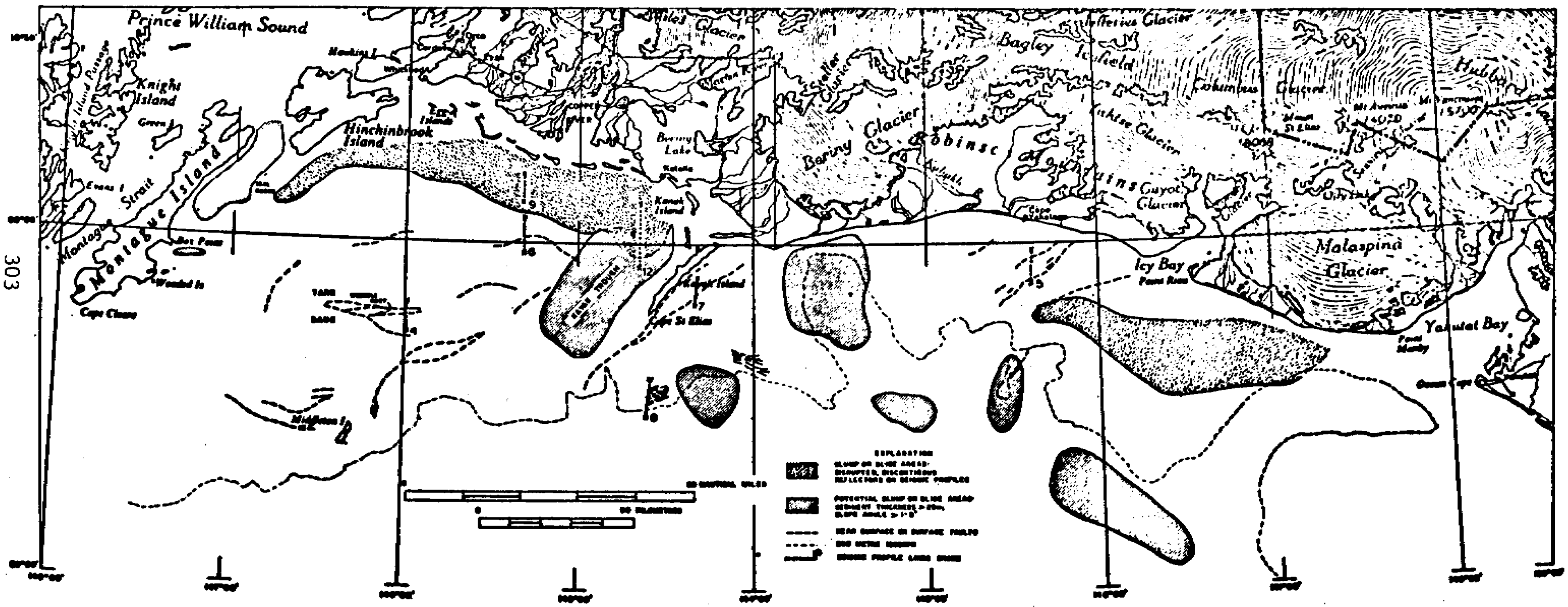

Figure 3. Preliminary map of submarine slides and nearsurface faults, northern Gulf of Alaska. Modified from Carlson and others, 1975. Numbers by the heavy dashed lines indicate figure number of profile.

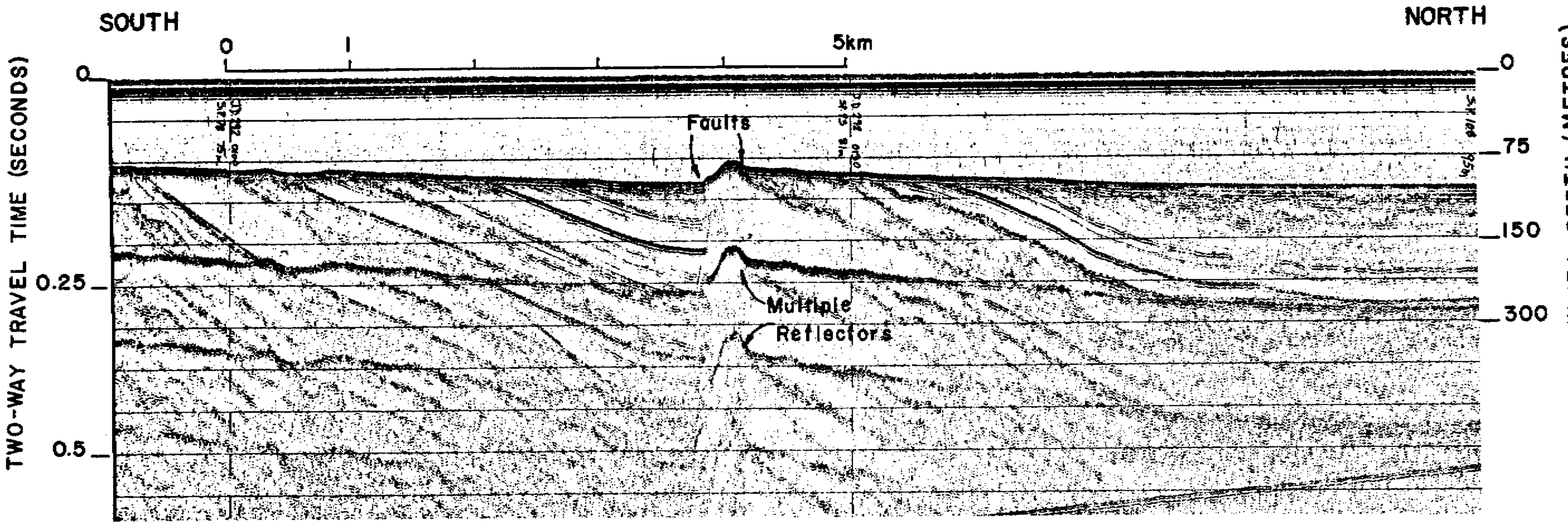

Figure 4. Minisparker profile showing older faulted and folded strata (Tertiary-Pleistocene) cropping out at the seafloor. (Vertical Exaggeration (V.E.) ≈ 10X).

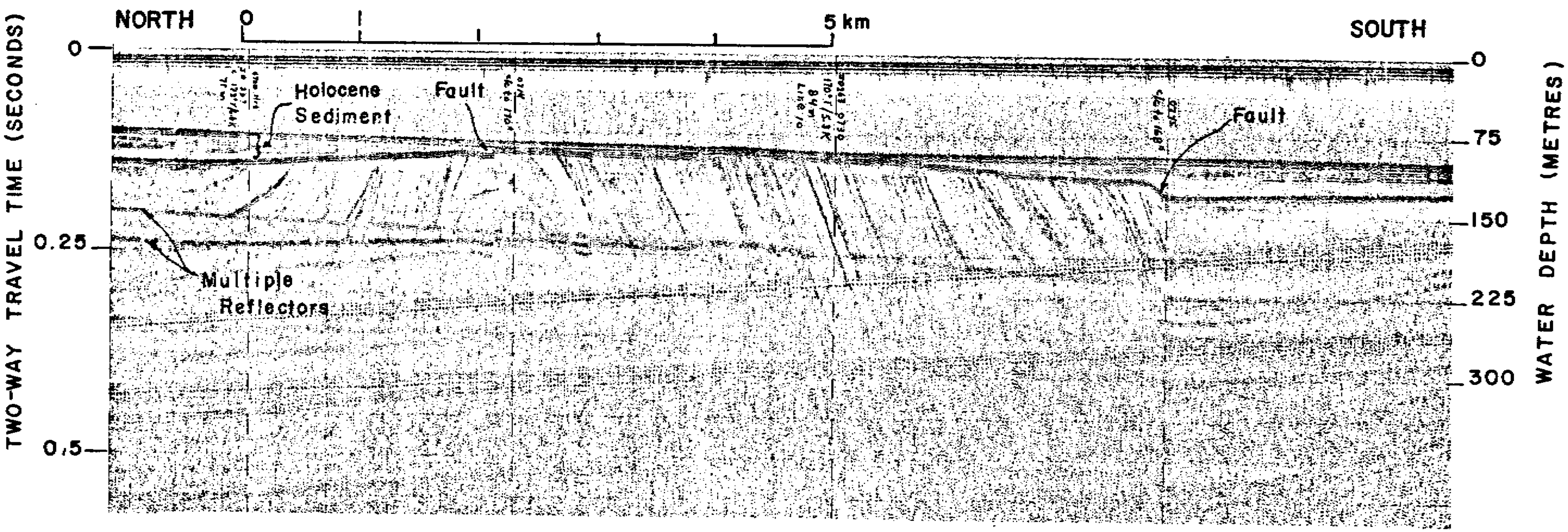

Figure 5. Minisparker profile south of Cape Yakataga showing older faulted and folded strata (Tertiary-Pleistocene?) overlain by thin blanket of Holocene sediment. (V.E. ≈ 10X).

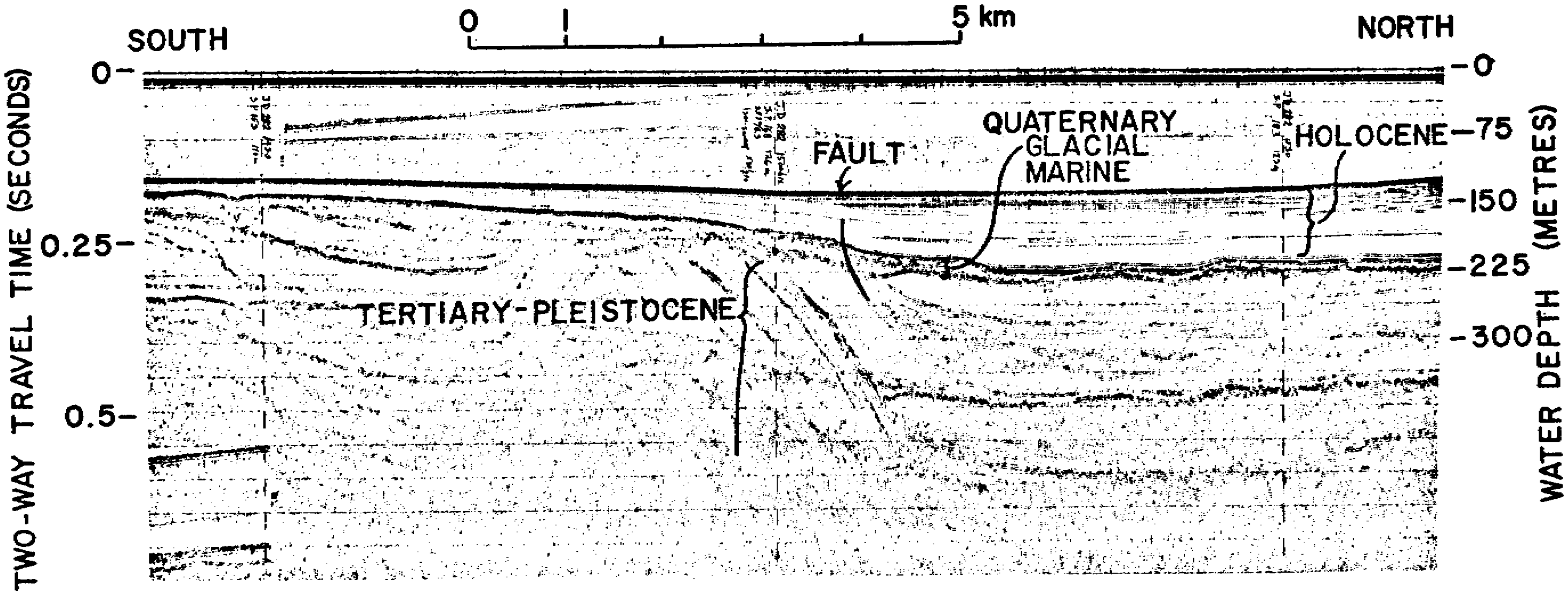

Figure 6. Minisparker profile south of the Copper River showing fault (sketched in) cutting lower part of Holocene sedimentary sequence. The fault also cuts through the underlying glacial marine unit and into the steeply dipping Tertiary sedimentary rocks. (V.E. ≃ 10X).

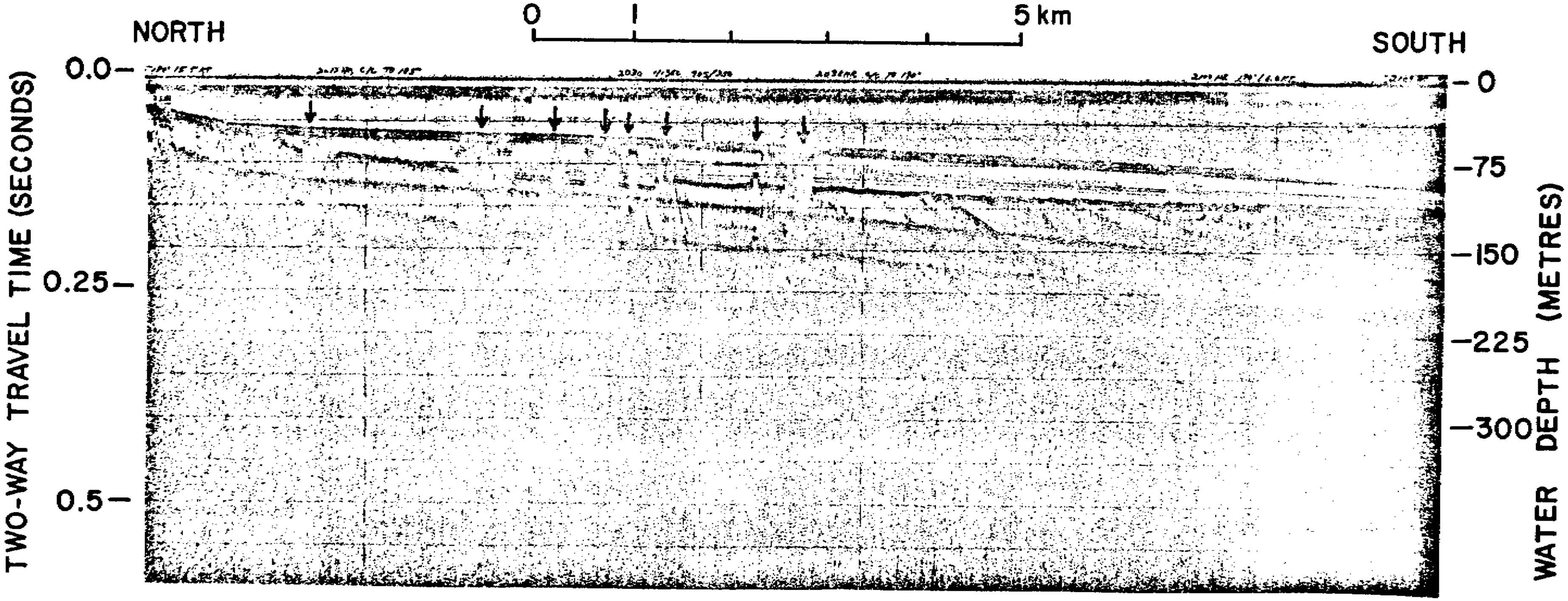

Figure 7. Minisparker profile east of Kayak Island showing gas-charged sediments (arrows point to disrupted reflectors, believed due to gas in the sediment). (V.E. ≈ 10X).

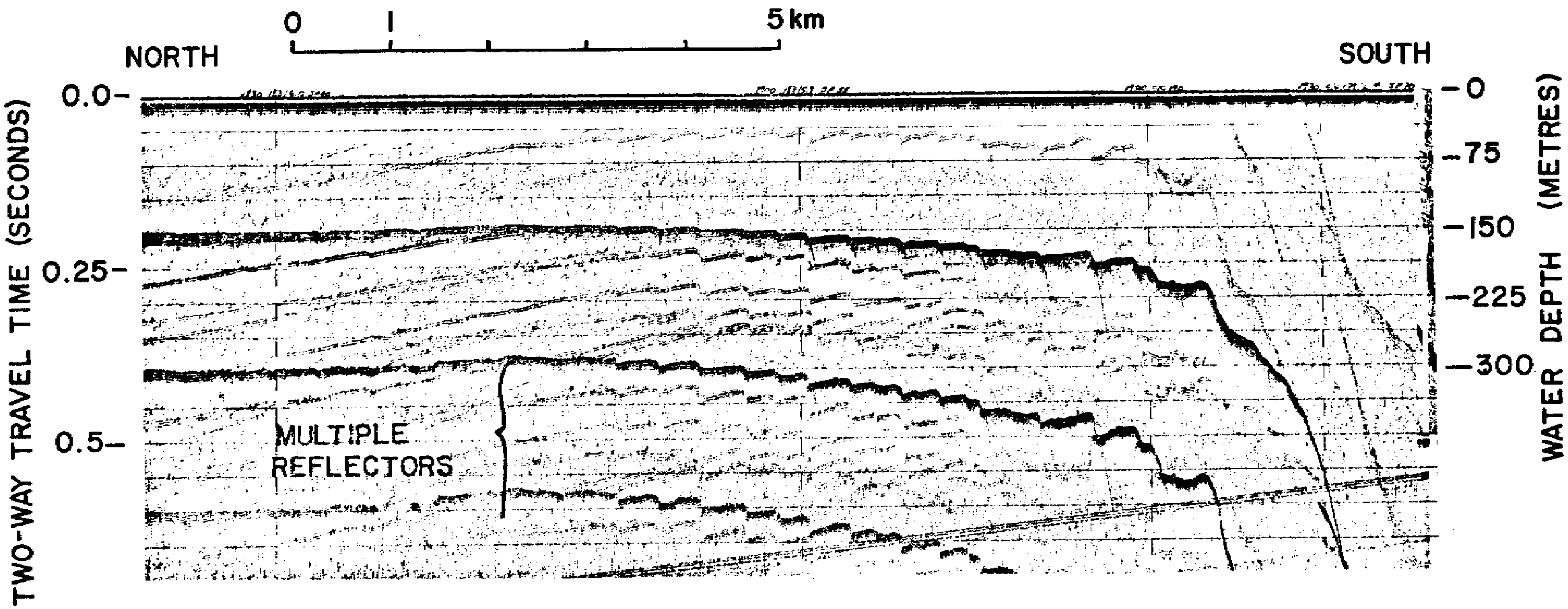

Figure 8. Minisparker profile of stepfaults at edge of shelf south of Kayak Island. (V.E. ≈ 10X).

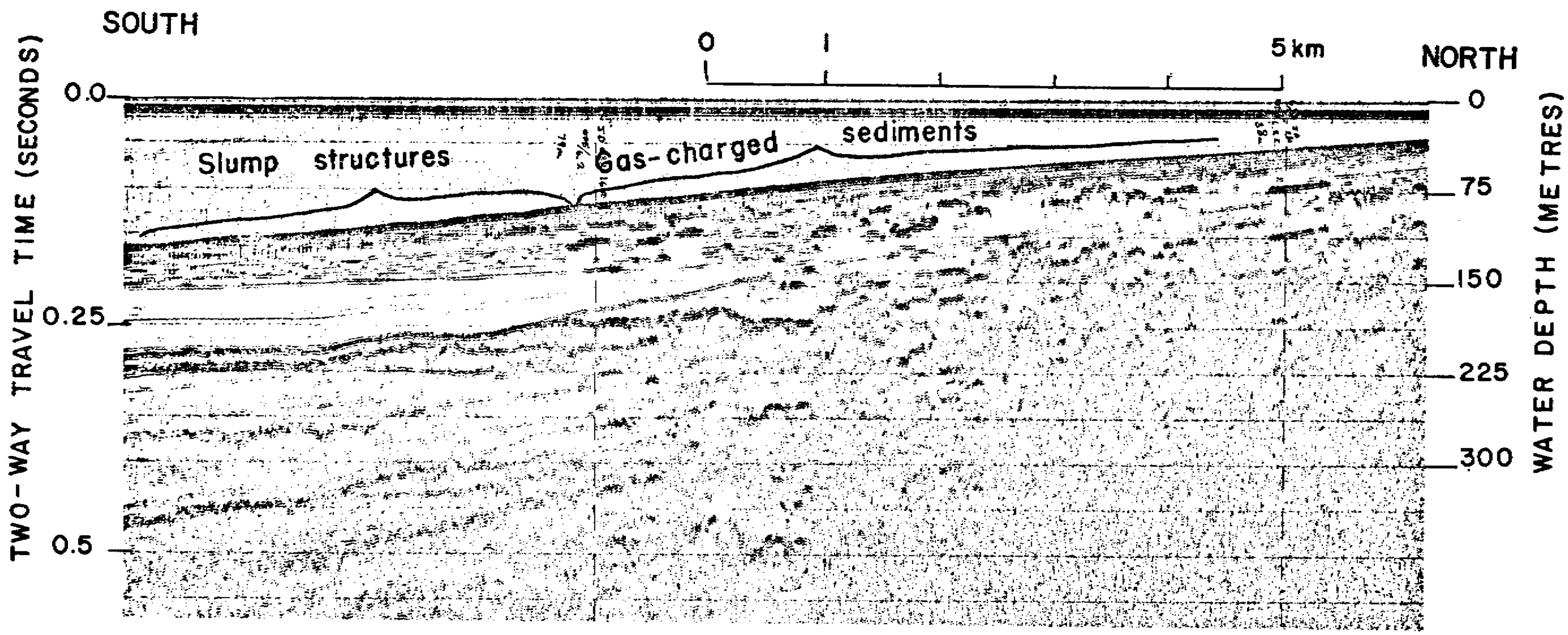

Figure 9. Minisparker profile showing two types of disrupted reflectors (slump and gas-charged) in nearsurface sediments along the Copper River prodelta. (V.E. ≃ 10X).

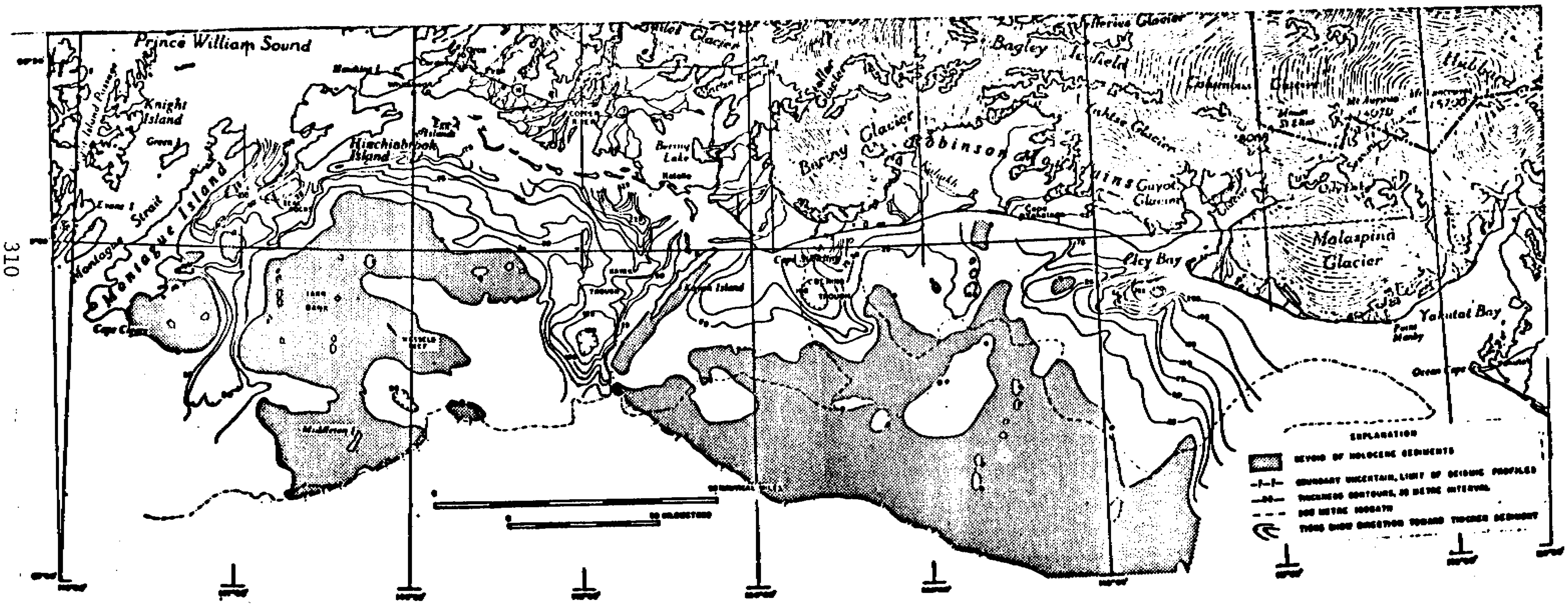

Figure 10. Preliminary isopach map of Holocene sediments, northern Gulf of Alaska. Modified from Carlson and Molnia, 1975.

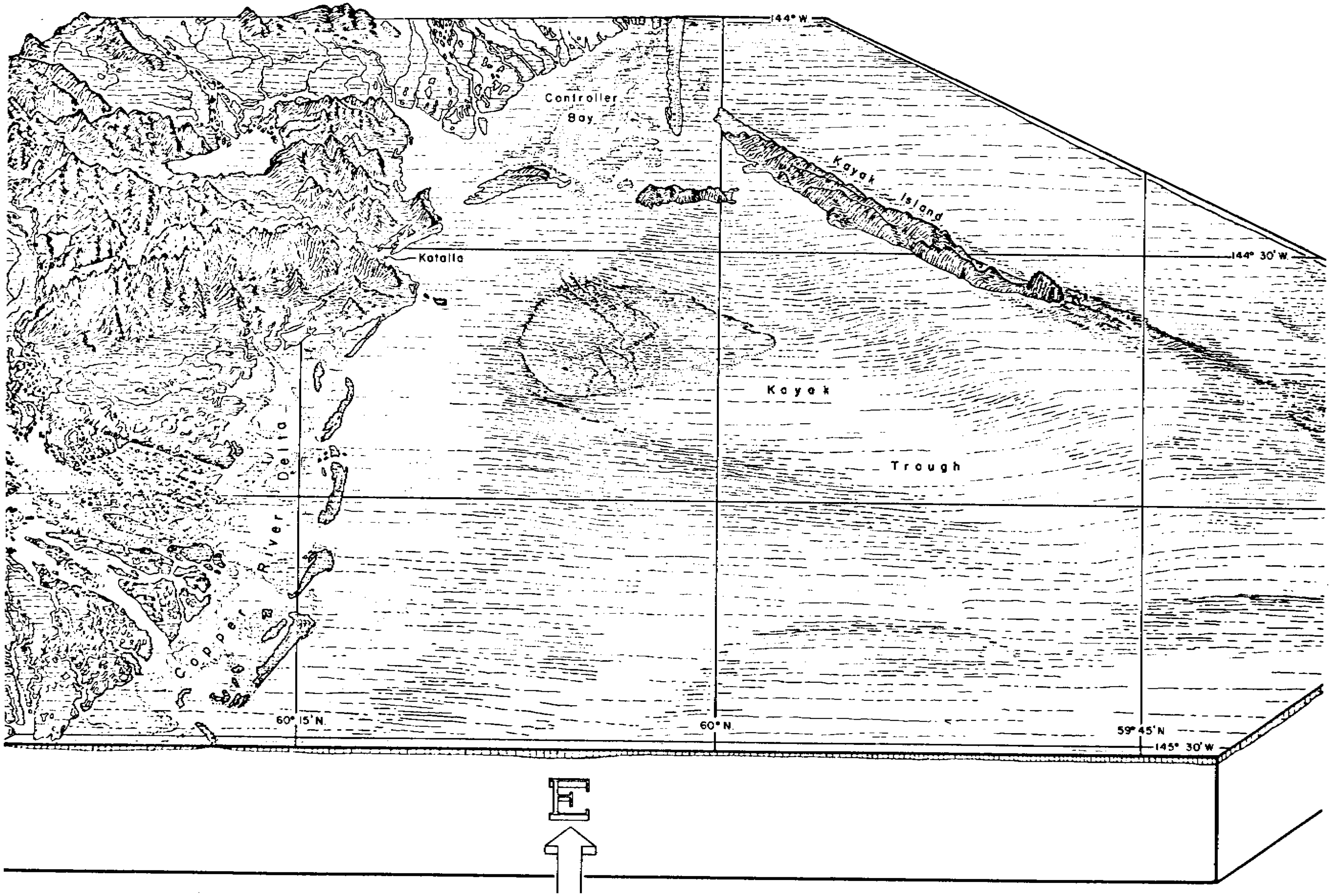

Figure 11. Physiographic diagram of Kayak Trough showing massive submarine slide. Orthographic drawing by Tau Rho Alpha; vertical exaggeration 3:1. Bathymetry based on U.S. Geological Survey soundings (Molnia and Carlson, 1975a; von Huene and others, 1975). Topography from U.S. Geological Survey 1:250,000 maps Cordova, 1959 and Middleton Island, 1955.

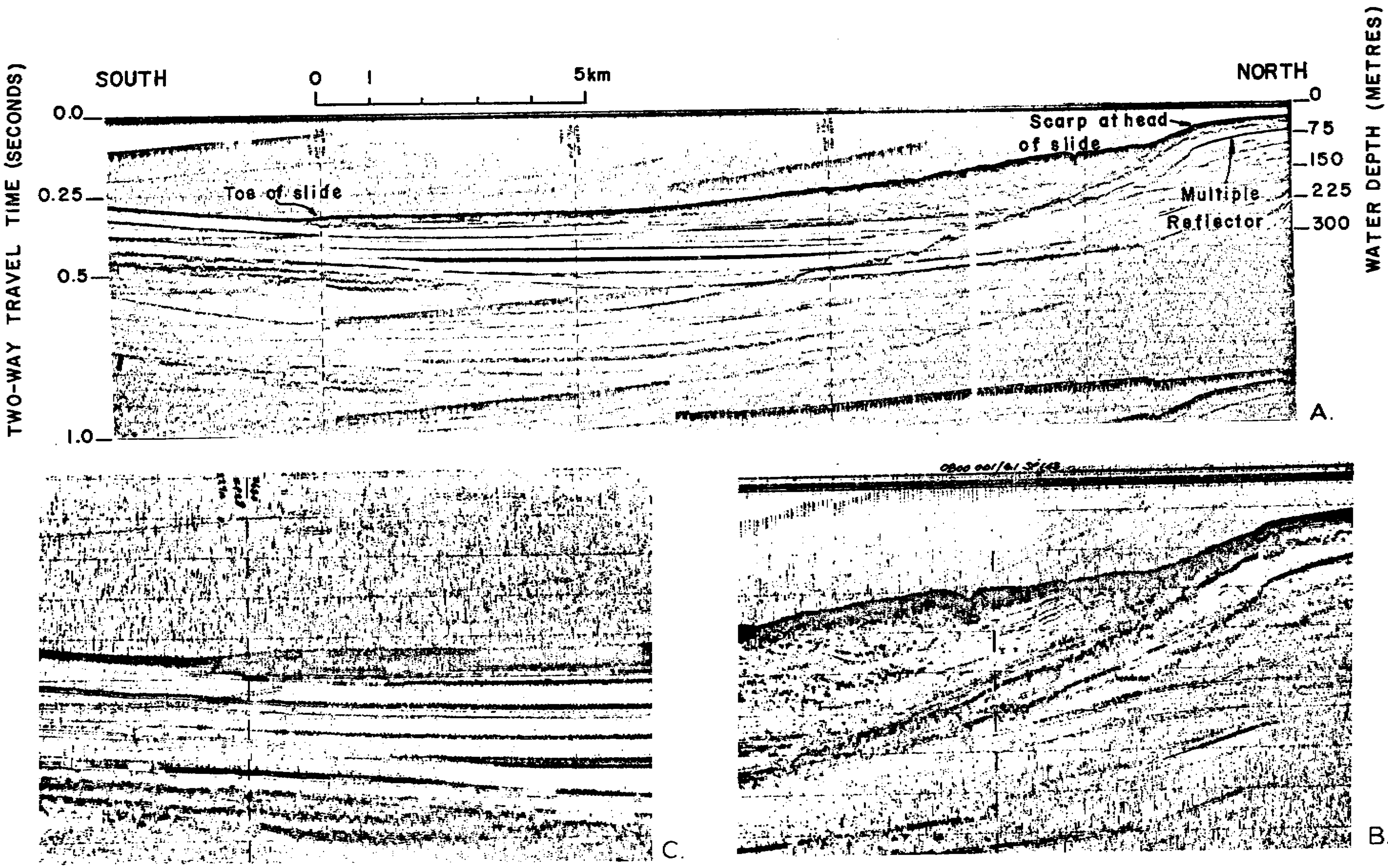

Figure 12. A. Longitudinal profile of submarine slide at north end of Kayak Trough (V.E. ≈ 10X) (see fig. 11).
B. Close-up of scarp at head of slide.
C. Close-up of toe of slide.

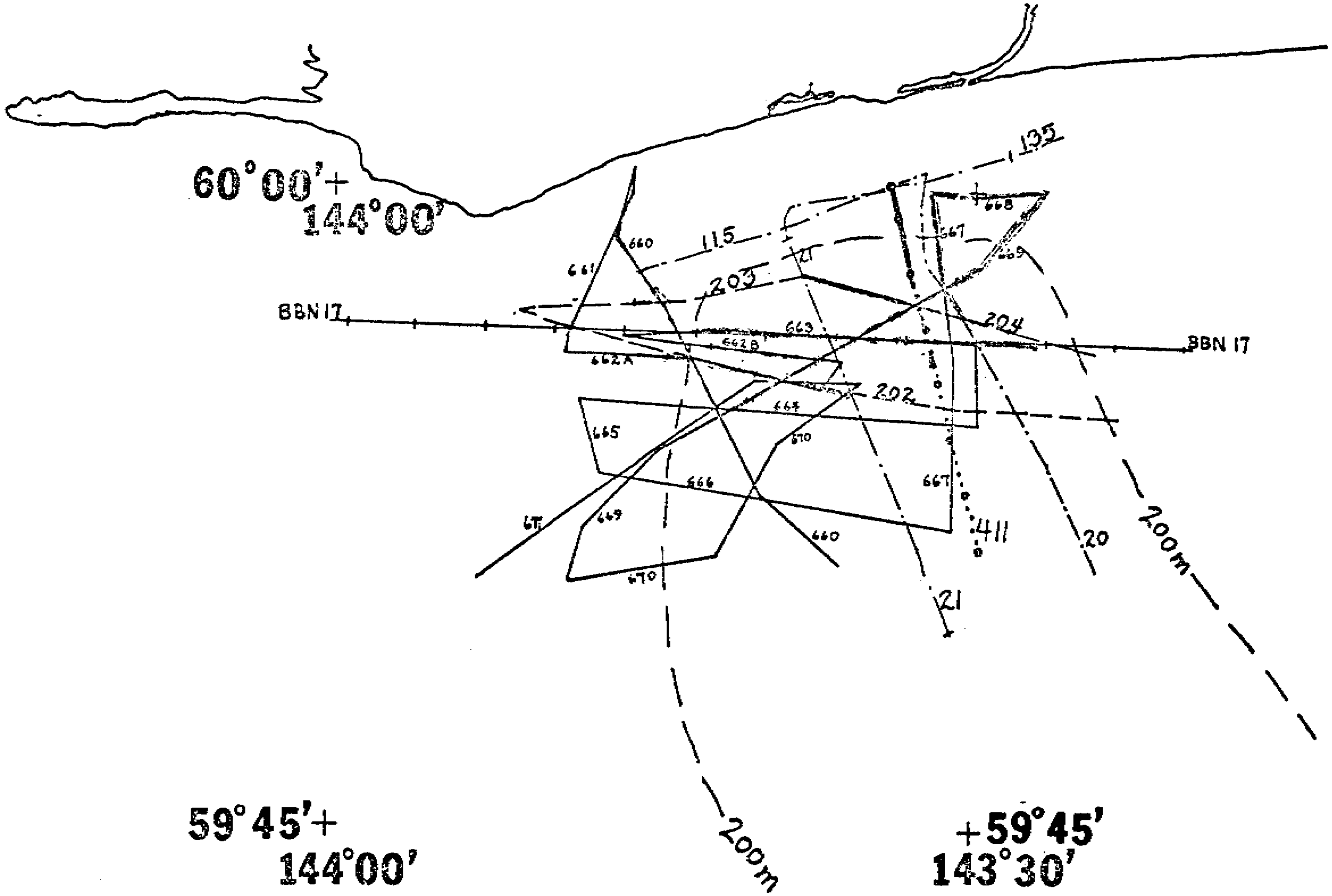

Figure 13. High resolution seismic lines in Bering Trough over possible ice-cored sediment.

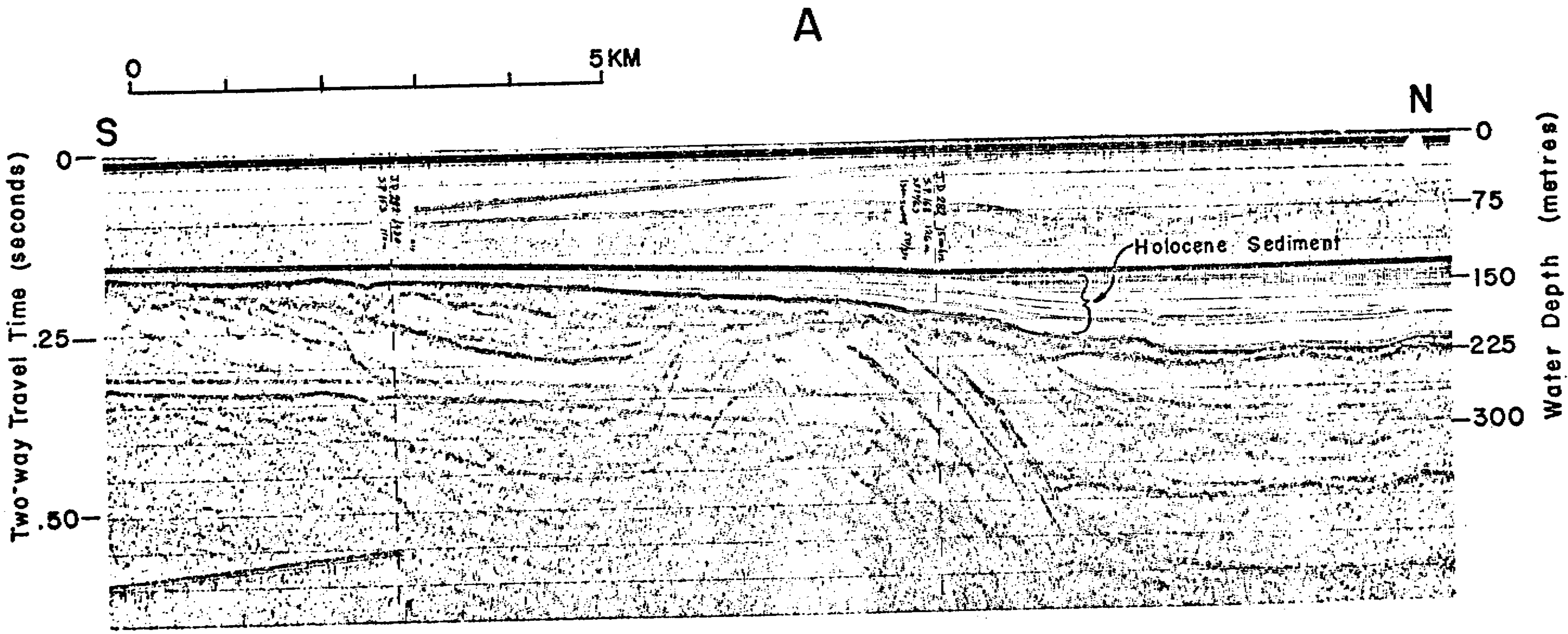

Figure 14. Holocene sediment overlying folded stratified deposits south of Copper River (Vertical Exaggeration ~9X)

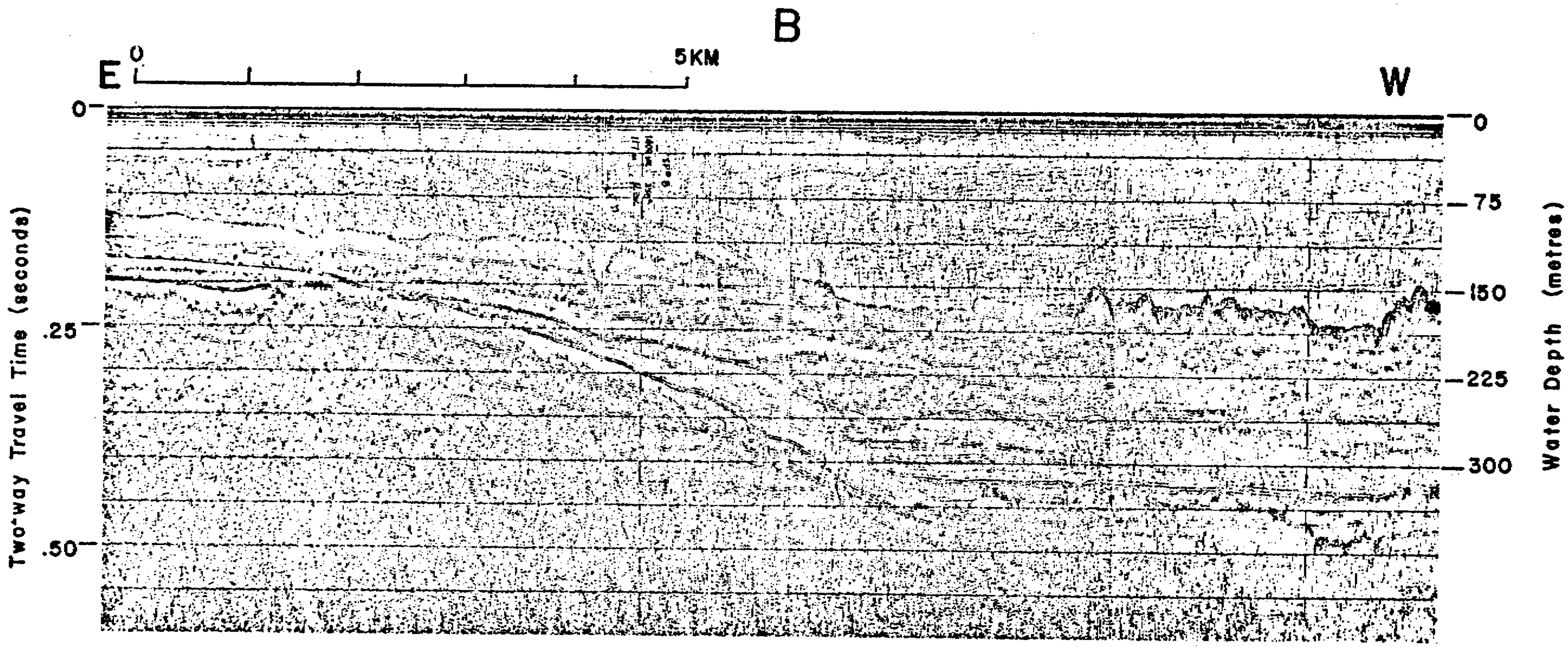

Figure 15. A portion of the Holocene Bering Glacier end moraine (V.E. ~9X).

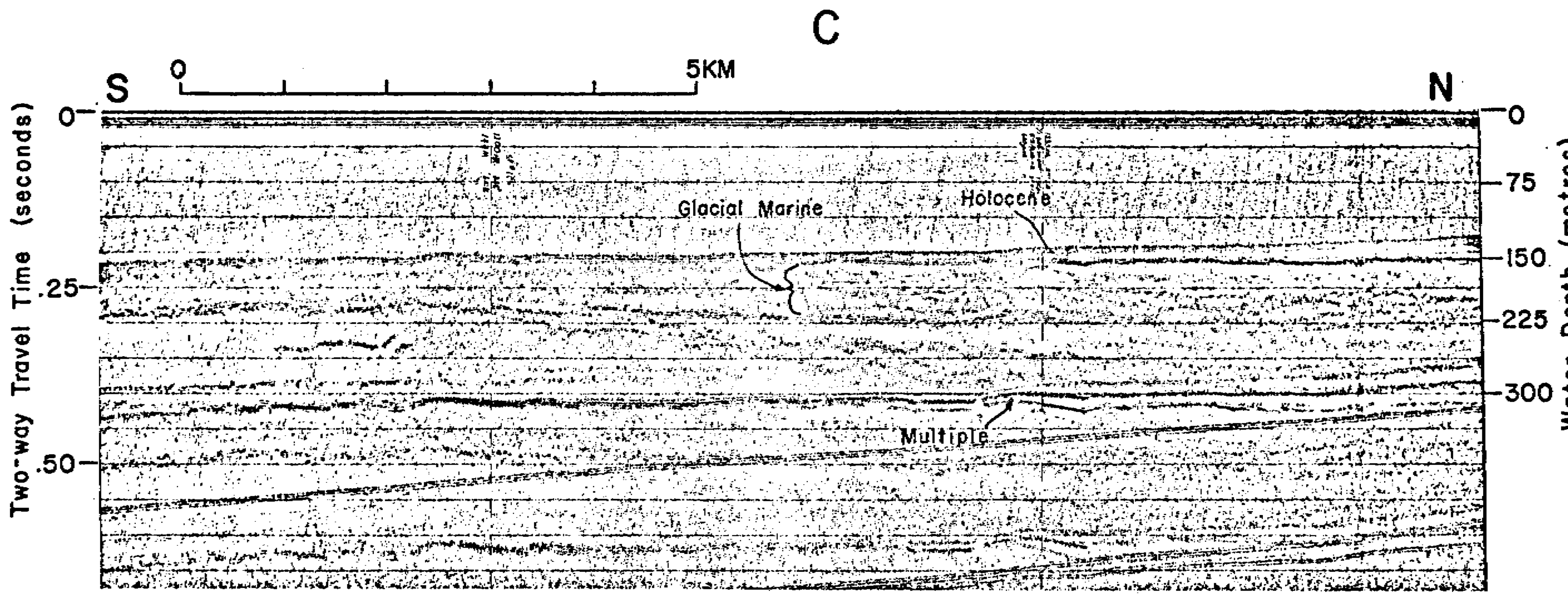

Figure 16. Quaternary glacial marine sediment filling Bering Trough (V.E.~9X).

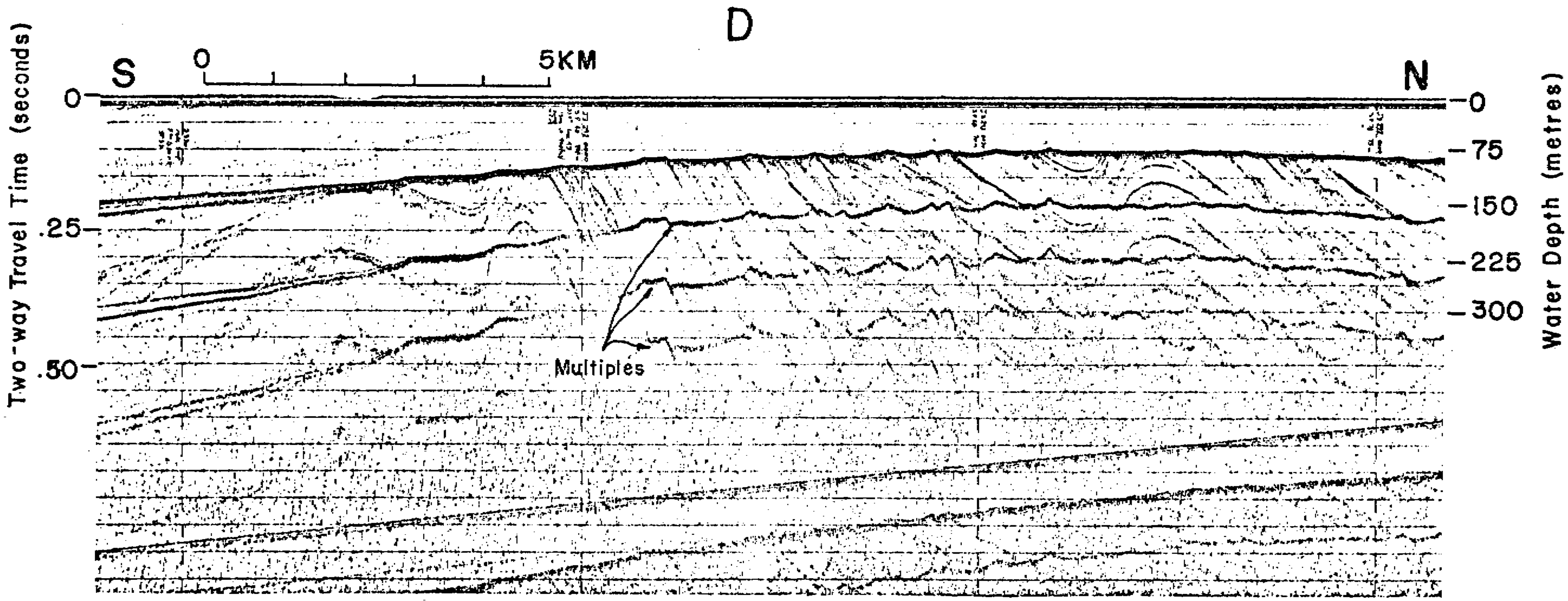

Figure 17. Seismic profile showing folded Tertiary and Pleistocene stratified deposits on Tarr B
(V.E. ~ 9X).

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SEISMIC AND VOLCANIC RISK STUDIES - WESTERN GULF OF ALASKA

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March 31, 1977

I. OBJECTIVES

It is the purpose of this research to determine the seismicity of the lower Cook Inlet, Kodiak Island, and Alaska Peninsula areas and the associated seismic risk to onshore and offshore developments. It is also the purpose to monitor the earthquake activity of two recently active volcanoes and evaluate their eruption potential and associated risk.

II. FIELD AND LABORATORY ACTIVITIES

A. Seismic Network

1. Changes in Layout of the Net

Figures 1 and 2 show the layout of the seismic network in the lower Cook Inlet, Kodiak, and Alaska Peninsula areas at the end of 1975 and present, respectively.

The following changes have been made:

Station	Change
BRB (Bruin Bay)	relocated
HOM (Homer)	new installation
SKS (Sitkalidak Is.)	abandoned
CHI (Chirikof Is.)	added horizontal component
SII (Sitkinak Is.)	relocated
MRS (Marine Range)	abandoned
DVP (Devils Prong)*	abandoned
CCH (Cape Chiniak)*	new installation
SPI (Spruce Island)*	new installation
UGI (Ugak Island)*	new installation
UGB (Ugak Bay)	new installation

The above changes, except for CHI, HOM, and BRB, all part of the Kodiak network, were conditioned by excessive snowfall at some of these stations. This resulted in complete burial of the antennas which are mounted on masts, 6 feet high. Excessive snow load and/or icing caused destruction

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* indicates telemetry repeater only

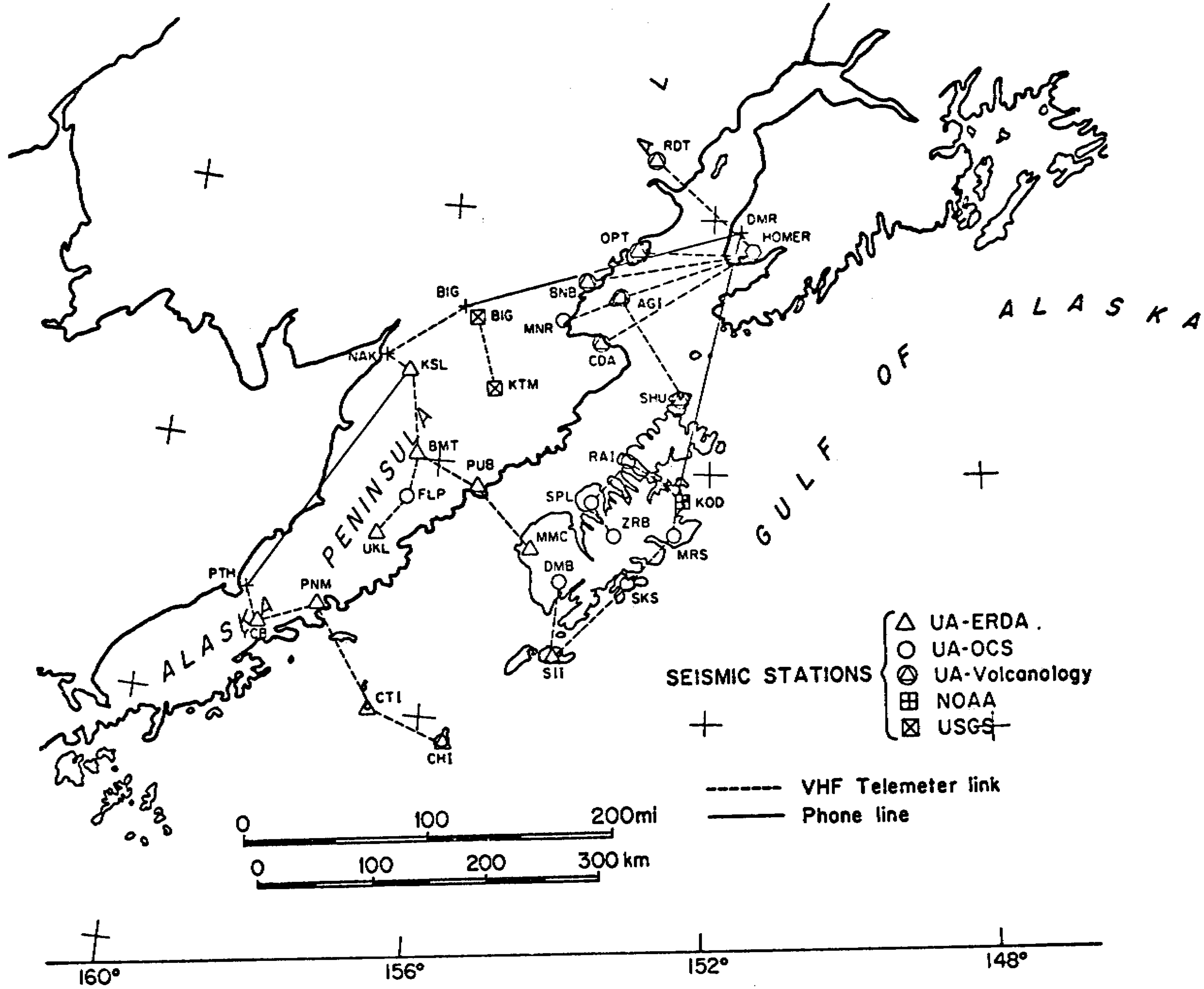

Figure 1. Western Gulf of Alaska seismic network, recorded in Homer (1976).

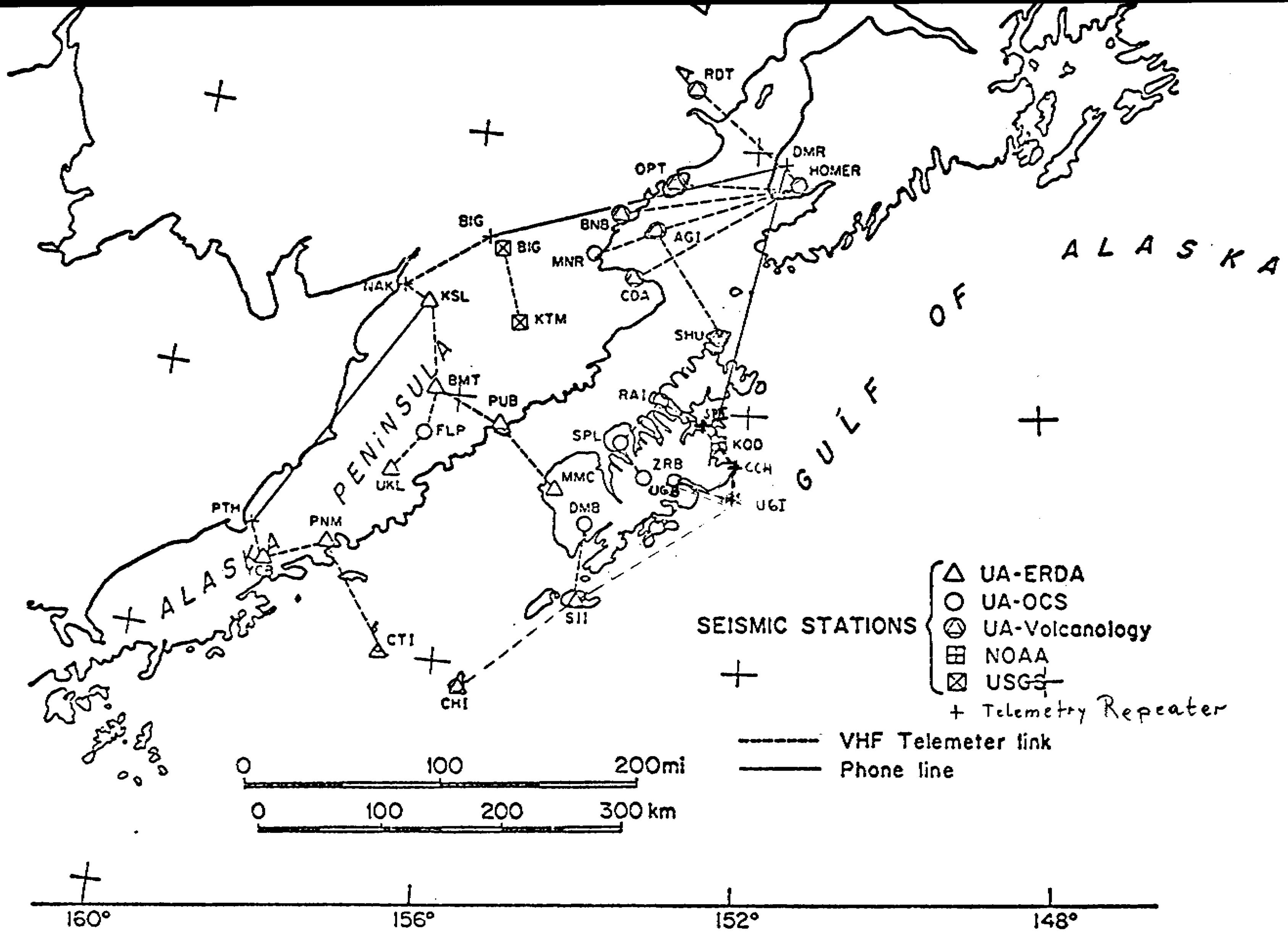

Figure 2. Western Gulf of Alaska - Seismic network, recorded in Homer (1977).

of some of the antennas. Rearrangement of the system permitted us to place the station at lower elevations, but required an additional telemetry repeater on the southern leg of the system.

The horizontal component was added on CHI in order to provide better identification of the S-phase, which is a strong constraint in the hypocenter determination.

Appendix 1 lists the major field operations, their purposes, and the personnel involved.

Table 1 gives the present locations of the seismic stations.

2. General Remarks on Seismic Network Operation

The lower Cook Inlet portion of the network has so far been the most successful one. This is partly a consequence of the high station density there, primarily however because it presents technically the least difficulties. Most signals of these stations are telemetered in one single shot to the recording site in Homer. Hence in the case of malfunctioning of one of these stations, the signal of only that station is lost. Also the receiving end of these stations is readily accessible. The situation is radically different on Kodiak and the Alaska Peninsula, where all stations are part of daisy-chain like arrangements where signals from some stations have to be retransmitted four times before they can finally be put on a commercial telephone line. The heavy snow load causing the failure of two Kodiak stations mentioned above, involved the last repeater stations before Kodiak on the northern and southern leg of the system, respectively. As a consequence of the failure of these two stations, all Kodiak signals were lost. A fly-by over all Kodiak stations in early 1976 revealed that five of the seven seismic

Table 1

UNIVERSITY OF ALASKA

LOWER COOK INLET, KODIAK ISLAND,

AND ALASKA PENINSULA SEISMIC NETWORK

STATION NAME	CODE	LATITUDE (NORTH)	LONGITUDE (WEST)	ELEVATION (METERS)	COMPONETS
AUGUSTINE IS. KAMISHAK	AUK	59 20.05	153 25.62	259	SPZ
AUGUSTINE IS. MOUND	AUM	59 22.26	153 21.17	106	SPZ
AUGUSTINE IS. WEST	AUW	59 23.16	153 33.02	80	SPZ
BLUE MOUNTIAN	BMT	58 02.8	156 20.2	548	SPZ
BRUIN BAY	BRB	59 25.20	153 56.78	500	SPZ
CAPE DOUGLAS	CDA	58 57.32	153 31.77	386	SPZ
CHIRIKOF ISLAND	CHI	55 48.5	155 38.6	250	SPZ,SPE-W
CHOWIET ISLAND	CHO	56 02.0	156 42.7	160	SPZ
DEADMAN BAY	DMB	57 05.23	153 57.63	300	SPZ
FEATHERLY PASS	FLP	57 42.7	156 15.9	485	SPZ
HOMER	HOM	59 39.50	151 38.60	198	SPZ
KING SALMON	KSL	58 42.2	156 39.7	25	SPZ
SITKINAK ISLAND	SII	56 33.60	154 10.92	500	SPZ
MCNEIL RIVER	MCN	59 06.06	154 11.99	273	SPZ
MIDDLE CAPE	MMC	57 20.00	154 38.1	340	SPZ
OIL POINT	OPT	59 39.16	153 13.78	625	SPZ
PINNACLE MOUNTIAN	PNM	56 48.3	157 35.0	442	SPZ
PUALE BAY	PUB	57 46.4	155 31.0	280	SPZ
RASPBERRY ISLAND	RAI	58 03.63	153 09.55	520	SPZ
REDOUBT VOLCANO	RED	60 25.14	152 46.32	1067	SPZ
SHUYAK ISLAND	SHU	58 37.68	152 20.93	34	SPZ
SPIRIDON LAKE	SPL	57 45.55	153 46.28	600	SPZ
UGAK BAY	UGB	57 29.00	152 55.00	100	SPZ
UGASHIK LAKE	UKL	57 24.1	156 51.3	410	SPZ
YELLOW CREEK BULFF	YCB	56 38.9	158 40.9	320	SPZ
ZACHER BAY	ZRB	57 32.58	153 34.68	770	SPZ

stations were still operational. Since the annual service trip took place only in October, most of 1976 data from Kodiak were lost.

The rearrangement of the system during this year's service trip was not only in order to allow placing of the installations at lower altitudes, but also to permit servicing of stations that involve three or more signals, during most part of the year. This policy has already borne fruit when the southern leg of the Kodiak network failed because (as was found out later) a receiver failure at the repeater on Ugak Island (carrying all four signals on this loop) and apparent human vandalism at SII (transmitting three signals). SII could be serviced by commercial air service and Ugak Island with help from the U.S. Coast Guard Kodiak Air Station, and thus the signals could be recovered.

Another consequence of the frequent retransmission is a strong deterioration in the signal quality, unless all electronic equipment is perfectly tuned and RF signal strength arriving at the receiving station is sufficient. We have installed RF preamplifier at some critical links, which decreased the noise level of the signals substantially. Such RF preamplifiers are planned for all but the shortest telemeter links.

The recording equipment in Homer was relocated in larger quarters (this required installation of electricity and plumbing). All recording equipment was recalibrated and a new, more accurate timing system was installed.

B. Volcanology Field Operations

Augustine Volcano was visited two more times after the emergency field operations in late January and February 1976 following the initial vent clearing eruptions of January 22-25, 1976 and the extrusion of a new lava dome in early February 1976.

A field party consisting of Hans-Ulrich Schmincke, University of Bochum, W-Germany, and David Johnston and Mark Utting, both of the University of Washington, spent almost one month on Augustine Island, from August 10 to September 1, 1976 to study the petrology, geochemistry, stratigraphy, mode of deposition of the pyroclastic flows, surges and ash falls on the island, to map the deposits and also to study the effects of the eruptions on a man-made structure, our former base camp at the northern point (Burr Point) of the island. Dr. H.-U. Schmincke generously participated in the field work at no cost except for transportation to and from the island to Homer, Alaska, and the cost of the food while there. Dr. Schmincke is an expert in the classification, stratigraphy, and mode of emplacement of pyroclastic rocks; and is presently on sabbatical leave in the United States and writing a book about the subject. He has previously worked on ash flow deposits in W-Germany and the Canary Islands. David Johnston, a Ph.D. candidate in geochemistry at the University of Washington, participated in the field work for the cost of transportation from Seattle to Augustine and living expenses only. Mark Utting was his field assistant. While servicing the Cook Inlet seismic network, Juergen Kienle spent two days with the Augustine field party.

Since the field party operated on foot, the focus of the investigations was the western and particularly the northern part of the island, where the main thrust of the eruptions was directed.

From September 24-28, 1976, the NOAA vessel "Surveyor," OSS 32, was operating around Augustine Island in support of our seismic and volcanic risk studies in lower Cook Inlet. Aboard were J. Kienle, D. J. Lalla, a University of Alaska Ph.D. candidate in volcanology, D. Johnston, University of Washington, and M. Holmgren, an electronic technician of the Geophysical Institute. The purpose of the cruise was threefold. Firstly, we attempted to service four lower Cook Inlet seismic stations (BRB, OPT, and RED; see Figure 2). Because of marginal weather conditions, we only managed to service MCN and relocate BRB. The second purpose of the mission was to establish a grid of ocean bottom grab sampling stations, mainly in the northeastern sector off Augustine Island in an attempt to delineate zones of ballistic fallout and offshore danger zones associated with glowing cloud activity. Figure 3 shows the grid of grab samples obtained near Augustine Volcano. The critical northeastern sector off Augustine was sampled to a distance of 42 km from the center of the volcano. Gravity coring was attempted but was unsuccessful because of the sandy nature of the ocean bottom material. The third part of the mission was to map on a reconnaissance basis by helicopter the distribution of the pyroclastics on the less readily accessible east and south flanks of Augustine Volcano, to conduct thermal measurements on the pyroclastic flow deposits on the northeast flank of the volcano and on the new summit lava dome, and to collect gases emitted from the new dome and pyroclastic flow deposits. An attempt to resurvey island gravity benchmarks to measure vertical deformation following the eruptions failed because of high winds, which did not allow for precise gravity measurements and also because many of the benchmarks were deeply buried by the new pyroclastics.

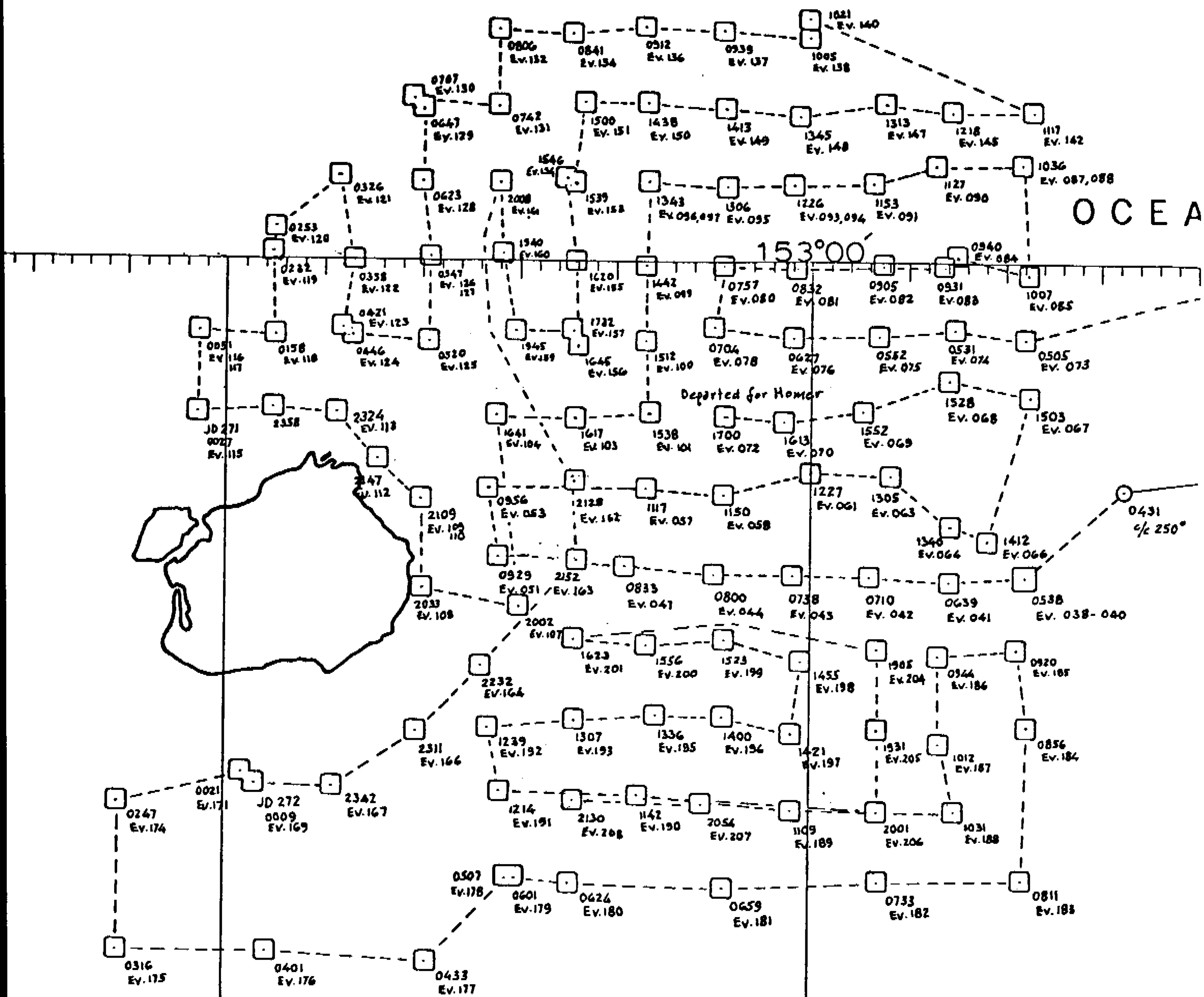

Figure 3. Grid of grab samples near Augustine Volcano, obtained aboard the NOAA vessel "Surveyor" September, 1976.

III. RESULTS

A. Seismology

1. Hypocenter Determinations (files and maps)

Appendices 2 and 3 give the listings of hypocenters and plots of epicenters, respectively, of all earthquakes located with the system between February 1976 and December 1976.

HYPO 73 is used for the earthquake locations, using the following structure:

Velocity (km/sec)	Depth (km)
4.16	0.0
5.50	1.6
6.60	11.6
8.06	41.6
8.09	60.0
8.11	80.0
8.14	100.00
8.27	150.00
8.41	200.00
8.59	250.00
8.74	300.00
9.02	350.00

Magnitudes are listed beginning November 1976 only, when systems calibrations were completed. The data files will be updated with respect to magnitude after incorporating a magnitude determination routine from coda length readings. We are presently addressing the problem of uniform magnitude determination by all agencies in Alaska involved in seismology work.

B. Volcanology

1. Hazard Evaluation

In the fall of 1976, we were able to obtain a small grant from the State of Alaska, Department of Natural Resources, Division of Geological and Geophysical Surveys, to prepare a volcanic risk map of

Augustine Island and to prepare a hazard report which discusses the geologic hazard of Augustine Volcano to the public. The grant consists principally of a small consulting fee for Mr. D. Johnston, Ph.D. candidate in geochemistry, University of Washington, who has been involved with our Augustine studies since 1975.

Appendix 4 gives a preliminary assessment of the Augustine volcanic hazards. The risk map and the report are in preparation and should be completed by about June 30, 1977.

IV. INTERPRETATION

A. Earthquake Hypocenters

The higher density of locations in the lower Cook Inlet seen from the figures in Appendix 3 is, of course, a reflection of the higher reliability of that network and the higher station density there. Until a sufficiently long period of reliable operation has been achieved, no comparison of the seismicity level between the different areas can be made. In lower Cook Inlet, three cluster areas of seismicity seem to emerge: These are, going from north to south, near Iliamna, around Augustine Island, and at Cape Douglas. These clusters are all of a shallow nature or can be seen upon comparing Figures A3-4 and A3-5 in Appendix 3. The Augustine cluster seems associated with post eruptive activity as very few events have been located there during the last months in 1976. The activity below a depth of 50 km is exclusively associated with the underthrust associated with the subduction of the Pacific Plate beneath the American Plate. Figure 4 shows well the Benioff zone that is emerging from the data. In this figure, all

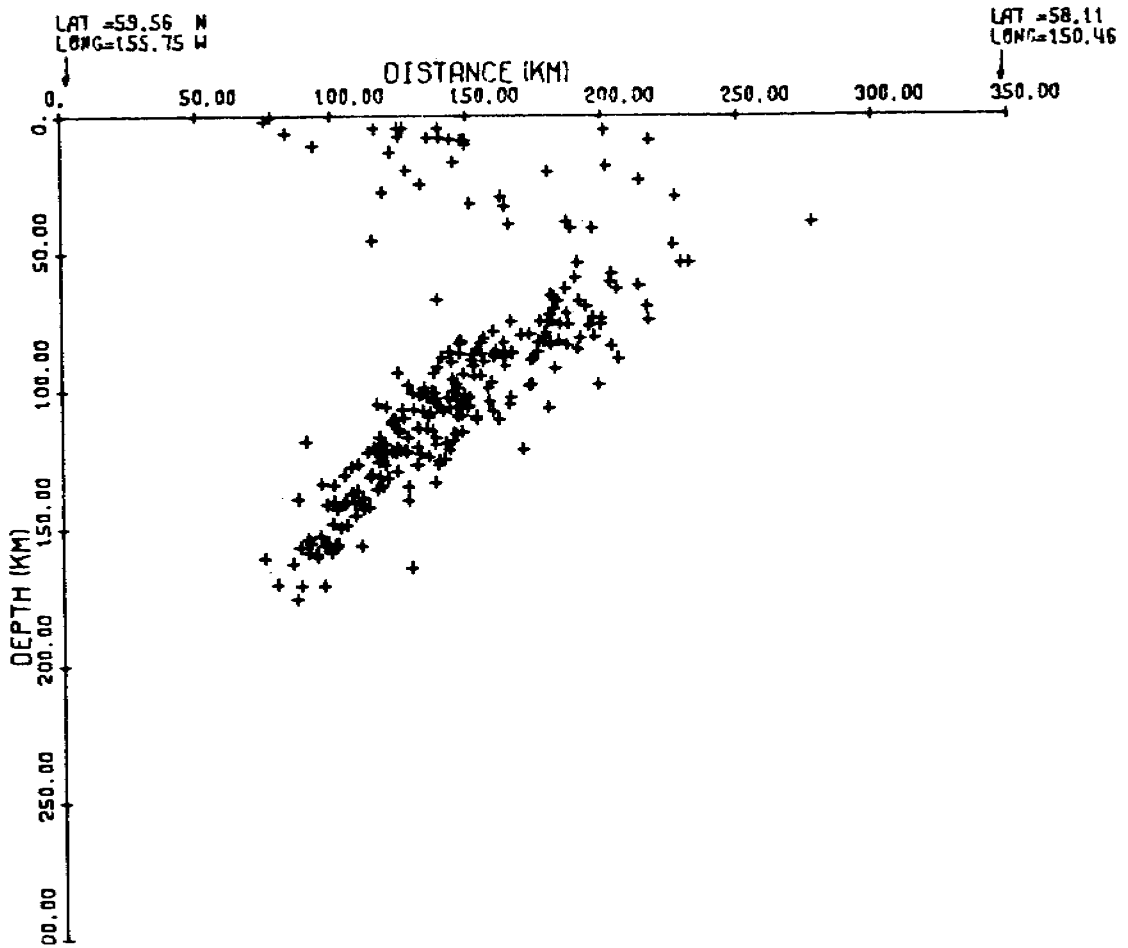

Figure 4. Projection of all class 1 events into a vertical plane, perpendicular to the volcano line.

class 1 events (see Appendix 3 for definition) have been projected into a vertical plane that is perpendicular to the line of volcanoes.

The next step in the analysis will be an attempt to obtain more accurate locations with the master event technique in order to study the above-mentioned clusters in detail.

B. Augustine Volcano Eruption

1. Narrative of the 1976 Eruption

After 12 years of dormancy Augustine Volcano entered a new eruptive cycle on 22 January 1976 when height-finding radars at King Salmon Airport, 205 km west-southwest of the volcano, and Sparrevohn Air Force Station, 230 km north-northwest of Augustine, recorded ash clouds at 4-5 km. Ash from this eruption fell at Iliamna Lodge, 90 km northwest of the volcano, late that afternoon.

At least 6 eruptions, as detected by the Geophysical Institute infrasonic array in Fairbanks, 690 km from the volcano, took place on the morning of January 23, which were observed from Iliamna Airport, 90 km northwest of Augustine, and by the height-finding radars. At least two of these eruption clouds penetrated into the stratosphere reaching heights of 10 to 11 km. Lightning discharges could be seen in some of the clouds. Heavy ash fall was reported at Iliamna Airport on the morning of January 23, reducing visibility to less than 30 m.

Another large gas and dust cloud was erupted at 16:32 local time on January 23, which leveled off at about 8 km. A few higher velocity gas jets injected material into the stratosphere to a height of 11 km. Sand-size particles from this eruption fell later that evening in Homer, 110 km south-southeast and downwind from Augustine. Fine ash from this eruption reached Anchorage, 280 km northeast of Augustine, in the early morning hours of January 24. At least 6 more eruptions occurred up to January 25, with ash falling out over the entire Kenai Peninsula including Anchorage and southeastern Alaska.

The vent clearing eruptions of January 22-25 removed a large part of the 1964 lava plug dome (0.1 km^3) and left a new crater breached to the north 200-250 m deep as based on radar altimeter data acquired during an aerosol sampling mission on February 1 (W. H. Zoller, personal communication). Numerous pyroclastic flows, surges and mud flows descended all slopes of the volcano, but mainly on the north and northeast side where they formed a new point of land of about 0.3 km^2.

A paper on the atmospheric effects of this initial explosive phase based on infrasonic observations, NOAA-4 satellite photographs, radar coverage, ground-based and aerial photo documentation, ash fall distribution, and damage to commercial and military aircraft is in preparation (Kienle and Shaw, 1977). With emergency funds from the State of Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys, and from the OCSEIAP, the volcano was first visited from January 29 to February 5, 1976.

The Burr Point research station (northwest tip of the island) had been severely damaged by blast and thermal effects of one or more _nuées ardentes_ and scoria and ash falls during the eruptive activity of January 22-25, 1976 (Figure 5). The island was mantled by ash, and at several pyroclastic flows had been deposited on the lower northeast slope of the volcano (east of Burr Point). One of these had reached the sea, and a fumarole field was actively degassing on the distal end of the pyroclastic flow where the hot ejecta had impacted on water-saturated

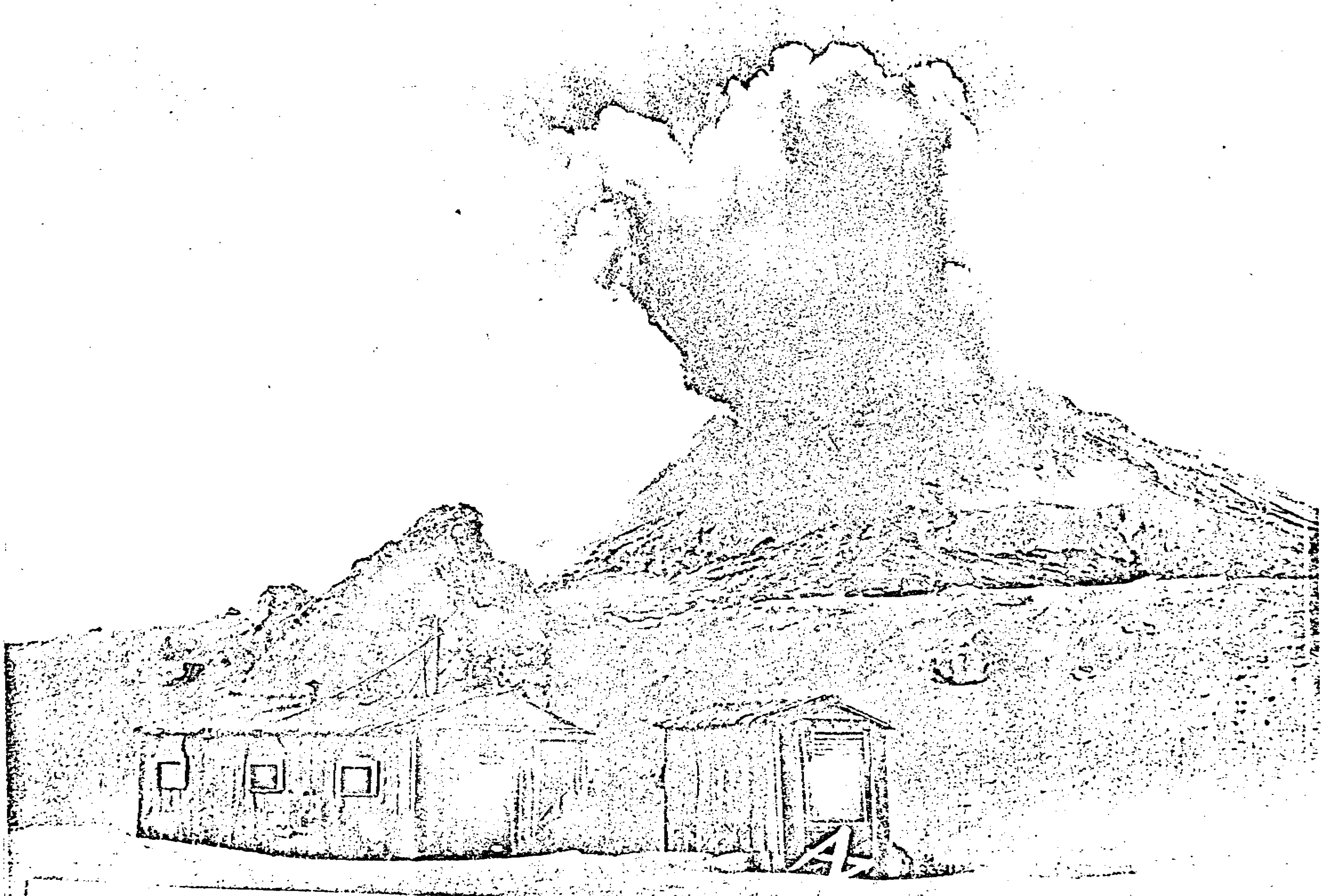

Figure 5. University of Alaska Augustine Research Station at Burr Point shows damage from the eruption. Note dent in smaller building and glass blown out of windows in main structure. Photo taken Jan. 30, 1976, by Juergen Kienle.

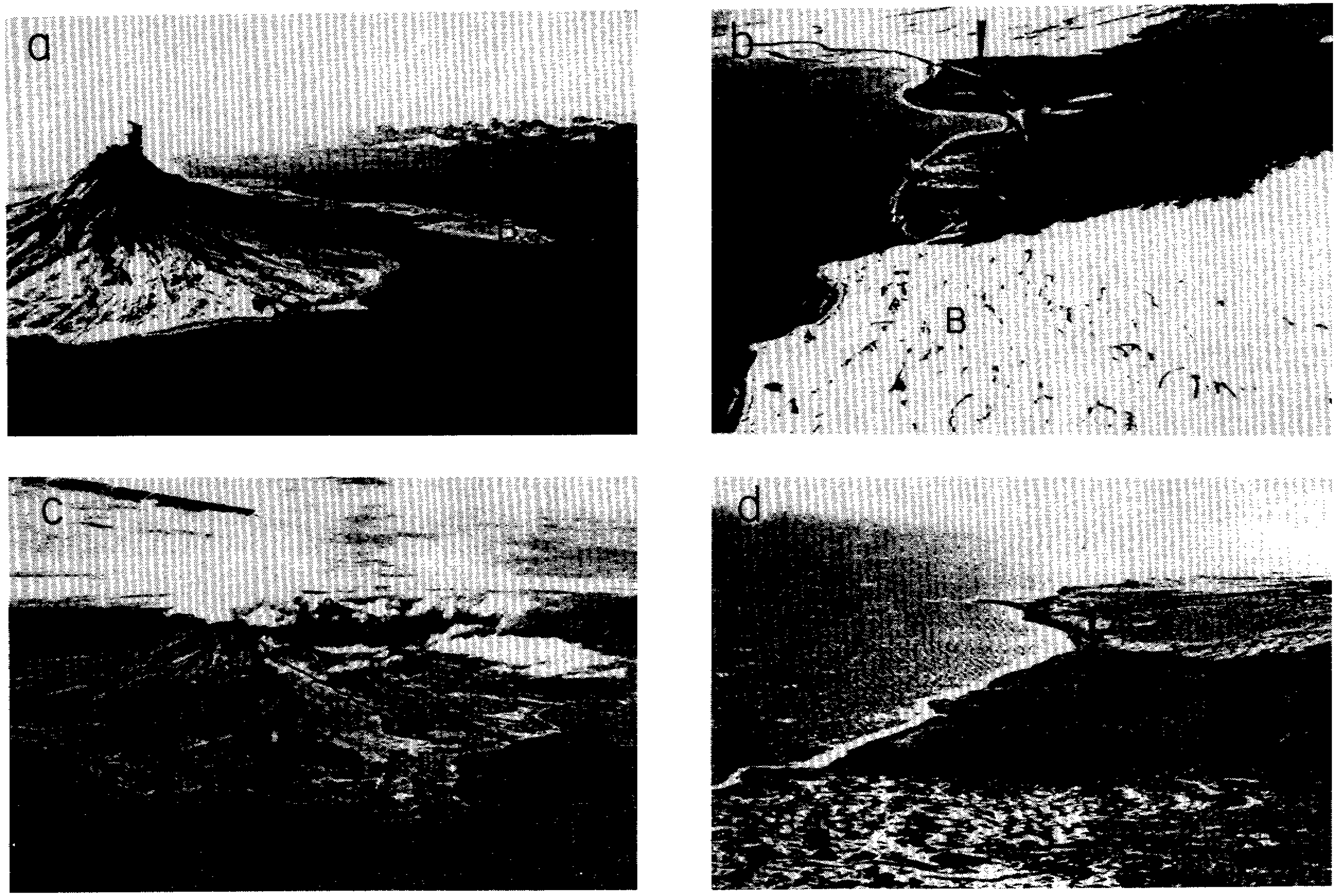

Figure 6. (a) Augustine from the east, February 1, 1976, showing new nuee ardente deposits on the NE beach. (b) Close-up of the nuée deposits, looking east, February 1, 1976; arrow points to old beach line, B marks the Burr Point Research Station of the University of Alaska. Note steam rising from the deposit seaward of the old beach line. (c) Augustine from the north, June 13, 1976, showing the distribution of nuée ardente deposits. (d) Same beach as in (b) on February 27, 1976; the early February nuée deposits have altered the beach line significantly. Photographs a, b, and c by R. E. Wilson; d by J. Kienle.

beach sands (Figures 6a and 6b). Temperatures greater than 400°C were measured 9 feet (2.7 meters) below the surface of the upper pyroclastic flow unit east of the research station.

After 14 days of quiescence, Augustine erupted again in the early morning hours of February 6, when muddy rain and ash fell on the Kenai Peninsula, 180 km northeast of the volcano and an infrasonic signal was recorded in Fairbanks. Very frequent ash explosions and nuées ardentes were reported by the crew of a University of Washington research airplane and Homer/Seldovia residents from February 6 to 15 (Hobbs et al., 1977).

During this period a new summit lava plug dome was intruded. The new dome reached a height of about 250 m above the new January 23 crater floor. A blocky lava flow issued from the base of the new dome filling much of the remaining crater. The flow was said to be glowing at night. Gas and dust were steadily emitted to low altitude levels during the week following the extrusion of the new dome and lava, but no infrasonic wave-generating explosions were recorded during that time.

The volcano was quiescent until early April. From April 13 to 18, renewed growth of the new lava dome was accompanied by the shedding of numerous hot block avalanches and pyroclastic flows mainly toward the north which this time did not reach the sea. This activity was eye-witnessed by University of Alaska personnel on the research vessel "Moana Wave."

Since late April the volcano has remained in a steady state stage of gas and steam effusion.

C. Seismological Aspects of the 1976 Eruptions of Augustine Volcano

Since the regional seismic networks of the U.S. Geological Survey and the University of Alaska overlap in lower Cook Inlet (Figure 2), efforts were combined in the analysis of the seismicity surrounding the Augustine eruptions. J. Kienle spent March 11 to 20, 1977 at the National Center for Earthquake Research in Menlo Park, to work with J. C. Lahr and a Stanford University Ph.D. candidate, J. W. Reeder, on the Augustine problem. A joint authorship paper by Reeder, Lahr and Kienle is in preparation and the following summarizes some of the principal preliminary results:

1. Precursor Seismicity (October 1975-January 22, 1976)

Microearthquake activity was remarkably low during the year preceding the recent eruptions. The build-up of microearthquake activity began as late as October 1975, only four months prior to the eruptions. From October to January 22, 1976, earthquake activity was still relatively mild, when we registered earthquake swarms on the local Augustine array only (Richter magnitudes less than 1 to 2). A few individual events within the swarms, usually less than 10 per day, were large enough to be barely seen on USGS stations Chekok (CKK), 80 km northwest of the volcano. Significant swarms with 80-160 events/day occurred on October 9, 24, 25, 28, 30, 31. Figure 7, November-December 1975, composes the Augustine seismicity registered at a summit station, with the Chekok seismicity. The Chekok earthquake counts for this early period do not compare very well with the microearthquake counts from Augustine because most of the events seen at Chekok were of such small amplitude that many

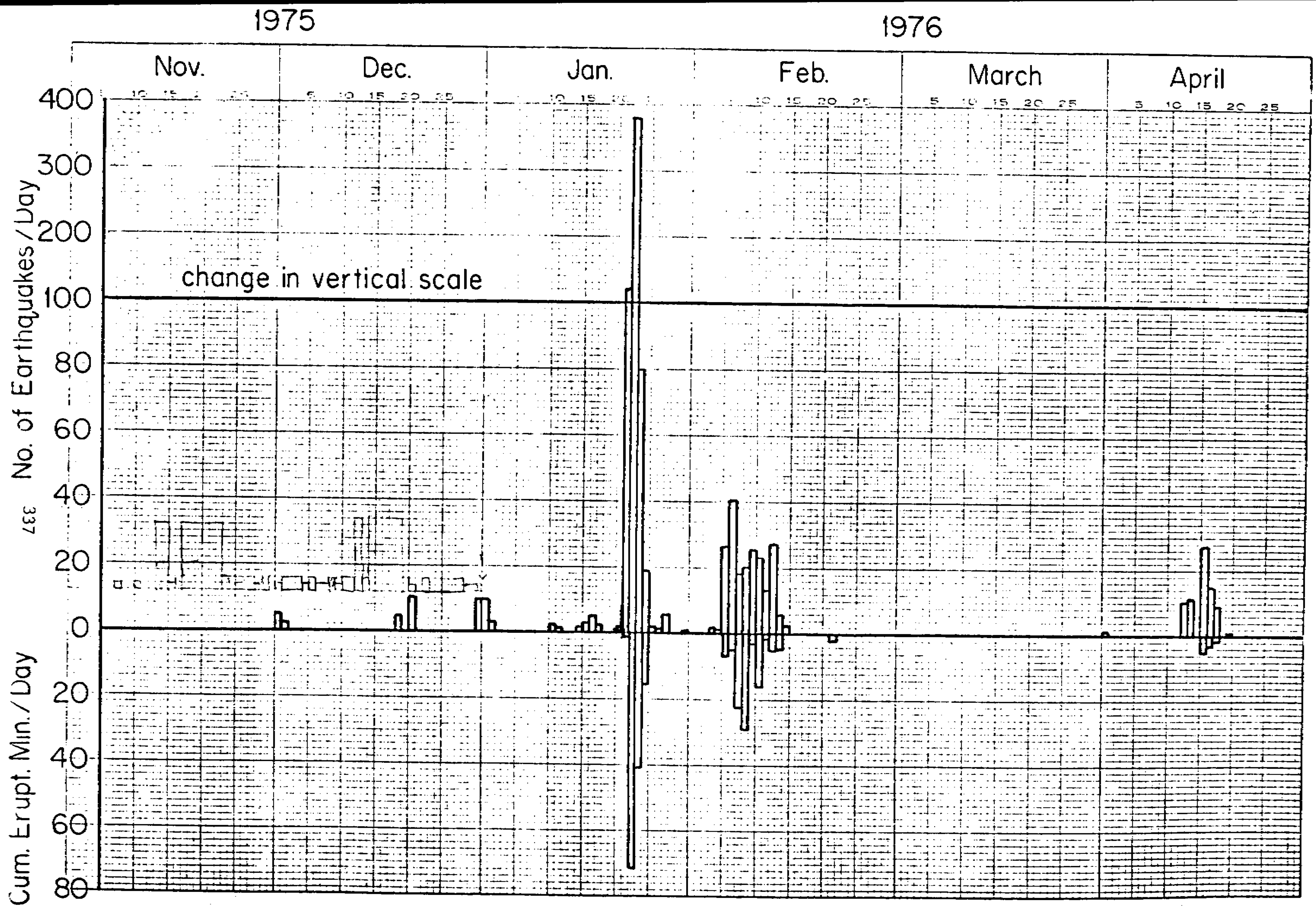

Figure 7. Earthquake activity during Augustine eruption.

were probably missed in the noise. Based on the Augustine data, significant swarms occurred on November 14, 15, 17-23; December 13, 15-19. We judged the November 17 and 23 activity intense enough to send a reconnaissance plane to the island and to announce the event in the Homer press. However, photographs taken revealed no changes at the volcano.

The majority of events up to this time were shallow, originating near the summit of Augustine and generally of too small a magnitude to be recorded on the regional network surrounding Cook Inlet. Preliminary activity on the island was, however, severe enough to put our entire five-station seismic array out of commission by January 2. On that date, we lost four stations, three of which relayed their data through a common transmitter. This repeater had been damaged already on December 21, probably by preliminary volcanic activity, resulting in very noisy data. On our first visit to the island after the January eruptions, we could only find one station on the south side of the volcano. Here, an air blast had ripped the antenna cable out of its socket, probably on January 2, when the station suddenly failed. All other stations had been deeply buried by mud flows and nuées ardentes.

Having lost our island data base, we had to rely on the regional network from January 2 onward to monitor the volcano. Up to January 21, Chekok only saw very few events per day originating at Augustine.

2. Seismic Signatures of the Eruption Phase (January 22-end of April, 1976)

Interestingly enough, no precursor seismicity was observed at Chekok, 80 km from the volcano, prior to the first infrasonic wave-generating eruption on January 22, 1759 U.T. The earthquake activity picked up dramatically from this time on (50-100 events/hr at Chekok) culminating in an intense major earthquake swarm which lasted 3 hours from 03 to 06 U.T. on January 23.

We interpret this intense earthquake swarm just prior to the main eruptive phase as the breaking up of the material blocking the conduit system, as large volumes of gas and magma began to move upward from a depth of about 6-10 km (Johnston et al., 1977). The level of seismicity dropped somewhat to generally 50 or less events/hr in the next 8 hours until the main vent-clearing eruption phase, which began with an infrasonic wave-generating explosion at 1347 U.T. The exact timing of the following vent clearing eruptions up to January 25 will be discussed later under the heading of tidal triggering. Chekok recorded in excess of 100 earthquakes/day on January 22 and of 300 events/day on January 23; by January 24 the seismicity level had dropped to 80 events/day and was normal by January 26 (Figure 7). Figure 7 also shows cumulative eruption duration/day which amounted to some 72 minutes on the most active day, January 23.

Figure 8 shows a preliminary epicenter plot of locatable Augustine events from January 22 and 23, 1976. The earthquakes were located using a master event technique choosing a well located shallow master with an epicenter near the summit of Augustine determined by stations surrounding the island (BIG, CKK, ILM, RDT, RED, NNL, SLV, KDC, CDA, MNC and OPT). The elongated epicenter distribution in a northeasterly direction is most likely an artifact of trying to locate with a one-sided station distribution (BIG, CKK, RDT, NNL). Depths are generally shallow with

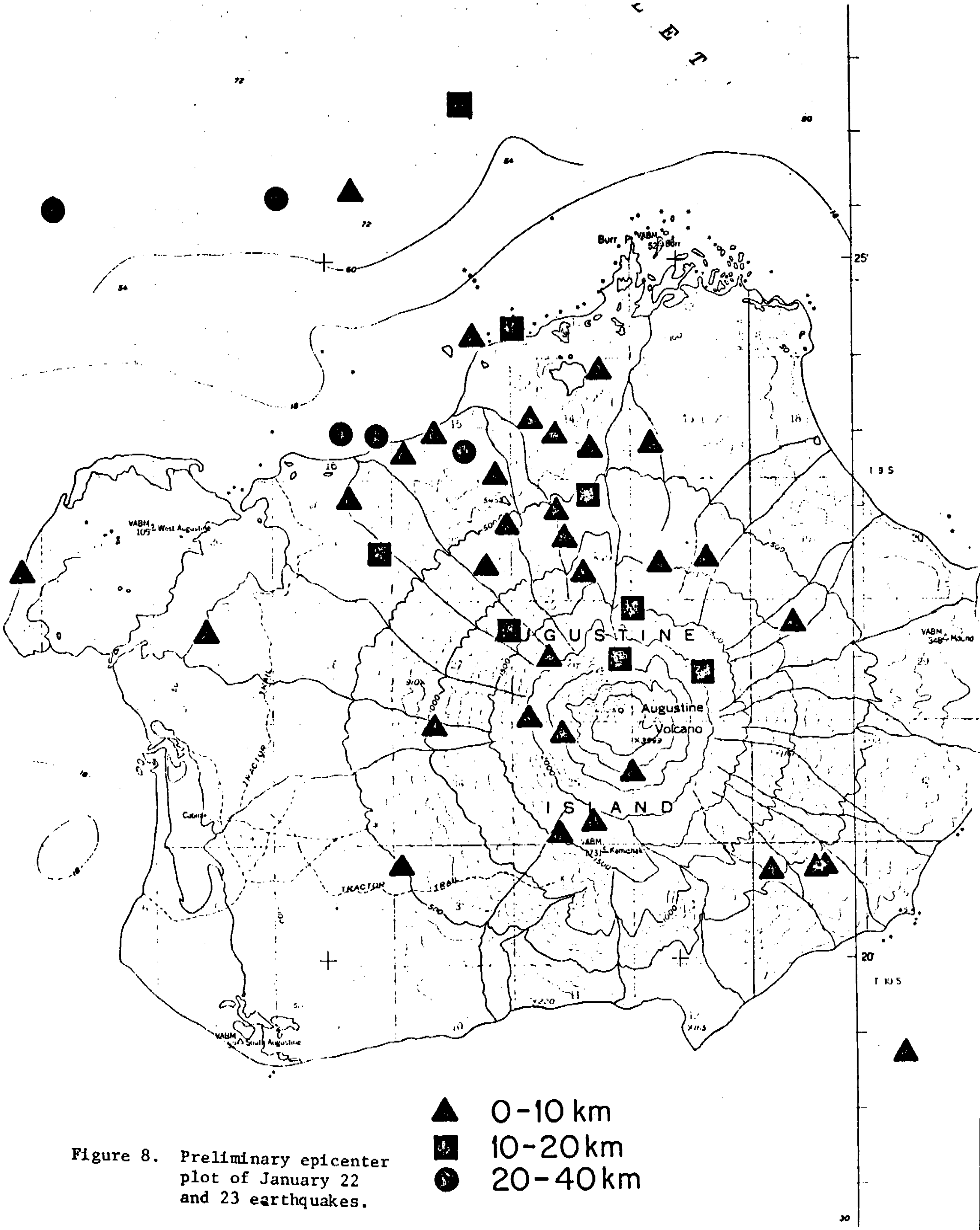

Figure 8. Preliminary epicenter plot of January 22 and 23 earthquakes.

most hypocenters located at less than 10 km, magnitudes were rather uniform, ranging from about 1.5 to 2.5 on the Richter scale. The next steps that we might try to refine the data may involve better crustal models and fixing the epicenters at the summit of Augustine in order to refine our depth control.

Between 20 and 40 earthquakes/day were recorded at CKK during the second cycle of eruptive activity from February 6 to 13. On February 12 and 13 our station (CDA) 50 km south of Augustine recorded continuous harmonic tremor. We predicted in a press release that magma may be moving up in the conduit, and we could later confirm that a new dome had been extruded.

As mentioned before, by the end of February we had managed to re-establish a new 3-station array on the island itself, and we have had continuous data from Augustine ever since. Little activity was observed from February 16 to early April, except for some swarm activity from March 15 to 25. However, in early April we began to record noise trains which dramatically increased in number up to April 12. Based on this increase and considerations of tidal triggering, we predicted a new phase of activity. The volcano was in almost continuous eruption from April 13 to 18 as the new dome underwent renewed growth. The noise trains were most likely caused by numerous hot block and ash flows which were shed off the new lava dome. The seismic activity tapered off by April 19 and returned to normal by April 24. Since then, the volcano has remained seismically quiet.

C. Tidal Triggering of the 1976 Eruptions

There is a strong suggestion that the Augustine eruptions were tidally triggered. The largest short-period stresses (12 and 24 hours, 14.7 days) to which the earth is subjected come from the solid-earth tides. Figure 9 compares the variations of the solid-earth gravity tide to initial eruptions of major eruptive cycles at Stromboli (after Johnston and Mauk, 1972) and Augustine. The tidal plots (31 days) begin 10 days before the eruptions. There is a clear correlation between eruption times and the fortnightly modulation envelope for both volcanoes. Striking is the fact that Augustine erupted again 14.9 days after the initial explosions after a period of quiescence. The tidal period is 14.7 days! Figure 10 compares eruption times to the short-period tides (12 and 24 hours) and also the ocean tide. There is a fairly good correlation between eruption times and high ocean tide (maximum loading) the earthquake swarm associated with the breaking up of the conduit system. We are working on the problem of the observed events seasonal periodicity of microearthquake swarms since 1970 and of tidal triggering which appears to be related to the thermal and mechanical evolution of the volcano betweeen and during major eruptive cycles.

D. Pyroclastic Flows and Surges

The main direction that the pyroclastic flows and surges associated with the recent Augustine eruptions followed was to the north and north-east, where some of the flows entered the sea east of Burr Point, 4.5 km from their source (Figure 8). The pyroclastic flows (*nuées ardentes*) exhibited extreme mobility as they surged down the volcano on an air cushion formed by trapped air, as well as large volumes of gas released from the autoexplosive magma leaving the cloud. For example, Figure 6b shows the former beach bluff which the flow simply jumped leaving no deposits. Seared grass blades which grew on the bluff were left standing.

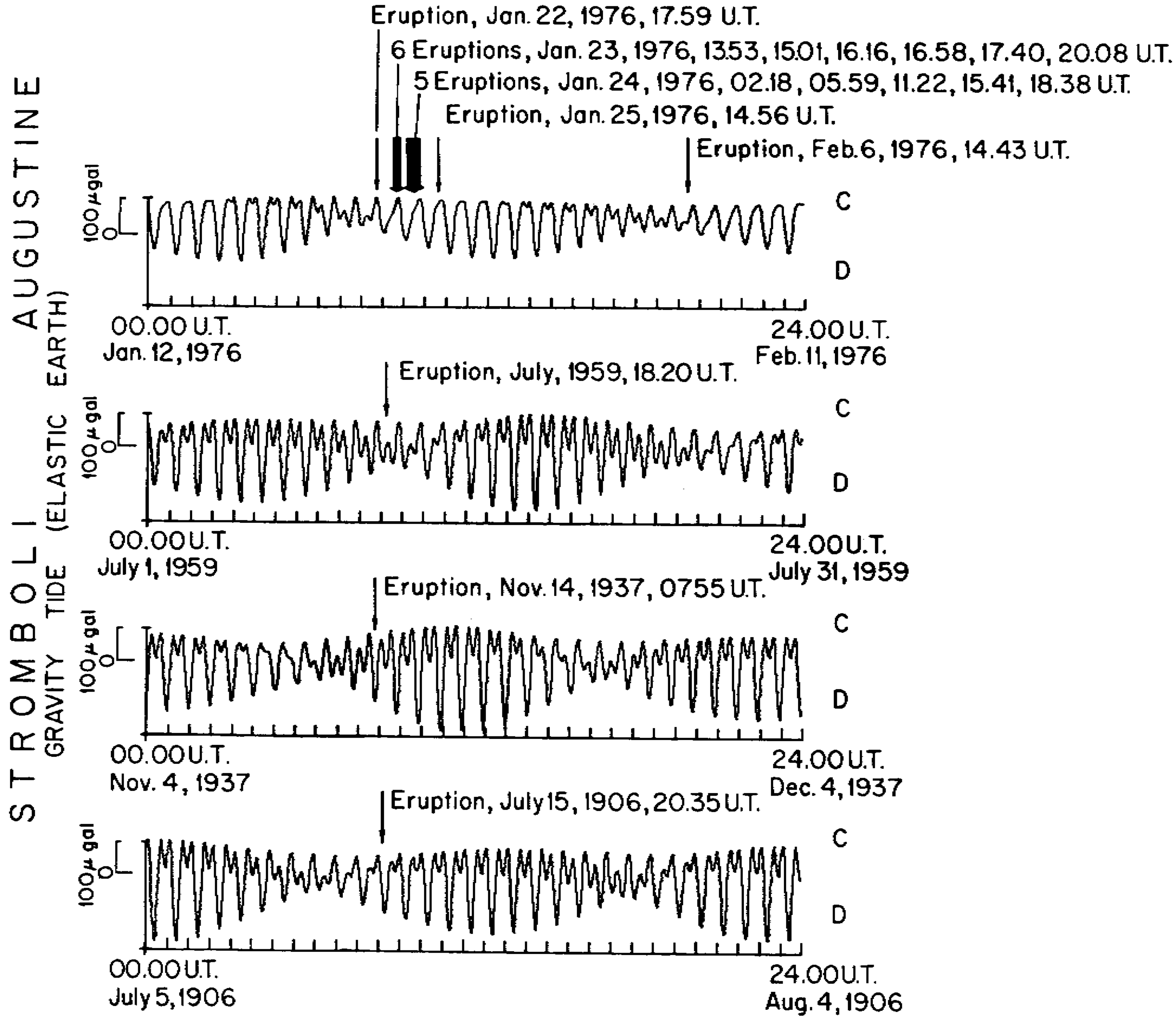

Figure 9. Solid-earth tides and eruptive activity.

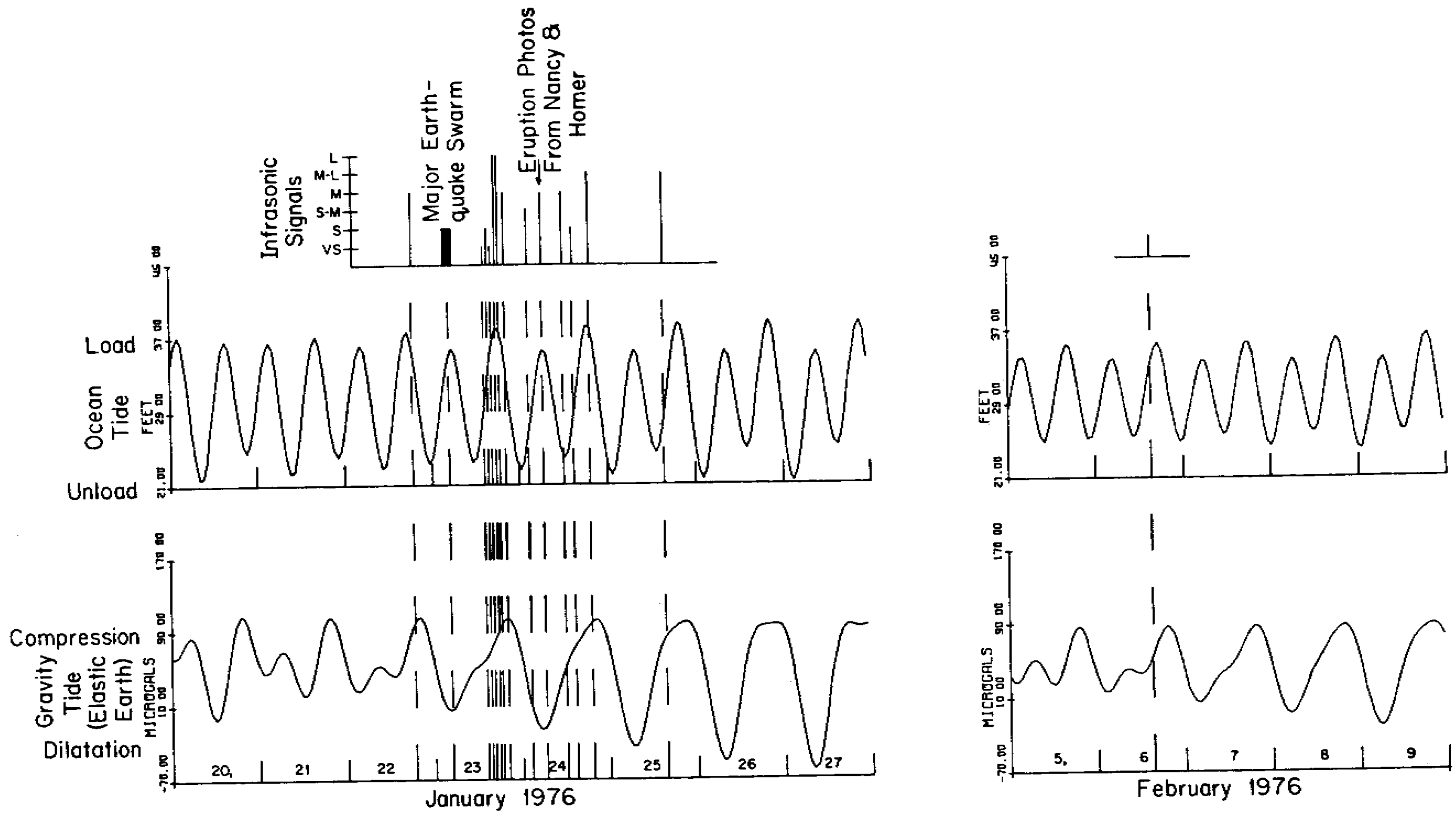

Figure 10. Short-period tides and Augustine eruptions.

Hobbs et al. (1971) estimated from aerial photography with a sequence camera that some of the smaller February nuées traveled with a speed of 50 m/sec (180 km/hr).

The distribution, petrology, stratigraphy and cooling of the pyroclastic flow are now being compiled in two papers by Johnston, Schmincke, Forbes and Kienle (1977) and Lalla and Kienle (1977). A joint proposal to study the hydrodynamics of pyroclastic flows at Augustine, clearly with strong hazard complications, has just been submitted jointly with M. Sheridan from Arizona State University to NSF.

The following are some of the principal results from this work:

1. Petrology of the Pyroclastic Flows

During the first visit to the island, two units were recognized in the pyroclastic flow deposits which had descended the northeast flank of the volcano--an initial flow unit, composed of ash, white and banded pumice, and blocks of dacite and andesite, and an upper unit which contained a higher percentage of ash, white and banded pumice, and large dacite blocks and "bread-crust bombs."

The andesitic and dacitic blocks that characterized the lower unit were rare to absent in the upper unit. These blocks are accidental and were probably blasted out of the crater rim, including the older domes, by the vent-clearing explosions of January 23. The white pumice is believed to be representative of the initial juvenile magma erupted from the conduit system. The banded pumices which are present in both of these units are of special interest, as there is a significant difference in the chemical composition of the dark versus light layers. The dark layers tend to be more andesitic, and some of the banded pumice blocks show viscous flow structures which appear to be formed from the incomplete mixing of rhyolitic and andesitic magma in a layered chamber. Although we are as yet unsure of the genesis of the banded pumices, banded pumice production was associated with the early eruptive processes, as such pumice was not found in subsequent pyroclastic flows erupted in February.

Returning to Augustine in late February after the eruptive activity of February 6 to 15, we found that the January pyroclastic flows had been covered by more recent flows. The youngest flow unit was characterized by ash, unbanded pumice lapilli and blocks, and vesicular dacitic blocks and bread-crust bombs. Most of this material appears to have been of juvenile origin and derived from the new lava dome which was emerging from the vent during the February activity.

2. Temperature Measurements in the Pyroclastic Flows

The most recently deposited pyroclastic flow unit had developed a large fumarole field by the time we arrived for our second visit. Most of the fumarole vents were rimmed by native sulfur and other sublimates, and the fumarole field extended for two kilometers upslope from the beach line. Some of the fumaroles were caused by the vaporization of water in underlying beach and terrace deposits near the former beach line, but this explanation is not adequate for the fumarolic activity at higher elevations where the underlying surface is composed of preceding pyroclastic flows. The emplacement temperature must have been greater that $600^{\circ}C$ as documented by the measured thermal profile shown in Figure 11. Temperatures as high as $590^{\circ}C$ were measured in the more highly pressured fumaroles. We were unable to drive casing deeper than

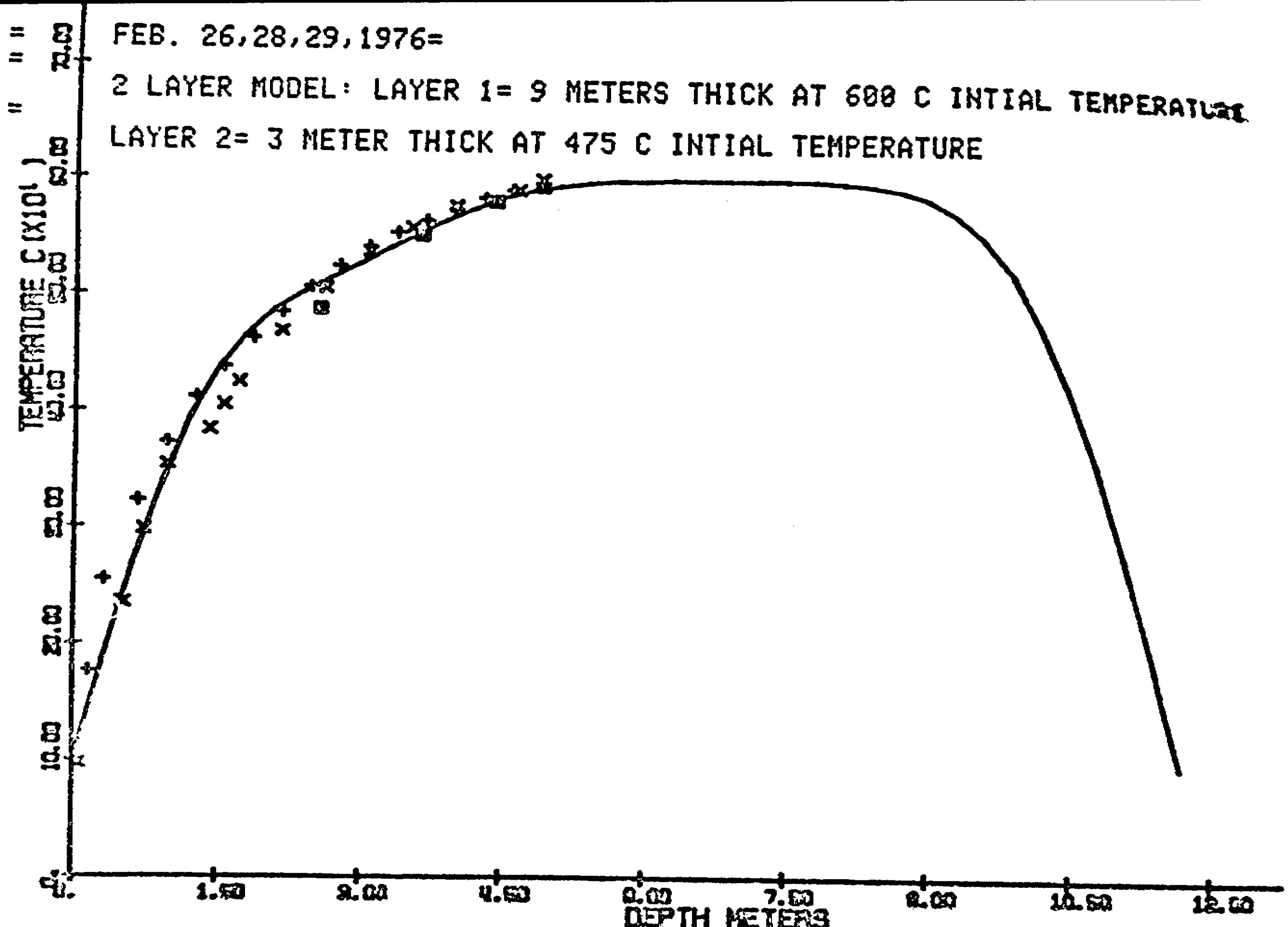

Figure 11. Two-layer conductive cooling model of Augustine pyroclastic flows (solid line). The model assumes deposition of the two flows in rapid succession, within a few hours (0.2 days) of each other, 18 days before the temperature profiles were taken, i.e. on February 10, 1976. The surface temperature boundary condition was 100°C. The bottom temperature boundary condition was 0°C. The diffusivity was assumed to be 0.004 cm^2 sec^{-1}. Measurements on February 26, 1976 shown as squares, on February 28 as crosses. and on February 29 as pluses.

about 17 feet (5.1 meters), so we did not obtain the maximum temperature or point of reversal temperature which must exist at some unknown depth in the flow unit. Based on these measurements, however, we are relatively sure that this particular flow is undergoing a welding process in a zone of unknown thickness at a depth greater than 16 feet. Deeper soundings and sampling should produce exciting data and improve our understanding of welding phenomena in pyroclastic deposits.

The data now available are taken from a set of 8 holes ranging from 0.5 to 5 meters in depth. Temperature measurements were made at the distal end of the pyroclastic flows in February 1976 and again on 26 September 1976. These data show the development of a steam table within the top 4.3 m of the deposit. The temperature of this steam layer is $99 \pm 0.1^{o}C$ implying a nearly pure water vapor dominated system.

Preliminary modeling by D. J. Lalla has shown that cooling from the time of deposition to the first measurements in late February 1976 was predominantly conductive (Figure 11). The model consists of two layers, the lower one being 9 m thick at $600^{o}C$ and the upper one 3 m thick at $475^{o}C$ initial temperature, emplaced within less that 0.2 days; hence they might be two parts of the same eruption. Conductive cooling alone for 8 months (Figure 12) does not adequately explain the measured temperature profile of September 26, 1976 (Figure 12). Using precipitation records from the Iliamna weather station, 90 km northwest of Augustine, a rough estimate of the vaporization energy for 8 months of rainfall in the area was made. This energy accounts within 10% for the energy difference between the conductive cooling model (Figure 12) and the measured temperature profile in the top 4 m of the pyroclastic flow. This finding is similar to the results obtained by Wright et al., 1976,

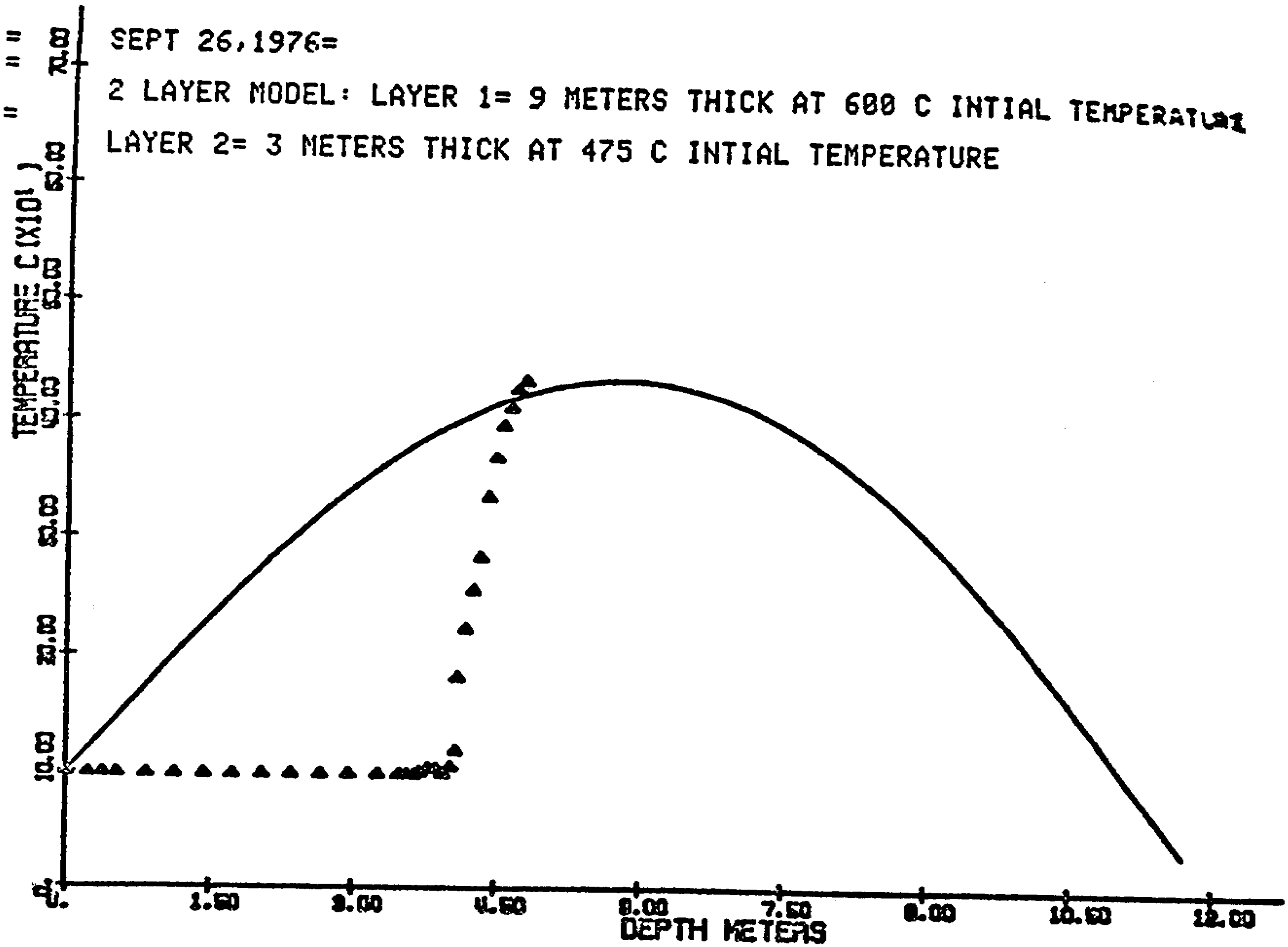

Figure 12. Same conductive cooling model as shown in Figure 1 after 230 days of cooling. The observed temperature profile shown as triangles does not match simple conductive cooling and now indicates a completely vapor dominated upper part of the flows at the boiling point of water.

at Hawaiian lava lakes, where vaporization of rainfall also accounts for the difference in temperature predicted from conductive cooling and actually measured.

E. Effects on a Man-Made Structure

When we helicoptered to the island in late January after the first set of explosions, we found that a small hut which had been built on the northeast flank of the volcano in the earlier years of the project had been completely destroyed by one of the glowing avalanches. The main research station at Burr Point, a corrugated aluminum building (Figure 13) had sustained major damage from air blast and thermal effects accompanying *nuée ardente* eruptions, although relatively little ejecta had fallen on the site (see Figure 6 for location of Burr Point--area B).

The location had been chosen for proximity to a sheltered harbor for resupply and access by sea. Additionally, the two corrugated aluminum buildings were sited on the lee side of a small hill for protection against possible blast effects--a provision which proved totally inadequate for the January *nuée ardente* activity.

The site and the surrounding low hills were mantled by a relatively thin blanket of ash lapilli and small blocks of pumice and andesite. Residual clumps of charred grass projected through the ejecta blanket, and driftwood along the beach was charred on the side toward the volcano though relatively undamaged on the opposite side. Drums of jet fuel cached at our helicopter pad were not ignited, although paint on the barrels was discolored. The helicopter pad was not in the lee of the hill, and the barrels were nearly covered by the snow and ejecta. All of the windows were blown out of the north side (seaward side) of the

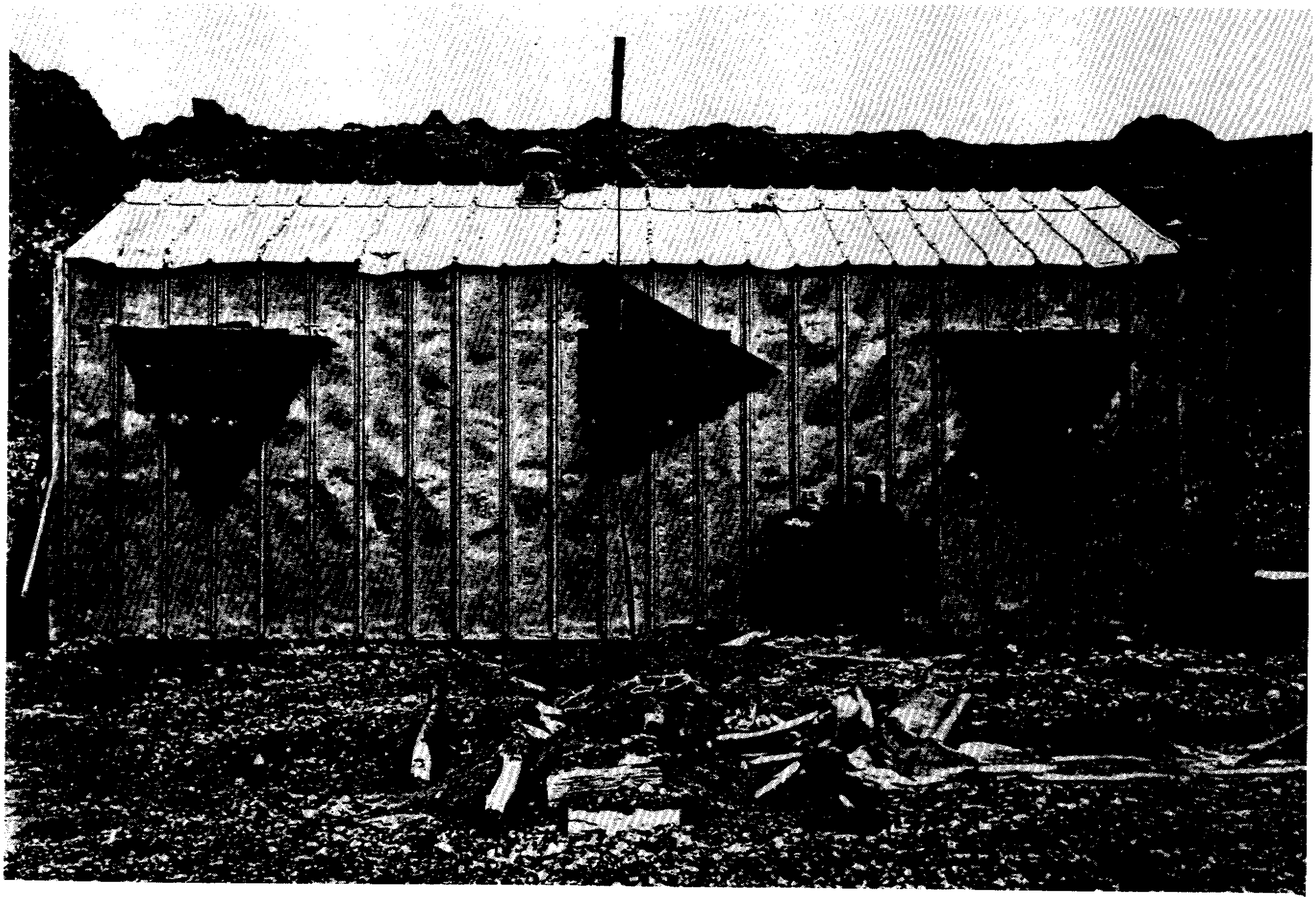

Figure 13. Damage to Burr Point camp.

main building, which faced away from the volcano. The corrugated aluminum sheathing was also dented in from the same side. The sheathing was torn loose from the east end of the building and two mattresses were incinerated near the window opening. Mattresses in protected positions were not ignited. The roof had been pierced by falling ejecta ranging in size from lapilli to small blocks. The floor was covered by about 5 centimeters of ash. A vertical 2 inch x 4 inch antenna support on the roof was charred on the side away from the volcano, uncharred on the other side. Exterior covering on R-G4U coaxial cable leading to the support was also partially melted. A plastic towel holder located under the kitchen window sill showed the effects of partial fusion, and a plastic measuring cup on a shelf at window level was also partially melted. Some of the paper wrappings and cartons on these same shelves showed incipient charring. A battery which was sitting on the floor opposite a window also showed the effects of incipient melting.

Based on the damage discussed above, we conclude that the camp was overrun by at least two *nuées ardentes*. Considering the relatively thin blanket of ejecta and the similarity of the pumice and lithic fragments to that in the lower pyroclastic flow unit in the January series, we deduce the following history:

(a) At least two of the major explosions of the morning of January 23 were accompanied by large *nuées ardentes* down the northeast slope of the volcano.

(b) The research station was not in the path of the basal inertial flow which turned east, but was overrun by two turbulent hot gas and dust clouds, which initially formed above the avalanche but then detached from the main flow and traveled over Burr Point and out to sea.

(c) The dust cloud flowed over the small hill mountainward of the buildings and formed a back eddy which dented the aluminum sheathing on the north side of the building and broke the windows.

(d) Gas and ash of a hot dust cloud passing over the camp flowed through the window openings, igniting mattresses and partially melting low-temperature plastics.

(e) Perforations in the roof and walls were made by small bomb trajectories.

Appendix 1

Field Operations April 1, 1976-March 31, 1977

Time Period	Means	Personnel	Purpose
Aug 3-Aug 12	--	Pulpan, Kienle, Estes, Stechman	Move recording equipment to larger quarters. Service of SHU, CDA, Augustine Is. stations.
Aug 10-Sept 1	--	Schmincke, Johnston	Post eruption field work on Augustine Is.
Sept 18-Oct 12	UH1 H	Stechman, Estes, Kupiec	Annual seismic station service. All stations except Cook Inlet and CHO, CHI.
Sept 20-Sept 25	Surveyor	Stechman	Service CHO, CHI.
Oct 13-Oct 18	UH1 H	Kienle, Spies, Stechman	Service CDA, MCN, BRB, OPT, Augustine stations.
Sept 24-Sept 28	Surveyor	Kienle, Lalla, Johnston, Holmgren	Moved BRB; attempted service of OPT, RED. Survey of pyroclastic flow from Augustine eruption
Oct 19-Oct 25	--	Siwik	Calibration of Homer equipment; new time standards
Nov 22-Nov 26	--	Siwik, Estes	Repair of equipment in Homer.
Oct 14-Oct 16	--	Siwik, Gregory	Repair King Salmon-Big Mountain telemeter link.
Jan 4-Jan 6	--	Siwik	Install preamplifier in King Salmon-Big Mountain link.
Feb 22-March 4	Commercial plane; USCG helicopter	Siwik	Service of SII and repeater at Cape Chiniak and Ugak Is.
March 14-March 18	--	Siwik	Channel recalibration in Homer.

Appendix 2

Listing of Hypocenters of Earthquakes in Lower Cook Inlet, Kodiak, and Alaska Peninsula, February through December 1976

This appendix lists origin times, focal coordinates, magnitudes, and related parameters for earthquakes which occurred in the lower Cook Inlet, Kodiak, and Alaska Peninsula areas. The following data are given for each event:

(1) Origin time in Greenwich Civil Time (GCT): date, hour (HR), minute (MN), and second (SEC). To convert to Alaska Standard Time (AST), subtract ten hours.

(2) Epicenter in degrees and minutes of north latitude (LAT N) and west longitude (LONG W).

(3) DEPTH, depth of focus in kilometers.

(4) MAG, magnitude of the earthquake.

(5) NP, number of P arrivals used in locating earthquake.

(6) NS, number of S arrivals used in locating earthquake.

(7) GAP, largest azimuthal separation in degrees between stations.

(8) DM, epicentral distance in kilometers to the closest station to the epicenter.

(9) RMS, root-mean-square error in seconds of the travel time residuals:

$$RMS = \sum_i (R^2_{Pi} + R^2_{Si}) / (NP + NS)$$

where R_{Pi} and R_{Si} are the observed minus the computed arrival times of P and S waves, respectively, at the i-th station.

(10) ERH, largest horizontal deviation in kilometers from the hypocenter within the one-standard-deviation confidence ellipsoid. This quantity is a measure of the epicentral precision for an event.

(11) ERZ, largest vertical deviation in kilometers from the hypocenter within the one-standard-deviation confidence ellipsoid. This quantity is a measure of the depth precision for an event.

(12) Q, quality of the hypocenter. This index is a measure of the precision of the hypocenter and is the average of two quantities, QS and QD, defined below:

QS	RMS (sec)	ERH (km)	ERZ (km)
A	< 0.15	≤ 1.0	≤ 2.0
B	< 0.30	≤ 2.5	≤ 5.0
C	< 0.50	≤ 5.0	
D	Others		

QD is rated according to the station distribution as follows:

QD	NO	GAP	DMIN
A	≥ 6	≤ 90°	≤ DEPTH or 5 km
B	≥ 6	≤ 135°	≤ 2x DEPTH or 10 km
C	≥ 6	≤ 180°	≤ 50 km
D	Others		

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976		ORIGIN HR	TIME MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
FEB	3	2	6	59.1	60	4.1	152	58.3	133.9	0.	9	115	40	0.13	2.2	4.5	B
	3	19	20	24.1	60	5.6	151	54.0	5.0	0.	3	218	60	0.05	0.	0.	C
	3	21	13	26.1	59	39.1	153	9.1	114.6	0.	6	93	4	0.04	0.8	1.4	B
	4	16	22	21.4	58	9.5	151	13.8	61.4	4.3	7	246	87	0.31	12.0	27.6	D
	4	17	20	36.6	60	53.5	151	51.2	115.1	0.	6	303	72	0.07	9.4	7.3	D
	5	9	36	35.6	60	0.4	149	8.8	1.3	5.2	8	288	149	4.12	205.5	324.4	D
	5	20	59	10.5	61	11.6	153	23.3	5.0	0.	3	253	92	0.02	0.	0.	C
	5	22	41	39.3	60	5.8	153	24.7	156.6	0.	14	124	48	0.62	5.3	5.2	C
	6	0	43	44.9	61	32.6	153	18.3	5.0	0.	3	331	128	1.72	0.	0.	D
	6	1	49	42.6	60	8.7	152	42.8	5.0	0.	3	214	30	0.01	0.	0.	C
	6	3	47	47.6	61	30.4	153	35.2	5.0	0.	3	328	129	0.75	0.	0.	D
	6	0	13	14.3	58	3.0	154	45.3	38.2	0.	9	166	93	4.29	98.4	147.9	D
	9	1	39	33.8	59	59.4	150	25.8	5.0	0.	5	307	138	1.20	132.2	95.9	D
	9	0	33	53.0	59	26.9	152	31.7	86.0	0.	6	139	45	0.05	1.1	2.8	C
	9	3	16	33.7	59	45.3	152	19.8	85.4	0.	6	145	51	0.06	1.3	3.2	C
	9	13	53	24.7	60	39.5	152	31.5	45.9	0.	4	326	30	0.33	0.	0.	D
	9	21	8	54.6	60	45.1	151	4.4	39.6	0.	13	135	98	2.65	20.9	169.2	D
	9	22	56	32.5	58	45.2	152	51.4	84.6	0.	6	264	44	0.18	9.1	6.8	D
	10	7	4	31.1	58	16.4	151	16.8	26.5	0.	4	250	92	0.11	0.	0.	C
	10	7	52	42.8	59	29.2	153	7.1	3.2	0.	6	191	19	10.44	5.8	6.8	D
	10	9	3	13.5	59	21.1	153	26.5	4.1	0.	5	167	35	0.	0.1	0.1	C
	10	8	5	14.1	60	2.7	152	55.4	119.7	0.	4	184	42	0.	0.	0.	C
	10	9	36	29.8	59	22.0	153	29.7	1.8	0.	4	163	45	0.15	0.	0.	C
	10	10	29	21.5	59	33.3	152	57.3	105.9	0.	5	200	18	0.03	1.4	2.4	C
	10	13	36	54.1	59	9.4	153	29.6	85.1	0.	6	169	22	1.60	41.5	47.5	D
	10	14	2	43.4	59	20.7	153	25.9	24.0	0.	6	169	36	0.23	3.5	10.8	C
	10	14	35	11.8	59	46.2	155	0.4	35.1	0.	4	224	44	0.	0.	0.	C
	10	14	55	38.5	59	30.1	151	14.0	5.0	0.	5	285	20	8.00	73.9	25.9	D
	10	15	5	21.3	59	4.6	153	16.3	5.0	0.	6	217	20	13.12	232.9	281.6	D
	10	17	22	7.6	59	18.5	153	30.3	36.9	0.	6	160	39	0.81	11.1	11.0	D
	10	17	30	39.4	59	46.2	153	29.5	143.0	0.	6	102	19	0.10	2.9	8.3	C
	10	17	54	47.9	59	45.7	153	27.4	141.1	0.	5	106	17	0.12	5.7	14.7	D
	10	18	10	26.5	60	15.2	152	22.7	5.0	0.	9	254	28	3.61	562.0	319.7	D
	10	19	15	59.1	59	20.7	153	25.3	20.0	0.	6	171	36	0.11	1.7	6.6	C
	11	22	2	3.0	60	0.9	152	40.1	14.9	0.	4	210	45	1.85	0.	0.	D
	12	0	15	39.6	59	20.5	153	27.0	8.2	0.	4	168	43	0.28	0.	0.	C
	12	0	47	16.4	58	23.9	151	41.4	40.0	0.	7	210	86	6.15	99.2	386.3	D
	12	2	43	35.8	59	21.0	153	25.0	6.6	0.	4	222	44	0.12	0.	0.	C
	12	2	43	46.6	59	25.6	152	27.6	5.0	0.	5	238	80	5.51	191.6	316.7	D
	12	13	14	49.2	61	32.5	151	37.5	0.3	0.	4	309	139	1.68	0.	0.	D
	12	15	53	11.0	60	20.3	150	45.8	17.1	0.	5	311	111	3.73	16.8	1.7	D
	12	16	47	42.9	58	41.1	151	48.2	11.7	0.	7	217	104	8.64	83.9	94.4	D
	12	17	26	53.6	59	21.0	153	25.6	10.7	0.	5	170	44	0.19	3.3	424.1	D
	12	18	57	1.6	59	21.0	153	28.7	7.3	0.	5	165	44	0.24	0.7	1.1	C
	12	22	37	39.6	59	10.1	153	38.6	85.6	0.	5	145	24	0.48	26.1	49.8	D

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
FEB 12	23	25	10.9	59	5.5	153	38.6	99.0	0.	5	138	16	0.93	63.3	113.1	D
13	0	30	36.8	59	23.1	153	28.1	8.4	0.	4	165	48	0.38	0.	0.	D
13	1	47	11.1	59	21.5	153	34.4	26.4	0.	6	146	38	0.98	13.5	45.2	D
13	2	55	23.7	59	52.1	151	47.7	352.5	0.	5	206	45	1.06	149.4	485.3	D
13	7	19	51.7	59	13.4	153	46.3	54.5	0.	4	132	33	0.	0.	0.	C
13	7	26	30.2	60	1.8	153	23.9	36.5	0.	5	145	47	3.53	36.3	26.4	D
13	10	12	10.1	59	51.8	152	10.4	5.0	0.	4	246	70	0.25	0.	0.	C
13	10	30	55.2	59	4.1	153	44.5	104.5	0.	5	142	17	0.92	65.9	116.8	D
13	11	21	52.3	59	20.0	153	45.7	31.8	0.	4	138	44	0.	0.	0.	C
13	13	22	13.7	59	21.7	153	29.7	18.5	0.	4	164	45	0.59	0.	0.	D
13	13	33	22.7	60	9.0	153	48.9	118.7	0.	4	195	31	2.12	0.	0.	D
13	14	49	28.9	59	4.3	153	13.4	5.0	0.	3	278	114	0.48	0.	0.	D
13	15	18	5.6	59	8.1	153	39.9	87.9	0.	5	140	21	0.49	28.3	51.4	D
13	16	7	16.7	59	17.5	153	24.5	11.7	0.	5	175	38	2.04	35.7	558.9	D
13	16	30	16.9	59	30.2	152	33.9	358.0	0.	5	228	82	0.74	66.7	325.9	D
13	18	14	13.4	59	8.9	153	40.1	85.9	0.	5	140	22	0.50	28.2	51.9	D
13	19	57	55.9	59	51.0	153	55.8	243.3	0.	6	100	21	1.22	60.9	275.1	C
13	21	23	16.5	59	51.7	153	36.9	90.6	0.	5	110	36	1.99	10.0	26.8	D
13	22	17	15.5	59	21.6	153	33.7	23.2	0.	6	148	37	1.06	14.4	54.6	D
13	23	34	58.5	59	22.6	153	41.1	11.5	0.	6	129	40	0.94	9.8	633.6	D
14	1	2	22.8	59	49.3	152	37.1	5.0	0.	3	216	68	0.01	0.	0.	C
14	2	20	32.0	59	22.1	153	36.5	10.3	0.	6	140	38	1.06	11.3	828.8	D
14	3	38	10.5	59	40.0	151	56.3	5.0	0.	3	166	29	0.01	0.	0.	C
14	3	43	59.4	59	19.3	153	31.9	0.8	0.	5	155	40	1.23	23.1	121.4	D
14	5	36	44.8	59	21.4	153	42.8	0.6	0.	5	127	42	0.65	14.3	88.7	D
14	5	55	3.5	59	21.7	153	33.5	32.9	0.	6	148	37	0.94	11.8	12.8	D
14	8	12	7.3	60	21.5	153	22.6	175.5	0.	5	212	34	1.82	118.0	254.2	D
14	8	20	36.6	60	55.8	150	38.6	11.5	0.	6	332	129	4.84	220.2	866.2	D
14	10	7	34.6	60	21.6	152	46.4	336.5	0.	4	145	6	1.29	0.	0.	D
14	12	39	49.4	60	10.0	154	11.9	235.9	0.	7	217	23	1.00	48.2	128.6	D
14	13	29	3.6	58	53.8	152	8.6	5.0	0.	3	299	167	1.06	0.	0.	D
14	15	7	47.0	59	46.0	152	54.9	5.0	0.	4	107	73	0.32	0.	0.	D
14	15	37	28.5	59	58.0	153	14.5	59.7	0.	4	161	55	3.03	0.	0.	D
14	0	0	10.2	59	51.3	152	16.5	94.4	0.	5	161	57	2.19	55.3	149.7	D
14	17	14	22.2	59	10.8	153	35.9	7.2	0.	4	152	25	0.02	0.	0.	C
14	19	21	41.2	58	45.1	152	43.2	231.0	0.	4	327	51	0.	0.	0.	C
14	23	56	16.4	58	56.5	153	12.5	5.0	0.	3	302	18	1.46	0.	0.	D
15	1	12	24.9	59	52.4	154	1.8	205.0	0.	6	99	14	0.93	25.1	89.1	C
15	2	1	33.3	59	33.9	152	51.2	5.0	0.	5	111	72	2.48	33.9	534.9	D
15	2	40	32.7	59	14.0	153	45.1	54.0	0.	4	135	33	0.	0.	0.	C
15	15	22	42.0	57	48.6	153	45.9	1.3	0.	9	149	76	1.27	6.7	45.4	D
15	23	40	6.3	60	33.3	156	32.5	140.4	0.	4	304	143	0.01	0.	0.	C
16	0	30	5.7	58	18.2	151	12.3	12.9	0.	7	307	132	0.35	34.0	9.7	D
16	6	56	30.8	60	13.7	151	49.7	56.8	0.	6	238	56	3.00	368.5	540.3	D
16	11	36	43.9	59	58.7	151	29.8	5.0	0.	3	240	56	0.04	0.	0.	C

1976	ORIGIN TIME HR MN	SEC	LAT N DEG MIN	LONG W DEG MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
FEB 16	15 7	36.1	60 13.7	155 45.4	270.0	0.	6	281	89	2.43	443.3	766.6	D
16	15 41	36.6	59 50.8	153 35.5	180.0	0.	4	111	38	0.14	0.	0.	C
16	15 53	5.4	60 17.4	152 34.9	64.2	0.	6	184	17	3.11	134.8	188.0	D
16	17 26	33.1	59 4.7	147 52.8	5.0	0.	4	329	313	4.05	0.	0.	D
16	18 17	4.5	58 56.3	153 38.1	6.0	0.	4	226	6	0.11	0.	0.	C
16	20 3	41.7	59 17.9	152 54.5	193.9	0.	5	199	43	0.73	41.1	113.9	D
17	2 5	39.8	60 38.2	151 35.6	58.4	0.	6	290	69	3.18	296.1	220.9	D
17	7 9	32.6	60 12.7	149 46.8	5.0	0.	3	313	130	5.54	0.	0.	D
17	8 19	32.7	59 4.3	152 54.0	122.7	0.	6	248	38	0.49	28.6	41.9	D
17	8 31	47.2	60 24.5	153 35.2	299.7	0.	5	230	44	1.32	170.0	534.7	D
17	8 53	45.8	60 36.0	151 50.2	53.7	0.	7	285	55	3.10	202.7	151.4	D
17	13 46	33.0	59 14.5	153 45.9	64.5	0.	4	248	55	0.	0.	0.	C
17	19 46	9.2	58 23.8	154 23.8	34.7	0.	6	223	57	2.10	61.4	25.2	D
17	19 55	17.4	57 5.7	154 52.2	5.0	0.	4	311	140	2.39	0.	0.	D
17	20 45	51.1	59 49.7	153 7.0	5.0	0.	5	98	64	2.16	29.4	833.6	D
17	21 50	15.9	58 56.8	153 34.7	9.8	0.	7	192	3	0.32	4.3	1.9	D
18	3 48	30.5	59 56.9	153 24.0	186.2	0.	5	122	34	0.09	5.6	19.6	D
18	4 50	37.9	59 5.2	153 11.0	143.9	0.	5	225	24	0.20	14.8	27.4	D
18	6 36	53.6	60 3.2	152 10.7	174.0	0.	6	192	52	1.92	90.1	209.9	D
18	9 20	9.4	59 4.5	151 45.2	46.7	0.	5	250	45	0.05	4.3	6.2	D
18	10 16	5.1	60 1.5	151 48.9	5.0	0.	7	218	63	3.30	46.4	34.3	D
18	10 26	40.5	60 17.5	152 9.9	5.0	0.	5	227	36	1.22	42.5	48.0	D
18	11 16	3.8	58 38.0	151 20.8	2.8	0.	4	313	156	0.85	0.	0.	D
18	12 6	12.5	58 56.3	153 38.0	5.0	0.	5	227	6	0.31	167.2	568.3	D
18	15 20	21.8	59 49.8	153 2.6	242.5	0.	7	103	22	1.32	46.2	202.4	C
18	19 4	57.8	57 17.2	154 11.4	31.7	0.	9	240	96	4.17	106.8	43.9	D
18	20 0	4.5	59 39.0	153 5.2	5.0	0.	4	187	73	2.86	0.	0.	D
18	20 33	45.0	59 55.2	152 50.2	2.0	0.	4	122	55	0.25	0.	0.	C
18	22 36	10.8	58 42.8	154 49.1	41.7	0.	8	147	54	2.51	29.9	393.2	D
19	2 39	31.0	58 56.8	153 38.6	4.9	0.	4	217	6	0.	0.	0.	C
19	3 35	3.2	59 29.9	152 8.1	75.9	0.	5	138	31	0.10	3.3	7.0	D
19	4 23	5.3	58 47.8	152 44.0	11.7	0.	4	292	49	1.55	0.	0.	D
19	5 11	39.0	59 25.2	151 19.2	11.5	0.	4	284	15	0.01	0.	0.	C
19	6 30	14.3	63 8.5	149 41.3	33.5	3.5	6	95	175	0.18	2.3	315.1	D
19	7 11	32.4	59 20.3	153 25.8	116.5	0.	7	106	36	0.06	1.2	2.9	B
19	7 49	32.6	62 14.8	151 16.6	70.1	3.9	14	104	99	0.54	4.4	14.6	C
19	8 52	17.5	57 2.0	149 21.1	2.3	0.	5	319	204	0.24	256.5	85.9	D
19	9 4	24.0	59 47.4	153 28.9	155.8	0.	11	95	20	0.30	4.5	7.4	C
19	10 34	55.1	58 47.8	152 52.2	25.6	0.	5	293	42	0.25	19.4	8.4	D
19	11 45	44.3	61 46.3	150 38.5	5.0	0.	5	327	189	1.39	476.0	416.4	D
19	13 55	35.9	60 8.8	152 39.9	110.9	0.	7	152	31	0.13	3.8	7.3	C
19	14 57	42.0	59 57.8	152 8.0	5.0	0.	4	185	61	0.90	0.	0.	D
19	15 51	32.0	60 14.3	151 40.2	5.0	0.	4	248	64	0.06	0.	0.	C
19	20 52	47.9	59 8.4	153 17.5	0.5	0.	5	202	24	3.03	5.5	17.8	D
20	3 9	2.4	53 35.4	157 55.6	0.6	0.	6	291	111	9.09	675.5	758.4	D

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
FEB 20	4	5	40.0	58	45.2	155	8.9	128.9	0.	6	190	67	0.15	4.7	7.8	D
20	4	26	38.9	59	7.1	153	18.7	0.1	0.	4	203	22	0.47	0.	0.	D
20	4	41	41.3	60	16.5	153	4.0	169.6	0.	4	164	22	0.	0.	0.	C
20	9	33	22.0	58	35.3	154	33.9	159.1	0.	5	282	61	0.14	27.7	35.5	D
20	23	56	23.2	59	51.8	152	5.2	5.0	0.	4	178	52	3.10	0.	0.	D
21	1	31	33.7	60	44.4	151	46.7	228.5	0.	4	329	65	0.80	0.	0.	D
21	7	48	13.5	60	56.6	150	16.7	0.1	2.3	5	317	148	2.07	551.0	569.7	D
21	11	31	29.2	60	15.5	153	20.3	5.0	0.	3	184	36	0.01	0.	0.	C
21	13	32	6.9	59	23.3	154	31.4	12.5	0.	4	120	37	0.23	0.	0.	C
21	16	32	30.0	59	49.1	152	35.3	96.9	0.	4	218	40	0.	0.	0.	C
21	21	44	15.4	58	56.6	153	38.1	5.0	0.	3	221	6	0.01	0.	0.	C
21	22	27	19.9	59	32.5	152	33.9	5.0	0.	5	227	85	3.66	103.2	181.2	D
22	0	20	12.4	60	6.6	151	7.7	5.0	0.	4	269	75	0.17	0.	0.	C
22	2	11	29.0	60	18.2	151	12.2	5.0	0.	4	274	87	0.84	0.	0.	D
22	5	56	23.5	60	9.6	153	51.5	197.5	0.	4	201	30	0.	0.	0.	C
22	7	15	55.4	60	19.1	152	41.0	25.0	0.	4	167	14	0.73	0.	0.	D
22	7	36	29.5	60	12.4	153	34.7	5.0	0.	5	189	45	4.34	718.3	792.9	D
22	14	53	37.8	60	14.2	152	14.4	117.3	0.	7	212	35	0.28	11.8	19.9	D
22	16	43	7.1	60	22.8	151	16.6	5.0	0.	5	277	82	0.86	51.4	912.1	D
22	17	15	16.5	59	25.5	152	36.4	5.0	0.	4	140	58	0.01	0.	0.	C
22	17	31	53.6	60	10.3	152	37.4	110.1	0.	5	160	28	0.08	4.2	9.6	D
22	17	48	21.2	59	47.1	152	47.3	5.0	0.	3	204	70	0.	0.	0.	C
22	21	39	30.5	60	13.9	153	2.4	159.1	0.	10	150	25	0.36	8.2	13.0	D
22	22	29	22.0	59	19.3	153	19.6	5.0	0.	5	183	40	4.40	8.2	13.6	D
22	22	43	30.4	59	43.3	147	29.9	38.4	3.5	13	116	73	1.86	29.1	44.5	C
23	0	26	7.8	58	47.5	153	6.9	5.0	0.	3	301	30	0.12	0.	0.	C
23	1	55	40.7	58	58.2	153	36.3	4.8	0.	4	182	4	0.	0.	0.	C
23	5	12	21.7	59	28.1	153	14.3	2.3	0.	4	118	59	1.79	0.	0.	D
23	6	21	26.5	59	19.9	155	30.1	6.6	0.	9	182	17	0.49	5.2	4.2	D
23	8	15	56.3	60	7.6	152	38.0	121.8	0.	9	154	33	0.13	2.9	6.1	C
23	10	46	55.1	60	9.1	153	1.0	148.6	0.	5	132	32	0.02	1.4	3.9	C
23	11	55	23.2	58	53.5	153	38.0	7.7	0.	5	261	9	0.10	5.8	1.5	D
23	13	36	2.6	59	39.7	151	44.8	76.1	0.	5	190	23	2.92	424.5	680.6	D
23	13	49	32.7	58	48.6	153	12.8	62.1	0.	9	248	24	0.25	5.6	5.3	D
23	14	7	56.9	58	53.4	153	1.3	94.4	0.	4	279	30	0.	0.	0.	C
23	15	2	55.3	59	52.3	151	52.8	98.0	0.	9	198	47	0.26	6.7	12.3	D
23	19	21	42.8	64	33.9	153	2.7	21.9	3.5	5	131	170	0.50	8.6	129.0	D
23	17	11	54.5	59	39.2	152	10.2	81.9	0.	9	143	39	0.21	3.6	7.3	C
23	17	36	44.6	59	37.4	152	36.9	5.0	0.	4	221	89	0.19	0.	0.	C
23	22	14	43.2	59	36.6	152	45.3	106.2	0.	6	212	27	0.08	2.7	3.9	D
24	1	18	55.8	57	48.1	156	56.9	0.3	0.	5	337	45	2.72	563.3	162.7	D
24	2	9	57.2	60	39.8	149	35.7	5.0	0.	4	328	176	3.64	0.	0.	D
24	2	40	52.9	60	2.1	153	8.2	140.3	0.	8	162	42	0.13	3.6	8.2	C
24	3	10	24.1	59	0.5	151	18.9	35.9	0.	6	295	127	0.41	34.9	711.6	D
24	5	1	32.6	59	49.3	153	35.9	19.5	0.	6	101	28	0.16	2.0	2.9	C

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
FEB 24	9	46	23.1	59	42.4	154	35.1	79.1	0.	4	251	34	0.	0.	0.	C
24	12	23	3.2	59	17.4	155	2.1	2.6	0.	5	203	15	0.30	8.3	8.4	D
24	15	28	4.7	59	36.8	152	45.8	5.0	0.	3	211	85	0.	0.	0.	C
24	21	11	4.0	59	24.6	151	33.4	61.8	0.	7	277	98	0.28	14.1	16.2	D
24	21	33	55.3	59	34.9	153	8.3	5.0	0.	4	107	73	0.30	0.	0.	C
25	1	11	39.6	59	23.1	151	49.2	88.2	0.	6	189	16	0.13	5.3	8.0	D
25	5	52	3.8	60	8.8	152	21.4	133.3	0.	5	187	38	0.01	0.6	1.5	C
25	7	39	33.2	59	13.7	152	10.1	73.3	0.	7	198	43	0.16	4.3	7.6	D
25	9	1	50.7	59	51.5	151	40.9	33.3	0.	9	217	43	0.43	7.6	3.5	D
25	12	45	49.3	60	48.6	150	40.0	13.8	0.	6	309	123	0.09	11.2	2.9	D
25	14	44	8.3	60	21.9	153	52.2	229.4	0.	4	230	49	0.63	0.	0.	D
25	16	34	22.6	59	7.6	152	54.7	47.8	0.	4	178	40	0.01	0.	0.	C
25	21	21	39.0	60	8.2	154	16.9	327.0	0.	9	217	20	0.81	47.7	165.0	D
25	22	30	0.5	59	25.2	152	15.0	5.0	0.	7	153	38	2.46	58.3	137.6	D
25	23	49	35.3	59	33.2	153	3.5	5.0	0.	5	106	71	2.28	30.9	99.2	D
26	2	6	35.6	59	56.2	153	4.4	56.6	0.	5	105	56	2.80	8.9	31.8	D
26	6	55	12.4	60	18.3	153	7.3	5.0	0.	8	178	23	4.27	85.0	166.3	D
26	8	39	13.5	59	7.0	153	25.5	5.0	0.	6	184	19	0.31	5.5	4.0	D
26	12	25	24.7	58	10.6	155	22.3	8.7	0.	5	187	45	0.10	6.4	12.2	D
26	13	2	39.1	58	55.9	153	1.4	27.2	0.	6	221	29	1.03	29.0	21.1	D
26	14	14	6.7	59	2.1	153	31.4	4.1	0.	5	167	8	0.93	4.9	6.8	D
26	15	49	25.1	59	16.2	152	16.9	198.3	0.	6	183	45	1.07	55.7	147.4	D
26	18	20	33.0	58	1.3	156	24.2	0.5	0.	11	127	4	3.30	22.2	19.8	C
27	3	2	13.9	59	22.7	152	14.4	9.6	0.	4	163	38	0.	0.	0.	C
27	4	38	52.8	60	25.2	153	21.9	5.0	0.	5	227	32	4.07	562.7	612.8	D
27	7	1	16.7	59	12.1	151	2.4	9.8	0.	5	295	133	0.49	45.2	90.7	D
27	13	35	41.9	56	58.4	154	34.8	2.0	0.	5	312	105	2.23	191.0	25.7	D
27	13	49	9.3	60	34.9	154	22.7	275.3	0.	4	262	69	1.23	0.	0.	D
27	18	9	13.6	59	30.1	154	15.9	291.4	0.	4	112	51	0.	0.	0.	C
27	19	39	15.1	59	8.5	153	29.6	200.9	0.	4	170	20	0.	0.	0.	C
27	20	14	37.7	59	26.9	153	2.9	214.3	0.	7	118	24	0.79	24.1	96.2	C
28	4	25	36.0	62	37.4	156	46.0	6.3	0.	3	332	325	1.95	0.	0.	D
28	4	41	25.9	59	46.4	153	1.2	5.0	0.	4	187	71	3.38	0.	0.	D
28	7	33	59.7	59	36.5	151	32.7	64.1	0.	4	225	15	0.	0.	0.	C
28	9	16	29.7	59	31.8	154	25.3	220.1	0.	5	122	47	0.23	19.9	74.2	D
28	9	32	34.5	60	14.2	153	58.9	159.7	0.	4	217	34	1.88	0.	0.	D
28	9	36	41.8	60	2.9	152	36.4	10.4	0.	4	151	42	0.09	0.	0.	C
28	10	53	44.7	59	46.8	152	44.7	5.0	0.	4	207	71	0.23	0.	0.	C
28	12	59	17.8	58	8.2	151	32.3	1.6	0.	4	324	147	0.28	0.	0.	C
28	14	5	39.5	59	5.5	153	20.6	16.2	0.	5	203	18	0.08	3.0	5.7	D
28	16	32	30.6	59	33.7	151	51.4	186.2	0.	7	151	18	1.45	74.4	182.8	D
28	19	27	43.4	59	39.8	152	53.2	102.6	4.1	15	68	42	0.23	1.6	2.4	B
28	20	10	43.4	63	0.6	149	27.3	9.5	3.1	8	97	153	0.29	4.0	31.9	D
28	20	16	13.5	59	15.3	154	10.5	7.2	0.	5	101	17	1.07	13.4	17.6	D
28	20	53	32.4	60	6.2	153	45.2	122.3	0.	4	178	31	2.08	0.	0.	D

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
FEB	28	21	29	44.2	60	7.2	153	17.7	114.8	0.	8	150	44	1.94	25.4	59.3	D
	29	1	41	34.7	61	58.1	154	2.5	3.0	0.	4	326	185	3.07	0.	0.	D
	29	3	33	29.7	60	2.2	153	5.9	150.1	0.	7	121	46	1.68	22.1	65.5	C
	29	6	9	58.6	59	53.7	152	58.4	398.5	0.	5	186	59	0.93	125.1	720.1	D
	29	6	42	46.5	59	42.1	153	20.1	137.5	0.	5	160	36	0.09	4.2	13.3	D
	29	7	13	1.7	60	18.2	153	1.6	42.4	0.	5	167	19	3.60	239.5	331.3	D
	29	12	9	56.6	59	2.0	152	17.8	2.5	0.	9	145	63	8.96	79.0	173.7	D
	29	14	21	1.7	59	9.1	153	41.6	4.1	0.	5	137	23	0.45	1.2	2.1	D
MAR	1	0	36	50.9	60	16.3	153	50.5	165.7	0.	5	216	40	1.62	76.1	164.9	D
	1	2	17	9.7	59	59.9	152	4.9	115.2	0.	4	194	60	0.01	0.	0.	C
	1	3	14	46.3	60	20.7	153	10.1	253.0	0.	6	195	23	1.37	92.1	247.7	D
	1	8	0	2.0	58	19.9	154	4.6	4.3	0.	5	333	76	0.50	40.8	32.5	D
	1	9	21	54.9	57	48.4	151	34.8	3.3	0.	5	318	171	0.16	56.4	36.2	D
	1	10	47	59.3	58	36.0	152	43.6	72.3	0.	5	311	61	0.07	11.7	8.1	D
	1	11	29	41.3	60	7.0	152	11.2	146.5	0.	4	199	46	0.	0.	0.	C
	1	12	54	42.2	60	9.4	150	56.7	5.0	0.	6	279	84	0.33	14.6	563.4	D
	1	13	29	39.8	59	45.2	153	8.9	105.7	0.	5	173	12	0.08	3.1	6.6	D
	1	13	39	32.8	61	3.4	152	26.7	129.9	0.	5	306	73	0.13	31.3	26.7	D
	1	15	0	13.3	60	14.5	149	50.0	7.0	0.	4	312	130	0.63	0.	0.	D
	1	16	17	30.6	58	0.9	151	33.3	12.3	0.	5	313	155	0.43	118.4	26.6	D
	1	16	35	45.2	59	49.5	153	11.6	20.4	0.	4	167	19	0.	0.	0.	C
	1	16	51	17.4	60	11.6	152	34.3	54.9	0.	7	169	27	2.99	65.2	120.6	D
	1	17	11	14.7	53	31.6	153	0.2	75.4	0.	6	309	56	0.10	13.9	7.8	D
	2	-1	59	52.6	60	11.2	152	22.2	267.0	0.	7	192	34	1.49	90.3	271.4	D
	2	2	13	54.5	62	59.2	152	59.6	5.0	0.	3	347	286	0.54	0.	0.	D
	2	2	31	26.3	59	39.4	149	7.3	15.2	3.2	12	126	104	1.99	32.4	79.7	D
	2	3	46	36.2	59	59.2	152	35.0	113.7	0.	6	217	49	0.11	4.8	9.7	D
	2	8	11	20.5	59	48.3	153	4.4	192.0	0.	4	194	19	1.38	0.	0.	D
	2	8	40	33.0	59	43.7	151	17.7	37.3	0.	10	256	32	1.71	80.8	31.0	D
	2	9	57	29.9	57	39.5	156	21.0	5.0	0.	5	345	7	10.29	220.8	37.1	D
	2	15	17	23.2	59	54.6	153	36.5	171.8	0.	6	120	35	0.08	3.9	11.1	C
	2	15	35	9.1	60	7.7	154	31.8	309.7	0.	5	227	25	0.66	73.1	267.4	D
	2	20	4	34.8	59	25.9	153	3.7	101.0	0.	5	205	11	0.04	2.5	5.1	D
	2	21	15	25.5	60	4.0	151	41.8	5.0	0.	5	231	66	0.86	23.6	927.6	D
	3	1	58	15.0	59	56.5	149	57.0	0.6	0.	6	312	105	0.59	44.0	61.5	D
	3	3	59	16.1	59	51.9	152	58.2	141.5	0.	4	187	27	0.	0.	0.	C
	3	22	55	16.1	58	51.9	152	48.6	81.7	0.	8	237	42	0.20	5.3	6.1	D
	4	1	38	6.5	54	50.6	153	31.2	5.0	0.	4	316	201	3.30	0.	0.	D
	4	4	42	12.2	60	38.4	153	16.5	290.9	0.	8	274	37	1.40	129.5	329.7	D
	4	8	36	35.5	60	15.8	153	23.1	171.0	0.	5	188	38	0.12	11.1	24.7	D
	4	10	14	53.8	59	41.2	154	35.6	70.0	0.	4	268	76	0.27	0.	0.	C
	4	22	16	19.9	60	16.3	152	55.9	345.4	0.	10	144	18	1.23	69.0	265.7	D
	4	22	50	30.1	61	57.9	154	5.1	5.0	0.	5	326	186	2.74	175.1	624.5	D
	5	0	12	32.4	60	31.5	152	44.8	39.9	0.	4	314	11	0.12	0.	0.	C
	5	7	10	22.5	59	59.8	152	17.6	89.4	0.	6	175	54	0.18	5.1	13.0	D

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
MAR	5	9	49	30.7	58	55.8	148	37.7	48.5	0.	5	325	274	2.01	555.3	201.1	D
	5	13	7	51.4	58	36.9	151	53.0	5.0	0.	5	281	97	0.90	58.7	14.2	D
	5	15	27	25.9	59	53.2	153	33.5	150.2	0.	4	114	31	0.	0.	0.	C
	5	21	2	52.9	59	49.5	151	55.9	87.8	0.	9	188	44	0.36	8.3	17.1	D
	6	7	42	1.7	59	48.6	153	19.5	133.9	0.	4	138	18	0.	0.	0.	C
	6	8	39	48.9	58	53.5	152	52.8	54.7	0.	6	232	38	0.25	8.6	12.1	D
	6	12	10	34.6	60	20.3	152	47.9	38.9	0.	4	136	9	0.12	0.	0.	C
	6	12	22	0.8	57	51.8	156	53.1	29.5	4.5	11	145	195	0.76	8.9	949.4	D
	6	13	37	41.5	58	29.1	150	20.1	81.1	0.	4	318	192	1.81	0.	0.	D
	6	15	56	30.9	59	52.7	153	36.1	141.7	0.	5	113	32	0.11	5.8	14.2	D
	7	21	45	17.6	59	26.9	150	51.3	5.0	0.	5	295	136	3.79	364.5	466.7	D
	7	22	15	54.4	59	32.6	152	47.7	104.6	0.	4	212	27	0.	0.	0.	C
	7	23	53	9.1	60	46.0	153	45.2	2.5	0.	4	289	66	4.89	0.	0.	D
	7	23	53	19.0	60	4.0	159	56.5	5.0	0.	3	354	341	0.91	0.	0.	D
	8	0	54	44.2	60	32.2	152	36.2	45.1	0.	4	322	16	0.27	0.	0.	C
	8	1	28	12.4	58	25.6	156	24.9	36.7	0.	9	288	148	1.24	63.7	659.4	D
	8	2	8	38.9	59	3.8	152	43.9	5.0	0.	5	175	47	4.04	85.7	110.4	D
	8	3	1	28.2	58	17.5	151	34.2	27.7	0.	8	222	81	0.37	6.5	3.8	D
	8	6	3	7.3	59	0.8	152	52.1	136.5	0.	5	258	38	1.03	102.9	165.0	D
	8	11	38	59.2	58	27.5	152	47.4	75.4	0.	6	311	70	0.15	24.1	12.1	D
	8	15	27	26.8	60	40.1	152	38.2	51.3	0.	7	288	28	3.08	191.7	100.5	D
	8	15	34	25.7	60	8.6	152	35.8	102.7	0.	4	219	32	0.	0.	0.	C
	8	17	25	11.5	56	2.9	155	46.1	39.0	0.	3	353	350	0.08	0.	0.	C
	9	20	26	11.3	60	6.7	152	44.6	150.8	0.	6	202	34	0.16	8.6	20.6	D
	9	21	4	21.6	60	7.4	153	14.8	0.4	0.	5	147	42	2.80	14.2	79.5	D
	9	21	47	44.6	59	38.6	151	23.6	19.9	0.	4	307	128	0.20	0.	0.	C
	9	23	41	52.7	59	13.6	153	33.6	1.3	0.	4	145	14	5.22	0.	0.	D
	10	3	25	51.4	58	32.7	150	13.5	39.6	0.	7	226	160	2.29	54.4	502.5	D
	10	4	37	22.0	59	21.1	152	52.8	93.9	0.	4	217	31	0.03	0.	0.	C
	10	7	36	57.3	60	13.1	155	33.0	5.0	0.	5	301	144	0.12	16.6	274.5	D
	10	9	0	42.6	57	49.2	148	29.8	26.3	0.	4	333	320	0.13	0.	0.	C
	10	9	50	27.6	58	46.5	157	6.3	55.9	0.	6	327	171	4.24	333.6	445.4	D
	10	12	26	22.3	59	26.2	152	36.5	154.7	0.	9	92	42	5.22	42.0	72.4	C
	10	14	36	46.2	60	4.4	153	10.3	141.7	0.	4	201	44	0.	0.	0.	C
	10	19	9	59.9	58	8.0	150	41.3	39.7	0.	5	273	115	0.30	25.4	679.1	D
	11	1	44	41.2	59	35.8	153	1.9	442.9	0.	8	102	12	2.02	115.7	433.1	C
	11	8	25	49.7	58	6.2	152	40.1	0.6	0.	4	299	142	33.59	0.	0.	D
	11	8	49	54.2	60	16.3	152	32.4	5.0	0.	6	187	20	1.65	37.0	63.8	D
	11	11	6	48.4	60	24.0	151	5.6	5.0	0.	3	309	92	0.90	0.	0.	D
	11	11	49	53.2	59	21.5	153	4.3	80.5	0.	5	202	20	0.39	17.8	21.0	D
	11	19	28	26.2	60	9.3	152	29.9	5.0	0.	9	173	33	5.79	64.0	123.9	D
	11	21	0	16.0	59	36.7	152	7.9	5.0	0.	5	138	34	4.48	124.4	297.2	D
	11	23	54	39.3	58	56.6	150	53.3	24.9	0.	5	303	151	0.35	11.7	4.5	D
	12	1	13	38.1	58	1.5	150	13.5	0.3	0.	4	283	137	2.49	0.	0.	D
	12	1	45	53.3	60	11.6	152	33.6	107.8	0.	5	227	27	0.10	6.7	12.2	D

1976	ORIGIN HR	MN	TIME SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
MAR 12	4	18	50.7	60	48.6	151	27.3	16.2	0.	7	304	84	1.09	107.6	21.1	D
12	6	2	4.5	60	49.6	153	22.1	1.3	0.	5	298	55	9.21	528.7	239.8	D
12	21	34	34.2	59	41.4	151	47.9	59.0	0.	7	187	27	0.05	1.5	2.7	C
13	0	55	27.3	60	8.0	152	48.8	5.0	0.	5	161	31	1.82	43.6	109.2	D
13	1	17	24.0	60	12.6	153	17.2	170.8	0.	5	169	36	0.01	1.1	2.9	C
13	1	19	45.2	61	4.3	151	50.4	52.2	0.	8	309	88	0.25	26.3	15.5	D
13	3	24	47.4	58	22.0	152	50.4	28.1	0.	8	162	72	2.18	25.6	18.1	D
13	3	29	46.6	58	24.4	151	26.9	16.3	0.	5	314	135	0.08	46.4	22.3	D
13	3	31	0.5	59	33.4	150	36.3	1.3	0.	5	300	148	3.34	341.0	804.2	D
13	3	40	35.6	59	34.0	153	51.6	135.8	0.	5	170	35	0.12	6.9	14.7	D
13	5	28	16.6	59	24.7	154	38.2	99.4	0.	7	121	33	1.65	17.7	41.3	C
13	5	39	48.2	58	55.5	153	38.3	5.3	0.	5	239	7	0.23	7.9	4.0	D
13	7	14	54.7	60	5.4	153	5.2	11.9	0.	4	164	40	0.26	0.	0.	C
13	9	12	19.4	59	56.6	153	31.0	170.6	0.	6	125	36	0.10	4.2	13.1	C
13	13	24	2.1	59	8.8	155	17.7	364.2	0.	9	253	63	1.71	100.7	221.9	D
13	13	33	45.4	60	9.0	153	9.6	2.3	0.	4	145	36	9.71	0.	0.	D
13	15	13	41.7	60	35.4	152	36.7	5.0	0.	6	283	21	9.40	59.1	23.3	D
13	15	19	59.9	59	7.4	153	30.1	7.6	0.	6	168	18	0.17	4.0	2.0	C
13	16	32	30.2	59	53.6	153	26.3	5.0	0.	4	213	58	0.47	0.	0.	D
13	16	38	42.7	59	28.4	151	50.6	64.2	0.	5	148	14	1.50	72.0	108.1	D
13	18	18	45.5	59	6.9	153	25.2	5.0	0.	4	185	18	1.31	0.	0.	D
13	19	52	16.0	59	43.8	150	31.9	2.3	0.	4	302	146	3.89	0.	0.	D
13	21	39	18.5	59	21.5	152	19.6	75.0	0.	7	163	44	0.10	1.9	4.0	C
13	21	45	3.6	58	58.0	153	25.9	5.0	0.	3	176	119	0.	0.	0.	C
13	21	49	52.8	59	12.8	149	34.0	5.3	0.	6	316	118	1.92	363.7	371.6	D
13	22	20	30.2	59	28.4	151	51.1	49.8	0.	5	170	15	4.19	64.0	95.0	D
13	22	24	36.6	59	34.1	153	2.8	102.3	0.	5	193	14	0.06	2.4	4.2	C
13	23	6	3.0	60	33.4	149	43.8	1.1	0.	4	316	159	6.06	0.	0.	D
14	0	7	4.7	61	9.1	153	11.4	32.6	0.	5	321	84	1.34	765.7	36.6	D
14	2	22	3.1	59	26.8	155	26.7	199.6	0.	4	179	80	0.	0.	0.	C
14	4	0	2.3	60	50.3	150	23.8	0.3	0.	4	313	138	5.71	0.	0.	D
14	3	31	36.4	59	55.8	154	6.4	247.4	3.9	16	70	7	2.55	35.5	51.4	C
14	4	55	35.9	58	44.5	152	54.0	2.1	0.	8	255	43	2.82	7.2	5.3	D
14	20	43	58.2	60	3.1	152	29.9	118.7	0.	4	226	43	0.	0.	0.	C
14	21	13	39.3	60	2.2	149	49.5	1.6	0.	6	313	117	0.19	21.6	26.8	D
14	23	40	57.1	60	37.7	151	56.4	118.2	0.	9	288	51	0.28	17.3	19.1	D
15	0	37	8.6	59	0.4	152	26.6	76.2	0.	8	221	62	0.20	4.8	7.5	D
15	1	6	10.1	59	56.9	153	18.8	1.2	0.	5	142	33	1.28	14.2	82.3	D
15	6	7	7.8	58	58.2	153	42.6	9.3	0.	8	198	10	0.17	3.2	2.1	D
15	9	45	3.2	58	4.7	153	46.7	0.3	0.	4	318	98	4.93	0.	0.	D
15	10	14	17.5	60	43.0	154	42.3	0.6	0.	6	305	88	9.03	894.2	51.9	D
15	13	53	53.1	60	12.7	153	12.6	155.1	0.	6	162	33	0.08	4.2	9.4	C
15	17	37	5.8	58	21.7	154	46.8	2.5	0.	5	300	89	0.93	106.3	74.7	D
15	18	3	2.5	60	5.5	153	13.9	2.5	0.	4	145	44	2.74	0.	0.	D
15	19	40	25.0	59	56.0	152	50.8	7.2	0.	5	122	54	0.97	13.7	172.4	D

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
MAR 15	20	1	15.2	59	51.2	153	7.8	45.3	0.	5	98	60	0.01	0.1	0.9	C
15	20	54	27.4	58	45.9	153	36.1	0.6	0.	4	331	21	8.31	0.	0.	D
15	22	5	51.8	59	27.1	153	26.3	142.1	0.	4	158	13	0.	0.	0.	C
15	23	7	13.4	59	52.3	152	55.9	5.0	0.	6	112	61	1.03	10.6	782.2	D
16	2	4	3.2	59	16.0	153	36.2	1.3	0.	7	120	12	7.63	54.6	285.2	D
16	13	56	23.6	63	25.4	149	22.1	0.3	3.1	6	127	195	8.81	119.7	664.4	D
16	4	47	48.2	59	19.8	150	40.7	2.7	0.	5	300	148	3.60	332.3	756.5	D
16	4	5	16.4	60	11.1	151	44.0	5.0	0.	5	239	63	0.25	7.8	563.5	D
16	13	43	47.8	57	4.5	150	11.3	24.8	0.	4	350	288	10.04	0.	0.	D
16	9	8	57.1	59	40.5	153	50.6	0.3	0.	4	158	38	1.14	0.	0.	D
16	17	24	58.1	58	42.3	152	58.1	2.5	0.	6	258	42	4.25	360.2	899.0	D
16	18	17	12.5	59	40.0	157	4.5	8.1	0.	5	319	175	5.26	471.6	70.5	D
16	21	57	15.7	59	56.9	153	3.0	5.0	0.	4	177	54	0.72	0.	0.	D
17	1	14	12.6	58	1.4	151	58.8	21.6	0.	9	216	43	0.29	4.5	2.7	D
17	2	33	52.9	58	47.9	155	11.3	0.2	0.	4	303	97	14.27	0.	0.	D
17	3	2	45.2	60	11.8	152	50.2	150.0	0.	8	131	25	0.29	9.5	23.4	C
17	9	53	14.8	58	53.6	153	37.7	7.7	0.	7	262	8	0.15	5.6	1.3	D
17	11	0	3.9	60	9.4	152	40.7	49.2	0.	6	151	29	6.63	333.0	672.5	D
17	18	18	42.0	59	56.8	153	7.9	5.0	0.	5	170	56	1.46	26.0	262.2	D
17	20	25	39.7	60	38.6	150	47.7	8.7	0.	4	322	111	0.62	0.	0.	D
17	21	21	42.5	59	37.3	152	40.8	124.8	0.	8	108	47	0.83	15.6	43.2	C
17	21	23	31.6	59	23.8	152	2.5	267.0	0.	7	260	73	1.47	149.1	310.4	D
17	22	39	3.3	62	7.9	148	28.7	3.7	3.0	7	198	69	18.31	82.4	190.4	D
18	4	10	46.6	59	55.5	152	51.7	8.3	0.	7	120	55	1.24	11.3	898.5	D
18	7	5	35.5	60	26.9	152	44.6	0.1	0.	8	273	3	4.70	48.1	26.7	D
18	8	44	1.9	59	42.0	151	27.0	4.1	0.	4	239	26	2.35	0.	0.	D
18	10	36	41.1	60	14.6	153	12.0	158.8	0.	9	104	30	0.17	3.0	6.8	C
18	15	10	26.9	59	51.3	152	54.7	5.0	0.	8	113	59	1.43	11.2	26.2	D
18	16	15	34.7	60	29.1	152	32.6	2.1	0.	4	275	14	11.12	0.	0.	D
18	17	3	25.3	59	32.0	154	34.4	4.5	0.	5	136	39	3.79	35.2	56.2	D
18	18	29	54.3	59	24.0	149	53.5	2.5	0.	4	311	197	4.57	0.	0.	D
18	19	57	16.5	57	42.0	152	17.7	0.2	0.	7	300	12	31.18	162.2	196.1	D
18	20	37	53.4	60	8.4	152	10.0	62.7	0.	6	203	45	1.82	17.2	34.7	D
19	0	18	19.5	60	7.5	155	9.5	440.3	0.	8	253	54	0.78	53.8	147.0	D
19	3	39	22.6	59	19.2	153	13.8	5.0	0.	4	123	44	6.56	0.	0.	D
19	5	21	28.6	59	51.1	152	23.1	5.0	0.	6	152	61	0.76	8.3	308.8	D
19	5	45	23.3	59	43.6	152	35.8	106.4	0.	4	219	58	0.	0.	0.	C
19	8	0	13.6	58	48.6	153	24.3	4.6	0.	6	291	17	2.82	220.8	74.9	D
19	8	46	55.0	60	25.2	151	57.2	5.0	0.	5	259	45	1.18	125.1	115.7	D
19	9	0	36.8	59	18.7	153	12.1	1.5	0.	4	194	13	3.80	0.	0.	D
19	10	23	10.1	58	30.6	152	4.4	2.5	0.	6	336	97	3.21	39.1	585.6	D
19	10	35	57.4	59	51.4	152	49.2	5.0	0.	6	119	62	0.93	9.6	615.1	D
19	11	25	30.3	60	13.9	152	32.3	5.0	0.	5	180	24	1.44	26.4	48.2	D
19	12	21	3.7	59	1.6	153	35.7	13.1	0.	7	135	8	3.50	173.3	351.9	C
19	14	5	53.6	58	32.2	153	22.9	2.1	0.	7	303	47	0.43	36.9	14.7	D

1976	ORIGIN HR	MN	TIME SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
MAR 19	16	52	51.8	59	47.8	153	21.3	26.2	0.	4	155	47	0.	0.	0.	C
19	19	1	39.5	60	7.6	150	1.4	5.0	0.	4	315	155	6.68	0.	0.	D
19	19	49	39.0	59	34.3	153	0.3	107.6	0.	6	135	29	0.16	3.8	9.5	C
19	21	28	55.6	59	22.7	153	44.9	147.0	0.	6	117	18	0.11	5.1	12.5	C
20	0	21	47.0	59	13.1	153	54.7	117.9	0.	5	116	21	0.08	5.4	10.5	D
20	1	14	11.4	57	50.0	155	24.0	6.7	0.	4	322	166	5.44	0.	0.	D
20	1	46	5.4	58	41.1	154	33.9	1.5	0.	6	271	67	3.23	208.9	203.4	D
20	6	2	21.8	60	23.6	153	34.6	45.7	0.	4	229	44	0.13	0.	0.	C
20	9	11	19.4	60	16.8	152	23.8	24.3	0.	4	206	25	0.26	0.	0.	C
20	13	32	33.5	59	37.6	152	53.3	126.8	0.	7	103	38	0.06	1.2	4.5	B
20	17	31	10.0	60	21.7	152	44.7	19.0	0.	6	209	6	0.73	76.9	104.4	D
20	17	35	35.4	60	16.0	152	45.1	2.5	0.	4	201	17	1.07	0.	0.	D
21	5	13	1.3	60	44.0	154	8.6	2.5	0.	4	292	82	0.20	0.	0.	C
21	3	18	2.4	59	37.1	152	43.0	114.8	0.	6	214	29	0.11	4.6	7.6	D
21	21	18	31.2	59	56.7	152	45.5	164.3	0.	5	202	42	0.	4.7	1.4	D
21	20	52	27.0	60	15.4	152	37.7	5.0	0.	4	223	19	1.45	0.	0.	D
21	19	7	2.7	58	56.9	153	37.7	0.1	0.	5	216	5	4.32	44.8	44.8	D
21	18	4	24.9	59	55.5	152	7.7	5.0	0.	7	182	59	1.75	18.7	667.1	D
21	18	50	44.5	58	27.5	155	27.5	166.9	0.	8	304	102	0.10	16.8	18.5	D
21	6	9	39.1	57	46.0	154	0.9	7.1	0.	5	302	135	0.57	82.1	92.6	D
21	8	47	57.1	58	11.5	154	53.6	18.7	0.	6	309	109	0.45	60.6	14.2	D
21	11	21	21.9	59	47.9	153	35.5	137.7	0.	5	97	26	0.12	5.6	13.9	D
21	13	8	57.4	59	34.3	151	44.6	5.0	0.	4	172	14	2.11	0.	0.	D
21	15	20	46.4	60	31.0	152	6.9	100.7	0.	4	272	37	0.03	0.	0.	C
21	16	44	46.1	61	10.4	150	16.9	1.3	0.	8	292	159	0.97	49.5	74.7	D
21	17	20	49.8	61	36.2	149	2.2	0.2	3.6	13	199	5	19.81	298.2	182.2	D
22	2	55	47.7	59	26.9	151	42.9	5.0	0.	8	122	8	8.46	64.2	92.5	C
22	2	58	12.5	55	54.1	152	57.6	26.6	0.	4	352	341	0.14	0.	0.	C
22	4	3	3.7	56	49.2	154	5.8	35.2	0.	4	339	240	0.73	0.	0.	D
22	5	21	30.3	63	41.4	147	2.5	29.7	0.	6	151	145	0.30	6.0	514.1	D
22	9	50	37.0	58	59.8	151	41.5	5.0	0.	6	288	103	3.85	230.5	667.7	D
22	9	54	16.7	59	0.8	153	13.5	2.3	0.	5	240	18	3.25	275.0	265.0	D
22	11	59	56.9	62	24.7	148	7.0	1.3	3.0	7	138	105	14.38	80.7	626.7	D
22	12	25	3.1	61	28.0	149	25.4	0.2	0.	6	171	20	43.61	110.8	886.4	D
22	15	18	7.3	60	45.4	152	25.0	0.5	0.	4	294	42	0.10	0.	0.	C
22	19	47	18.5	59	36.3	153	1.5	5.0	0.	5	101	77	0.30	4.1	681.4	D
22	21	30	37.8	59	38.7	153	0.6	5.0	0.	6	98	77	2.06	20.4	572.8	D
23	0	25	59.1	60	6.8	151	48.3	5.6	0.	4	228	63	0.10	0.	0.	C
23	1	0	49.2	59	32.8	151	47.6	44.3	0.	7	154	14	0.97	23.9	32.6	D
23	6	25	30.6	58	50.6	152	11.4	69.1	0.	8	253	78	0.26	8.7	10.0	D
23	15	34	23.8	58	52.2	153	36.6	6.9	0.	6	276	10	0.15	8.4	1.4	D
23	17	32	0.5	59	30.0	153	36.4	1.3	0.	10	67	21	9.18	43.9	185.3	D
23	18	2	25.0	59	4.6	153	21.3	1.1	0.	7	204	16	3.23	40.7	132.8	D
23	19	49	43.9	58	44.0	153	55.1	0.1	0.	4	296	33	14.78	0.	0.	D
23	19	1	45.5	60	37.4	151	18.9	25.5	0.	4	320	83	0.48	0.	0.	D

	ORIGIN TIME			LAT N		LONG W		DEPTH	MAG	NO	GAP	DM	RMS	ERH	ERZ	Q
1976	HR	MN	SEC	DEG	MIN	DEG	MIN	KM			DEG	KM	SEC	KM	KM	
MAR 23	20	27	12.0	58	48.3	153	31.9	0.1	0.	5	301	16	4.17	34.7	18.5	D
23	21	8	41.8	59	52.5	151	40.4	5.0	0.	5	219	45	2.97	176.8	237.6	D
23	23	44	58.3	58	57.3	153	32.9	1.0	0.	6	209	1	4.25	37.4	17.1	D
24	4	35	6.1	59	35.0	151	27.0	23.2	0.	7	249	14	0.27	5.9	3.6	D
24	0	53	4.2	58	51.5	153	33.9	0.1	0.	4	296	11	4.17	0.	0.	D
24	2	34	0.6	58	45.7	154	52.8	133.2	0.	6	270	54	0.10	11.5	14.9	D
24	6	52	17.8	59	52.0	152	19.5	2.5	0.	8	159	60	2.72	54.7	132.9	D
24	13	21	25.0	58	50.2	152	21.4	5.0	0.	5	249	68	4.10	167.7	144.8	D
24	14	28	49.7	62	11.5	148	40.7	1.3	3.5	10	105	70	15.60	88.0	538.3	D
24	14	45	40.8	59	57.1	152	54.6	9.3	0.	7	117	52	1.39	12.6	119.5	D
24	18	36	41.3	59	58.8	152	44.7	10.9	0.	6	133	49	0.85	9.3	474.2	D
24	21	48	50.1	57	5.0	150	17.8	39.7	0.	4	350	283	4.01	0.	0.	D
25	0	9	20.5	59	52.1	153	36.0	145.3	0.	4	129	36	0.01	0.	0.	C
25	0	26	49.5	58	50.9	153	34.8	5.0	0.	3	328	12	2.18	0.	0.	D
25	1	12	36.0	60	48.4	152	42.3	36.9	0.	4	235	126	3.61	0.	0.	D
25	3	33	9.8	58	14.2	156	6.0	2.5	0.	5	320	138	0.54	29.0	22.8	D
25	6	55	25.6	59	31.5	152	50.9	134.9	0.	4	209	39	0.	0.	0.	C
25	7	38	3.5	59	40.0	153	17.9	125.9	0.	8	83	33	0.11	1.8	5.1	B
25	9	27	9.4	56	27.1	154	44.4	5.0	0.	9	288	154	27.73	11.3	4.1	D
25	9	37	3.7	59	38.9	153	17.2	125.3	3.6	14	66	31	0.19	1.7	2.7	B
25	10	58	11.5	59	32.4	152	5.9	67.3	0.	7	127	30	0.06	1.5	3.0	B
25	16	8	25.8	61	51.6	143	49.2	2.5	3.5	12	130	34	17.49	110.3	95.0	D
25	20	33	41.3	61	36.3	149	11.3	0.1	3.0	12	91	3	21.73	68.7	79.1	C
25	22	26	4.4	59	33.3	153	57.3	0.2	0.	8	146	38	21.91	130.5	495.1	D
25	23	45	52.4	59	21.7	153	22.4	3.3	0.	4	227	46	4.13	0.	0.	D
26	3	2	30.1	59	0.9	152	58.6	84.7	0.	8	201	32	2.16	47.0	56.5	D
26	4	59	31.4	60	19.8	153	15.9	75.4	0.	6	197	29	3.56	173.3	296.7	D
26	9	37	54.8	59	40.6	152	53.3	100.2	0.	6	103	43	0.08	1.6	6.0	C
26	11	24	21.1	60	32.4	152	39.8	142.2	0.	7	280	14	0.08	4.8	7.6	D
26	14	40	13.2	63	33.9	147	45.2	14.7	4.1	7	134	157	0.39	9.0	10.2	D
26	22	46	45.2	59	12.3	153	56.2	126.8	0.	4	116	19	0.05	0.	0.	C
27	1	43	50.1	59	17.0	152	43.4	102.0	0.	8	160	37	0.07	1.5	2.6	C
27	17	32	3.2	58	0.5	151	42.7	1.3	0.	5	307	149	1.08	36.1	43.5	D
28	15	16	11.1	59	11.3	154	48.4	1.3	0.	6	204	32	0.28	5.5	18.2	D
29	7	59	39.8	59	36.6	152	55.9	96.8	0.	4	199	80	0.	0.	0.	C
29	8	49	36.4	59	34.5	153	6.2	120.1	0.	7	102	26	0.57	11.3	35.6	C
29	20	6	16.0	60	7.9	147	12.7	16.9	3.4	7	134	92	0.18	2.4	2.7	C
30	9	15	13.3	59	42.1	153	31.7	5.0	0.	6	96	48	22.73	306.0	622.4	D
30	11	16	57.6	58	49.5	152	25.6	62.7	0.	8	249	65	0.26	7.5	8.5	D
30	11	23	59.2	59	28.8	152	20.0	9.2	0.	4	138	42	0.14	0.	0.	C
30	13	17	46.9	59	54.7	152	40.8	5.0	0.	4	134	56	0.17	0.	0.	C
30	20	0	2.0	59	28.2	152	48.4	86.9	0.	5	215	32	0.07	3.5	5.2	D
30	20	13	37.6	59	14.3	158	46.6	39.9	0.	7	304	262	5.32	606.8	660.7	D
30	20	13	59.5	59	10.3	153	11.2	100.1	0.	4	210	22	0.	0.	0.	C
31	1	11	5.4	57	7.6	156	41.2	5.0	0.	6	304	261	1.01	120.3	748.1	D

1976		ORIGIN HR	TIME MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
MAR	31	17	27	20.2	59	38.8	152	3.4	124.4	0.	6	151	33	2.90	108.3	219.1	D
APR	2	0	5	6.9	59	26.6	152	45.9	82.1	0.	9	88	34	0.11	1.2	2.0	B
	2	7	46	15.0	60	7.3	151	45.2	5.0	0.	5	232	65	0.30	8.4	677.2	D
	2	2	37	0.7	60	6.9	151	16.2	5.0	0.	6	261	73	0.50	15.6	868.4	D
	2	18	51	49.6	59	26.6	152	54.5	93.6	0.	11	85	26	0.41	4.1	6.0	B
	2	23	9	46.5	59	49.2	153	16.5	143.3	0.	5	150	18	0.11	5.4	13.8	D
	4	11	4	40.2	57	57.1	154	27.6	29.3	0.	10	151	65	0.57	4.8	4.9	D
	4	10	58	10.0	61	35.5	151	20.8	31.8	0.	9	286	151	0.26	11.9	343.4	D
	4	10	8	17.7	60	27.2	151	43.2	71.7	3.7	16	118	58	0.41	2.7	5.5	C
	4	1	4	44.4	60	1.0	152	37.8	120.2	0.	10	146	45	0.15	2.1	3.7	C
	6	21	29	59.2	59	39.9	153	30.1	137.0	0.	8	77	33	0.10	1.8	5.3	B
	6	15	22	14.1	61	17.7	150	29.8	22.0	0.	6	322	157	0.85	70.9	17.7	D
	6	13	39	43.0	60	28.9	153	23.5	233.3	0.	9	242	34	0.43	22.3	53.3	D
	7	10	19	23.0	58	18.7	151	42.4	17.1	0.	9	213	78	0.96	11.7	10.7	D
	9	19	24	16.6	59	7.9	153	38.5	1.3	0.	6	126	20	2.17	22.0	123.5	D
	9	14	53	29.0	59	59.8	152	50.9	5.0	0.	4	222	77	5.67	0.	0.	D
	9	6	17	29.6	61	12.8	152	54.4	194.3	4.1	16	114	88	2.61	20.6	55.7	C
	9	5	54	38.4	60	15.2	153	29.8	1.9	0.	5	194	44	0.16	5.5	5.3	D
	9	5	33	43.6	60	0.6	153	26.4	153.8	0.	8	136	44	0.24	5.0	9.7	D
	9	5	23	49.1	57	58.3	154	50.6	76.5	3.5	14	137	45	0.30	2.4	5.1	C
	10	10	39	56.5	61	10.1	151	43.2	79.0	3.0	14	110	101	0.49	3.7	11.2	C
	10	19	36	33.4	59	35.7	152	31.4	96.6	4.3	15	75	53	0.29	2.0	3.0	B
	10	21	18	51.1	58	49.3	154	17.9	45.3	0.	8	182	31	0.98	12.9	16.5	D
	11	3	3	2.2	59	18.8	153	31.7	3.5	0.	4	263	6	0.35	0.	0.	D
	11	9	35	49.2	61	25.8	150	41.6	49.8	3.6	11	119	49	0.48	4.6	10.8	C
	11	21	7	34.0	60	24.4	153	54.4	82.1	0.	7	139	53	6.09	84.6	139.6	D
	13	17	16	39.9	59	38.9	153	15.3	152.6	0.	6	84	65	0.81	18.9	53.6	C
	13	16	17	32.1	58	52.1	152	33.6	40.6	0.	8	138	56	0.58	6.7	4.8	D
	13	13	7	38.8	60	2.3	154	8.5	243.2	0.	5	211	10	0.14	24.4	73.0	D
	14	4	16	15.9	62	4.1	150	11.3	2.4	3.1	10	95	77	1.79	24.5	124.3	D
	15	10	36	35.2	60	4.9	153	12.6	154.4	3.1	18	70	44	1.64	12.7	18.1	C
	15	13	38	6.5	60	2.9	151	5.2	70.6	3.0	15	148	69	0.53	4.1	9.4	D
	16	2	53	43.2	60	4.4	153	33.8	185.9	0.	9	157	39	0.18	4.7	13.1	C
	17	0	47	41.0	58	21.7	152	1.2	0.3	0.	5	295	109	16.68	737.5	98.5	D
	17	3	37	0.1	59	32.2	156	2.4	20.1	0.	8	167	99	0.38	5.1	7.8	D
	17	4	19	20.1	59	1.3	152	55.9	18.1	4.0	8	113	35	5.28	38.3	95.3	C
	17	5	59	26.5	58	37.4	153	19.9	62.0	0.	7	164	38	0.14	3.1	3.4	C
	17	20	26	37.5	59	29.5	152	43.7	94.4	0.	7	219	33	0.11	3.5	4.2	D
	17	21	58	0.9	60	1.0	152	19.0	86.1	0.	8	239	51	0.16	5.4	7.0	D
	18	7	22	0.4	60	5.5	152	35.3	100.8	4.3	17	56	37	0.37	2.4	3.6	B
	18	7	33	11.5	60	21.5	152	26.7	122.4	0.	7	223	19	0.06	2.7	4.3	D
	18	10	32	45.9	59	47.8	153	17.0	156.0	4.2	19	58	16	0.27	2.1	2.8	B
	18	18	58	9.7	59	7.9	152	33.8	66.0	0.	10	122	52	0.30	2.9	5.3	C
	20	21	45	23.7	59	25.5	152	51.5	90.6	0.	7	214	28	0.06	1.9	2.5	C
	21	0	51	36.7	59	47.9	153	27.8	156.6	0.	9	97	46	0.14	2.5	5.3	C

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
APR 21	11	53	59.3	59	45.1	152	39.3	89.1	3.5	14	60	57	0.19	1.4	2.5	B
23	6	2	8.8	60	20.6	149	20.5	34.9	0.	9	299	158	0.38	29.7	504.1	D
23	7	38	51.9	58	27.5	154	31.0	0.6	0.	13	94	73	0.56	2.1	25.9	D
23	12	12	11.9	61	0.2	152	6.3	93.8	0.	8	257	74	0.16	5.3	4.5	D
23	13	17	52.4	57	46.4	155	54.4	103.9	0.	15	103	23	0.25	2.0	2.4	B
24	1	12	55.7	59	47.6	152	45.0	5.0	0.	8	119	58	1.46	11.5	63.2	D
24	5	4	39.9	57	52.3	154	43.1	32.2	0.	9	254	133	0.13	3.3	171.2	D
24	6	6	22.9	60	3.7	149	53.3	0.4	0.	6	311	115	4.86	544.2	709.4	D
24	6	17	13.6	60	15.8	151	44.7	26.6	0.	6	247	59	0.47	12.3	8.8	D
24	19	1	28.2	58	55.9	154	40.4	142.7	0.	9	193	33	0.12	2.5	3.5	C
25	1	25	14.4	59	47.2	153	41.6	131.0	0.	5	102	30	0.15	7.1	16.7	D
25	4	50	58.6	58	56.2	153	38.4	2.8	0.	5	228	6	0.02	0.5	0.5	C
25	4	56	20.0	59	48.5	152	44.4	100.2	0.	6	207	32	0.10	7.5	5.5	D
25	16	26	38.8	59	43.3	152	38.2	109.1	0.	6	216	34	0.09	6.9	5.2	D
26	4	40	10.4	60	21.7	152	19.0	134.6	0.	6	279	25	0.09	6.9	9.9	D
26	1	25	12.7	59	49.0	153	41.6	146.0	0.	5	100	31	0.14	7.3	18.5	D
27	15	46	35.5	61	48.2	153	49.2	1.0	0.	4	324	164	0.15	0.	0.	C
28	4	52	32.1	58	53.1	154	2.4	6.5	0.	11	165	25	0.65	4.8	4.2	D
28	19	4	55.7	59	40.2	153	32.5	140.7	0.	9	77	17	0.07	1.2	3.0	B
28	23	5	46.2	60	14.3	151	59.2	7.2	0.	4	230	47	0.37	0.	0.	D
29	1	8	24.4	59	54.4	152	22.1	106.0	0.	9	159	56	0.09	1.6	3.4	C
29	17	23	52.3	58	32.1	153	28.6	68.9	0.	8	267	47	0.19	7.2	4.4	D
29	21	1	23.6	56	58.5	150	32.7	14.0	0.	7	319	145	0.20	80.7	13.5	D
30	13	1	58.0	62	19.0	149	58.0	30.5	0.	6	310	259	0.30	40.8	526.2	D
MAY 1	2	39	52.3	59	23.3	154	42.4	61.2	0.	7	125	29	3.51	25.9	38.8	C
2	15	29	35.2	61	49.9	151	21.3	31.9	3.0	7	292	174	0.47	30.4	724.9	D
2	9	53	5.3	60	14.0	152	30.0	5.0	0.	7	185	25	2.40	38.5	69.1	D
3	17	47	31.6	58	52.4	154	11.3	132.7	4.7	9	173	25	0.87	14.3	18.0	D
3	15	3	15.3	61	19.7	151	43.8	88.9	0.	5	274	116	0.08	6.7	5.6	D
3	5	38	17.1	61	21.0	151	30.2	25.3	0.	4	300	124	4.15	0.	0.	D
3	23	15	29.8	59	10.4	152	58.0	78.3	0.	9	103	31	0.19	2.1	3.2	B
4	12	0	46.9	61	32.8	149	40.5	34.2	0.	5	303	209	0.25	36.7	549.0	D
4	8	27	49.9	60	38.7	151	37.5	131.4	0.	7	291	67	0.21	23.7	29.7	D
4	7	3	42.6	58	57.1	153	4.4	74.5	0.	9	207	26	0.20	3.3	3.3	D
4	5	27	9.3	60	16.4	150	31.6	30.6	3.5	15	153	107	0.39	3.0	2.2	D
4	4	31	8.1	60	21.0	152	34.0	135.9	0.	10	206	13	0.22	4.1	5.8	D
4	22	26	58.3	58	46.2	154	58.3	148.4	0.	11	220	57	0.23	4.4	5.3	D
4	22	33	18.4	58	59.3	152	51.5	1.8	0.	10	118	38	8.54	60.1	85.3	D
5	9	35	25.4	59	28.4	152	56.5	99.9	0.	6	120	25	0.05	1.1	2.5	B
5	9	28	47.3	62	40.6	154	34.7	22.7	0.	5	318	183	0.67	237.3	496.6	D
5	6	51	30.4	60	8.1	153	7.2	161.2	0.	4	155	37	0.	0.	0.	C
5	0	47	21.4	59	42.1	152	26.2	98.4	0.	4	145	45	0.	0.	0.	C
6	17	31	9.1	59	14.8	153	54.4	57.8	0.	7	121	23	1.02	18.5	27.2	C
6	1	50	29.4	58	51.5	154	24.6	145.9	0.	8	267	29	0.19	8.3	9.7	D
6	23	35	31.8	59	44.7	152	37.5	108.8	0.	9	124	35	0.15	2.3	5.1	C

1976		ORIGIN HR	TIME MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
MAY	6	21	47	44.4	59	59.0	152	46.4	93.8	0.	7	130	44	4.04	34.9	85.8	C
	7	23	49	17.3	58	39.6	153	9.4	75.0	0.	8	260	39	0.27	8.6	7.1	D
	8	8	22	11.7	60	3.4	150	14.5	1.1	0.	5	303	99	0.45	54.4	68.8	D
	8	6	27	23.3	59	43.3	153	13.9	116.7	0.	7	88	7	0.09	1.8	4.8	B
	8	9	35	19.8	58	45.0	153	43.9	1.7	0.	7	283	25	0.41	21.1	6.9	D
	8	11	25	34.7	61	31.7	151	31.0	1.1	4.4	15	133	88	0.49	3.4	20.1	D
	8	12	34	3.1	61	19.7	151	34.6	2.5	0.	7	316	120	0.59	29.8	23.5	D
	8	11	33	13.8	60	44.4	151	53.8	0.3	0.	5	297	59	0.68	25.8	27.5	D
	8	21	55	33.8	60	7.4	151	57.7	39.8	0.	5	217	55	0.53	21.1	10.0	D
	8	23	42	2.6	56	47.4	156	30.0	72.8	0.	12	123	85	0.34	3.0	8.5	C
	8	23	19	25.3	59	46.7	151	46.0	86.3	0.	5	201	35	0.19	17.8	34.4	D
	8	23	50	54.1	61	13.9	151	49.6	0.6	0.	6	270	104	0.55	18.6	42.4	D
	9	0	9	47.6	59	47.4	153	2.2	5.0	4.7	17	64	50	1.01	4.5	6.6	D
	9	15	39	10.1	61	27.5	151	25.4	0.5	3.1	10	131	84	0.59	5.4	32.1	D
	10	6	50	48.6	59	55.7	152	53.7	119.2	0.	6	191	36	0.16	5.6	10.8	D
	10	18	6	59.2	58	44.3	154	7.6	109.6	0.	9	208	40	0.23	4.3	4.9	D
	10	19	27	1.7	60	7.3	151	49.0	39.5	0.	5	228	62	0.39	6.9	2.8	D
	11	4	21	7.5	61	17.1	151	43.8	1.3	0.	8	273	111	0.94	20.4	40.0	D
	11	5	29	16.9	61	17.7	151	34.3	11.6	0.	6	316	117	3.99	558.3	510.0	D
	11	6	31	26.5	60	2.9	152	42.0	106.5	0.	5	141	41	0.07	2.7	7.0	D
	11	13	47	59.3	60	22.1	152	2.0	88.2	0.	8	233	41	0.13	2.9	3.3	D
	11	16	46	16.2	61	29.4	146	57.3	31.0	4.2	8	141	80	0.29	3.4	3.5	D
	11	17	1	25.3	60	16.2	152	24.6	5.0	0.	7	203	26	2.42	41.6	63.5	D
	11	21	48	55.6	59	39.7	152	29.5	106.5	0.	5	123	41	0.11	4.2	14.0	D
	11	22	18	38.0	59	51.9	153	35.0	154.0	0.	6	110	30	0.17	6.9	17.9	C
	11	22	58	13.1	60	30.5	149	21.1	65.0	0.	13	85	82	1.74	13.3	48.5	C
	12	3	7	5.5	59	6.5	152	28.6	75.6	0.	6	202	59	0.04	1.3	2.4	C
	12	5	2	19.4	60	12.8	153	14.9	181.1	0.	7	166	34	0.11	5.3	14.1	D
	12	5	56	37.8	63	51.1	149	18.0	33.2	3.2	8	106	152	0.70	7.2	992.9	D
	12	8	58	37.8	59	45.9	152	58.7	122.3	0.	8	104	54	0.13	2.0	4.8	B
	12	9	36	12.5	59	40.5	152	1.3	20.5	0.	5	159	33	0.11	2.1	3.2	C
	12	10	17	59.9	59	44.0	152	36.7	41.7	0.	4	123	65	0.10	0.	0.	C
	12	13	58	53.7	60	56.6	151	49.2	1.3	0.	5	305	78	0.95	11.4	20.0	D
	12	14	24	56.6	60	18.7	152	44.2	77.4	0.	7	206	12	0.35	10.1	11.5	D
	12	14	43	43.2	59	58.8	152	35.6	5.0	0.	3	146	49	0.	0.	0.	C
	12	18	43	17.6	60	21.7	151	28.3	5.0	0.	4	268	71	0.93	0.	0.	D
	13	10	43	54.2	58	53.8	153	37.6	8.1	0.	5	261	8	0.05	2.8	0.7	D
	13	14	57	1.4	60	7.9	153	46.2	7.4	0.	4	186	32	0.	0.	0.	C
	13	15	8	20.0	59	51.2	152	31.5	5.0	0.	5	141	64	0.73	10.6	639.8	D
	13	16	3	36.4	59	23.3	152	24.4	82.2	0.	6	154	47	0.11	3.1	7.6	C
	13	19	56	41.8	59	48.8	152	45.9	5.0	0.	6	120	65	1.26	12.7	184.0	D
	13	20	38	43.7	59	43.5	153	49.3	139.0	0.	5	121	35	0.05	3.2	8.8	D
	13	22	10	37.4	59	22.5	154	15.3	0.3	0.	7	97	30	0.46	3.1	23.7	C
	14	1	49	38.5	59	7.6	155	8.9	2.7	0.	5	251	29	0.12	5.8	2.5	D
	14	3	2	59.3	60	3.4	151	48.1	5.0	0.	5	272	67	0.27	15.4	600.7	D

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
MAY	14	12	36	25.0	60	3.9	151	49.5	5.0	0.	6	221	65	0.64	11.3	115.2	D
	14	13	5	40.9	60	3.6	151	36.9	80.0	0.	8	236	65	0.21	6.8	9.3	D
	14	16	58	30.8	60	11.1	152	41.8	27.9	3.9	7	151	26	0.73	8.4	7.2	D
	14	22	34	12.0	59	39.5	153	20.7	129.6	0.	5	167	36	0.15	6.7	20.9	D
	15	0	38	22.2	59	39.1	152	51.7	5.0	0.	3	219	47	0.	0.	0.	C
	15	3	41	36.1	59	40.2	153	32.7	148.7	0.	6	99	37	0.13	4.5	17.5	C
	15	5	10	1.6	59	52.1	153	13.7	130.7	0.	6	102	57	0.15	4.3	18.3	C
	15	8	32	42.3	59	5.7	152	18.6	80.1	0.	8	213	59	0.26	6.4	8.7	D
	15	11	33	4.1	59	37.7	152	33.7	122.9	0.	5	115	58	0.06	2.2	10.5	D
	15	11	40	14.6	59	20.0	152	25.6	82.1	0.	9	109	50	0.21	2.4	4.2	B
	15	16	3	50.6	58	14.5	155	7.8	112.4	0.	8	248	109	0.11	3.3	4.2	D
	16	5	18	40.8	60	6.9	152	30.7	113.6	0.	9	167	36	0.11	1.8	3.4	C
	16	8	41	9.5	60	38.5	151	45.9	129.2	0.	7	290	60	0.05	6.5	7.3	D
	16	13	23	43.5	59	36.4	152	48.5	5.0	0.	5	107	71	0.77	10.5	711.8	D
	16	15	23	50.0	59	38.7	148	15.1	15.8	4.0	13	127	111	1.43	21.3	51.8	D
	17	2	8	50.0	59	55.8	152	52.4	129.2	0.	9	119	54	0.14	2.0	3.8	B
	17	8	25	1.2	59	40.6	153	19.6	120.6	0.	6	85	38	0.09	2.2	8.8	B
	17	10	25	0.2	60	8.4	151	51.3	29.1	0.	7	227	59	0.27	5.4	3.1	D
	17	11	51	43.3	59	5.4	152	25.2	67.1	0.	8	133	63	0.27	3.0	6.2	C
	17	19	19	52.2	59	50.2	152	33.6	5.0	0.	5	220	65	0.89	25.3	982.7	D
	17	19	41	35.1	59	43.6	152	43.4	102.1	0.	5	210	59	0.05	2.3	5.0	C
	17	23	40	30.2	58	46.5	153	50.9	5.0	0.	3	288	27	0.19	0.	0.	C
	18	0	15	50.5	60	24.8	150	34.9	39.7	0.	6	290	118	0.44	37.7	759.9	D
	18	5	58	24.8	59	3.8	154	12.1	149.9	0.	7	195	4	0.10	4.0	7.4	D
	18	22	22	24.4	59	48.5	153	46.2	162.9	0.	8	74	30	0.29	4.5	8.7	B
	19	4	4	42.2	60	46.8	149	5.8	33.3	0.	7	294	200	0.27	31.8	415.0	D
	19	7	37	1.9	58	7.1	150	27.8	5.0	0.	5	278	127	5.39	485.3	988.0	D
	19	8	37	43.8	61	18.7	151	35.6	1.5	0.	5	276	118	0.38	12.6	42.2	D
	19	8	56	5.3	60	29.1	152	16.6	11.0	0.	4	266	28	0.73	0.	0.	D
	19	9	18	23.2	59	32.2	153	10.2	5.0	0.	4	136	76	0.33	0.	0.	D
	19	14	17	55.9	59	45.6	152	47.9	5.0	0.	3	226	73	0.01	0.	0.	C
	20	17	25	53.5	60	5.3	152	41.7	3.7	0.	4	144	37	0.61	0.	0.	D
	20	20	50	13.8	60	11.9	152	24.8	4.5	0.	5	243	31	0.94	225.6	279.0	D
	20	21	1	24.8	59	33.2	152	43.5	31.8	0.	6	216	41	0.05	1.1	0.7	C
	20	21	47	52.3	59	16.1	153	2.1	88.8	0.	5	212	21	0.02	1.3	1.6	C
	20	23	16	51.7	58	58.9	150	58.7	0.9	0.	4	301	145	3.27	0.	0.	D
	21	0	5	8.7	58	56.0	154	0.6	204.8	0.	10	160	21	0.59	11.6	18.5	D
	21	2	23	1.1	59	33.8	152	44.4	26.8	0.	4	215	46	0.	0.	0.	C
	21	4	29	52.3	60	50.7	153	6.4	204.2	0.	8	295	50	0.19	16.8	25.9	D
	21	6	32	10.0	60	12.3	152	5.9	35.6	0.	8	218	44	0.46	39.5	19.2	D
	21	10	59	3.7	59	59.4	152	41.2	106.5	0.	9	139	48	0.12	1.8	3.7	C
	21	13	13	30.1	60	9.9	152	36.1	24.9	0.	4	160	31	0.36	0.	0.	D
	21	14	16	15.1	59	52.4	152	57.6	5.0	0.	7	110	60	1.49	13.4	280.0	D
	21	15	17	31.8	59	35.9	152	56.4	119.1	0.	6	105	40	0.10	2.2	9.6	C
	21	17	33	27.3	59	15.7	153	19.4	93.4	0.	14	87	10	0.44	3.4	4.2	B

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
MAY 21	20	9	46.4	59	53.2	152	53.0	5.0	0.	5	194	59	1.38	27.3	83.2	D
21	20	51	1.2	59	8.6	153	37.8	139.6	0.	7	133	21	0.06	2.4	4.9	B
21	22	14	17.4	59	53.5	153	2.4	12.1	0.	6	106	60	0.78	8.0	342.7	D
21	23	15	45.9	63	11.8	150	21.3	2.5	3.6	10	84	174	0.26	2.2	8.9	D
22	1	20	48.9	59	53.4	153	23.1	134.3	0.	8	148	48	0.11	2.4	5.1	C
22	3	24	11.5	59	55.9	152	55.3	12.1	0.	7	115	54	1.25	11.3	905.7	D
22	5	9	28.0	60	15.3	152	35.2	26.6	0.	4	177	21	0.36	0.	0.	D
22	11	0	52.9	59	52.9	153	30.0	152.9	0.	9	79	42	0.18	2.8	7.1	B
22	18	19	49.6	60	17.3	153	36.6	201.5	0.	8	209	48	0.20	8.5	22.0	D
22	19	11	2.3	59	33.3	153	6.1	101.3	0.	6	104	30	0.12	2.5	8.7	C
22	20	56	38.2	59	57.5	152	48.8	4.1	0.	6	197	51	1.12	117.3	252.9	D
22	23	11	24.1	61	49.5	152	44.0	0.3	0.	8	298	156	0.56	82.4	58.7	D
23	4	24	53.9	60	13.2	150	31.9	15.7	0.	6	310	125	5.87	16.6	207.0	D
23	4	26	42.5	60	13.2	152	15.3	5.0	3.2	5	208	36	1.28	21.4	31.6	D
23	8	14	4.4	59	51.0	152	54.3	126.7	0.	5	113	63	0.09	3.1	15.6	D
23	8	37	37.6	61	16.2	151	43.2	0.3	0.	6	273	110	1.13	24.4	52.2	D
23	9	24	37.3	60	23.9	152	44.9	0.1	0.	7	177	2	5.37	49.8	77.6	D
23	10	31	23.6	59	9.0	152	34.3	83.4	0.	9	121	50	0.21	2.3	3.8	B
23	17	30	9.4	61	16.9	146	49.7	28.7	3.3	7	152	98	0.53	6.9	8.4	D
24	7	44	50.1	59	52.1	153	2.6	5.0	0.	7	104	58	1.86	16.0	847.7	D
24	16	9	58.8	60	17.1	151	31.0	90.2	0.	10	250	70	0.27	6.6	7.3	D
25	0	6	33.7	59	11.7	152	51.7	32.9	0.	5	168	46	0.26	6.3	7.2	D
25	5	51	9.1	59	29.2	152	58.9	5.0	0.	3	202	67	0.	0.	0.	C
25	7	31	39.5	59	18.7	152	47.9	122.1	0.	4	151	57	0.18	0.	0.	C
25	13	36	19.2	59	51.6	152	47.5	1.5	0.	4	121	62	0.	0.	0.	C
25	15	5	29.8	56	51.1	156	26.5	10.9	0.	8	123	92	0.32	14.7	104.4	D
25	17	9	19.0	59	49.1	151	45.2	32.9	0.	4	206	39	0.	0.	0.	C
25	17	42	54.3	59	0.1	152	49.3	85.7	0.	8	209	41	0.11	2.6	3.2	D
25	17	38	21.3	57	50.7	153	33.3	23.9	0.	10	147	64	0.60	5.6	5.4	D
27	6	21	0.9	59	24.8	153	44.0	8.8	0.	4	192	43	1.42	0.	0.	D
27	9	42	3.7	58	28.8	154	43.4	75.0	0.	4	317	75	0.01	0.	0.	C
27	18	22	25.3	59	15.4	152	46.0	5.0	0.	4	206	71	0.57	0.	0.	D
27	18	59	4.8	59	28.0	152	48.3	90.6	0.	7	89	32	0.06	0.8	1.3	A
28	13	14	52.3	60	13.5	153	6.6	135.8	0.	4	156	28	0.	0.	0.	C
28	17	48	20.7	60	35.6	153	40.3	5.0	0.	7	173	53	2.93	22.2	38.6	D
28	22	53	39.2	59	21.3	152	53.2	2.0	0.	6	93	26	1.80	12.6	24.9	D
29	4	53	37.1	59	41.4	151	33.9	18.3	0.	6	222	24	0.11	2.3	2.4	C
29	17	26	19.1	60	16.9	152	13.2	103.5	0.	7	222	34	0.21	4.8	6.0	D
29	18	26	0.9	59	47.0	152	22.9	5.0	0.	5	145	57	0.54	7.9	208.5	D
30	5	10	4.6	59	3.9	153	37.3	24.5	0.	6	136	13	0.11	2.6	4.3	C
30	7	55	18.7	60	15.1	153	2.0	155.5	3.4	13	66	23	0.29	2.5	4.4	B
31	5	12	12.7	59	18.0	154	3.0	5.0	0.	5	117	23	1.80	18.4	29.8	D
31	8	48	49.3	58	3.9	152	13.8	2.0	3.8	13	181	38	1.92	18.5	27.5	D
31	10	52	43.1	60	23.2	152	54.1	141.4	0.	10	124	8	0.31	5.2	8.3	C
31	12	49	35.1	59	4.7	150	43.7	38.9	0.	9	252	65	0.28	7.1	2.6	D

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976		ORIGIN HR	TIME MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
MAY	31	13	2	38.8	58	58.4	153	23.5	0.1	0.	9	147	8	4.90	36.8	44.7	D
JUN	1	0	0	56.9	58	58.3	153	30.2	8.5	0.	6	208	2	0.03	0.7	0.3	C
	1	1	33	47.4	58	28.4	154	57.9	0.6	0.	6	295	82	0.57	27.6	51.3	D
	1	6	57	22.0	61	54.2	150	36.8	55.4	0.	15	92	47	0.49	4.0	7.3	C
	1	7	15	30.0	60	3.9	152	51.7	131.0	0.	10	125	39	0.13	1.8	3.3	B
	1	15	30	43.8	59	55.9	150	44.8	53.3	0.	8	267	69	0.24	8.9	8.8	D
	1	17	58	47.8	59	43.0	152	57.4	126.8	0.	9	102	44	0.10	1.4	2.4	B
	1	19	41	55.4	60	10.4	152	48.6	5.0	0.	6	192	27	2.16	25.4	43.0	D
	1	17	58	47.8	59	43.0	152	57.4	126.8	0.	9	102	44	0.10	1.4	2.4	B
	2	1	32	11.1	60	1.4	151	52.6	5.0	0.	4	213	63	0.01	0.	0.	C
	3	0	47	52.4	58	40.8	153	52.2	3.6	0.	7	283	36	0.26	12.3	3.8	D
	3	14	47	48.3	60	11.1	153	11.8	159.4	0.	8	94	35	0.14	2.7	5.9	C
	3	17	15	7.4	59	43.0	152	58.8	126.7	0.	7	192	44	0.71	21.0	47.8	D
	3	18	26	21.5	59	49.2	152	20.4	5.0	0.	5	152	57	0.56	8.4	255.1	D
	4	1	46	14.6	60	1.8	151	43.8	1.0	0.	4	225	62	0.26	0.	0.	C
	4	6	30	55.9	58	30.4	156	35.4	206.9	0.	11	240	22	0.11	2.9	4.1	D
	4	8	0	12.2	58	50.6	155	18.1	31.7	0.	6	176	69	1.19	27.7	[illegible]	D
	4	16	45	16.5	58	33.9	154	29.8	1.7	0.	7	284	62	0.28	12.9	6.9	D
	4	16	51	20.8	57	58.8	155	48.4	43.3	0.	7	322	156	0.10	22.2	155.5	D
	4	19	19	16.5	60	16.1	151	31.4	85.4	0.	10	249	71	0.23	5.5	6.1	D
	4	20	22	33.9	60	1.0	153	19.9	133.9	0.	5	146	50	0.02	1.5	4.2	C
	4	21	4	33.4	59	52.5	153	14.6	140.4	0.	8	104	56	0.12	2.3	7.3	C
	5	2	30	54.8	61	42.6	149	48.0	15.5	3.0	15	85	7	12.56	76.7	48.6	C
	5	6	24	9.1	58	51.1	154	18.5	117.0	0.	7	243	28	0.14	7.6	9.3	D
	5	22	31	50.6	59	55.9	155	2.1	372.4	0.	6	237	45	1.36	130.9	410.7	D
	10	35	36	7.4	58	44.3	153	34.5	1.4	0.	6	290	24	10.09	738.3	87.4	D
	6	12	37	24.0	59	44.7	152	37.5	103.1	0.	6	124	58	0.03	0.7	3.0	B
	6	20	35	52.5	60	8.4	152	33.8	97.9	0.	7	164	33	0.08	2.3	5.1	C
	6	22	1	29.3	62	20.5	149	26.6	49.6	3.3	8	101	108	1.18	16.3	173.4	D
	7	2	27	52.0	58	49.2	152	57.7	78.6	0.	8	246	36	0.15	4.1	3.9	D
	7	5	41	14.6	60	2.9	152	48.8	131.5	0.	9	130	41	0.26	3.8	7.1	C
	7	6	6	20.8	59	47.6	152	41.1	60.2	0.	10	124	60	1.74	15.4	35.7	C
	7	6	25	25.9	60	40.0	152	25.9	122.0	0.	6	235	33	0.28	11.4	12.0	D
	7	8	32	54.0	60	9.8	151	24.7	192.0	0.	10	252	77	4.84	138.2	182.5	D
	7	16	49	32.6	59	21.1	152	59.0	101.4	0.	7	210	21	0.06	2.0	2.8	C
	7	19	29	1.0	59	44.9	153	4.6	5.0	0.	6	97	68	1.05	10.4	821.3	D
	8	4	58	22.6	59	27.0	152	44.5	89.4	0.	8	131	35	0.05	0.7	1.4	B
	8	9	39	49.5	58	52.9	153	37.4	8.1	0.	5	268	9	0.10	6.4	1.4	D
	9	0	6	24.0	59	54.6	152	43.1	123.0	0.	10	130	56	0.12	1.5	2.8	B
	9	6	40	35.9	60	13.0	152	40.8	120.2	0.	5	156	23	0.05	1.8	3.0	C
	9	8	57	29.2	59	12.7	153	21.1	116.6	4.4	13	89	14	0.21	2.0	2.6	B
	11	2	14	33.5	59	58.6	153	2.4	122.5	0.	10	108	51	0.11	1.3	2.5	B
	11	9	50	19.3	57	59.3	156	51.6	2.3	0.	8	155	80	0.96	21.7	56.7	D
	11	9	55	1.7	57	59.9	156	51.5	2.5	0.	8	155	79	0.91	20.6	53.9	D
	11	13	14	4.0	59	14.1	152	47.0	104.9	0.	5	218	35	0.	0.5	0.8	C

1976	ORIGIN HR	MN	TIME SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
JUN 11	15	37	47.5	59	57.2	152	8.1	107.4	0.	8	184	62	0.12	2.5	4.6	C
11	15	41	38.2	61	35.4	150	2.2	33.2	0.	5	300	197	0.30	39.3	663.5	D
11	15	57	42.5	57	56.7	156	41.0	2.5	0.	11	141	84	0.80	9.9	32.9	D
11	21	51	51.1	59	53.4	153	3.8	5.0	0.	8	104	60	2.16	16.8	50.4	D
12	0	30	33.8	59	22.0	152	29.6	79.0	0.	6	155	48	0.09	2.3	5.2	C
12	0	53	14.6	59	25.5	152	56.8	103.3	0.	6	207	23	0.14	4.8	7.3	D
12	3	52	47.8	61	39.1	151	44.6	263.0	0.	4	305	148	1.23	0.	0.	D
12	13	34	4.7	59	49.5	153	38.4	10.1	0.	5	220	53	0.12	3.7	272.5	D
12	17	48	19.1	59	52.4	152	52.2	5.0	0.	6	144	61	2.16	26.6	740.1	D
13	0	49	51.3	59	56.8	152	1.5	5.0	0.	5	193	58	0.52	9.6	162.6	D
13	4	29	30.2	59	49.8	152	49.2	5.0	0.	6	118	59	1.13	11.8	959.6	D
13	5	25	52.7	59	53.2	153	19.0	141.4	0.	7	88	51	0.09	1.6	4.0	B
14	1	8	53.7	59	58.9	152	2.6	5.0	0.	5	195	62	0.40	7.5	885.6	D
14	19	52	7.8	60	2.3	152	54.0	104.6	0.	5	121	43	0.01	0.5	2.4	C
14	21	57	16.4	58	49.4	153	12.3	72.0	0.	4	327	58	0.20	0.	0.	C
15	6	0	30.5	60	15.6	151	14.3	29.9	0.	5	271	86	0.01	2.7	0.4	D
15	11	23	30.7	59	53.8	152	44.3	5.0	0.	4	128	58	0.81	0.	0.	D
16	5	36	30.1	59	13.9	153	39.1	49.3	0.	6	171	17	1.48	30.8	29.0	D
16	6	41	37.1	60	16.8	152	35.4	85.8	0.	5	181	18	0.31	14.8	27.0	D
16	7	49	54.5	59	10.4	153	10.3	10.3	0.	6	212	23	0.06	1.3	0.7	C
16	8	13	12.5	59	56.6	152	34.3	104.5	0.	7	145	54	0.06	1.1	1.8	C
17	7	44	59.3	57	22.7	154	13.7	24.9	5.2	8	185	111	0.22	4.4	5.7	D
17	8	47	29.0	60	21.5	152	8.6	110.5	3.0	12	104	35	0.28	2.3	4.0	B
17	13	51	5.3	60	1.1	152	37.5	2.9	0.	4	146	45	0.73	0.	0.	D
17	14	17	34.9	59	43.9	151	17.1	35.0	0.	5	257	33	0.09	42.0	11.4	D
18	7	2	44.5	59	41.9	153	22.2	142.9	3.5	11	116	36	0.27	2.9	3.9	C
18	11	24	37.3	59	51.5	151	1.6	5.0	0.	4	292	115	0.12	0.	0.	C
18	13	8	14.4	61	20.0	151	52.2	39.0	3.5	11	105	111	5.16	40.5	455.0	D
18	14	5	44.6	60	30.4	151	4.7	19.8	0.	4	315	93	0.18	0.	0.	C
18	18	50	2.1	57	48.9	157	40.2	5.0	0.	6	329	115	10.80	736.8	452.5	D
18	20	51	9.5	59	58.8	153	31.0	171.8	0.	7	134	40	0.13	3.6	11.5	C
19	3	22	30.3	59	54.1	152	20.1	5.0	0.	5	161	62	0.62	9.6	386.1	D
19	12	23	44.5	59	46.3	153	13.6	130.1	0.	7	97	45	0.07	1.4	3.1	B
19	14	48	0.5	59	28.2	153	48.5	155.7	0.	6	172	26	0.07	3.5	8.3	C
19	20	20	5.5	59	16.5	154	4.0	5.0	0.	5	214	37	2.89	20.4	31.5	D
19	20	37	21.4	59	53.0	153	6.3	5.0	0.	5	176	62	1.65	28.2	691.4	D
19	23	9	25.3	59	52.5	150	39.3	70.4	0.	7	292	68	0.11	14.6	10.9	D
19	23	49	56.4	59	52.7	152	48.0	5.0	0.	6	122	60	1.19	12.5	53.9	D
20	0	16	25.8	59	8.4	154	19.3	30.3	0.	5	184	49	5.69	6.3	6.4	D
20	2	1	59.1	60	2.6	152	37.3	10.9	0.	5	149	42	0.80	12.1	786.9	D
20	12	41	4.4	58	52.1	153	42.5	0.1	0.	4	257	14	0.01	0.	0.	C
20	16	28	18.9	60	4.8	153	17.5	6.8	0.	6	145	47	4.23	388.0	985.0	D
20	19	32	15.1	60	8.2	154	14.1	433.8	0.	4	249	19	0.47	0.	0.	D
20	18	59	23.7	59	16.3	154	29.9	105.1	0.	6	165	43	1.67	12.2	27.3	D
21	4	0	49.7	60	10.8	152	22.3	74.9	0.	7	190	34	1.67	26.7	49.8	D

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
JUN 21	9	28	20.1	59	57.0	152	44.0	10.5	0.	6	132	52	1.07	11.6	857.1	D
21	16	29	37.0	58	56.1	153	31.9	7.1	0.	9	107	2	0.68	5.4	3.0	C
21	16	45	16.3	58	52.9	153	41.8	5.6	0.	5	296	12	0.07	4.9	1.6	D
21	16	52	36.9	58	52.9	153	40.9	6.9	0.	4	298	12	0.05	0.	0.	C
21	18	1	39.5	59	17.0	151	49.4	80.6	3.3	11	159	25	0.83	7.6	10.4	D
22	0	10	1.9	59	27.0	152	27.3	121.0	0.	5	170	49	0.01	1.0	3.1	C
22	3	27	40.3	59	31.7	152	6.0	45.8	0.	5	152	30	0.11	18.1	41.4	D
22	4	47	36.0	60	51.7	153	6.0	0.3	0.	6	300	52	54.20	273.3	334.8	D
22	6	23	53.7	61	30.2	151	31.4	37.6	0.	6	282	138	0.65	41.0	128.5	D
22	9	19	6.8	59	40.7	151	33.4	5.0	0.	6	223	23	1.13	30.1	35.0	D
22	9	28	34.9	59	29.1	152	57.6	106.0	0.	6	118	25	0.03	0.8	2.2	B
23	1	35	54.2	59	36.7	153	33.2	127.7	0.	5	137	29	0.04	2.1	5.1	D
23	6	51	39.3	60	12.9	152	29.2	6.2	0.	7	183	27	1.55	22.1	31.2	D
23	7	46	16.1	59	53.3	152	37.8	5.0	0.	6	136	59	0.93	10.0	609.5	D
23	7	53	52.6	60	44.0	152	6.8	96.8	3.5	13	101	50	0.36	2.7	5.5	C
23	11	22	19.5	58	52.4	152	44.7	83.1	0.	6	237	46	0.07	3.5	4.4	D
24	0	26	4.7	59	22.0	151	53.6	60.3	0.	8	134	21	0.21	3.1	4.5	C
24	5	1	1.9	61	7.9	151	27.1	89.5	0.	6	273	107	0.21	11.1	8.9	D
24	6	24	35.6	58	39.2	153	50.7	13.7	0.	6	288	38	0.37	25.0	9.7	D
24	11	45	27.3	58	27.6	154	34.2	1.3	0.	8	235	81	0.73	9.0	38.8	D
24	13	37	0.2	61	56.9	150	55.3	53.7	4.8	15	94	64	0.95	7.0	20.2	C
24	15	42	49.1	60	10.8	151	34.8	22.1	0.	5	248	71	0.18	6.9	4.7	D
24	18	14	24.0	59	50.4	151	22.6	34.3	0.	6	246	42	0.30	58.1	17.8	D
24	19	2	0.8	59	15.2	152	0.8	83.5	0.	5	267	77	0.01	1.0	1.3	C
24	19	13	57.6	59	56.7	152	46.7	5.0	0.	5	201	52	1.01	96.6	192.8	D
25	12	32	42.1	59	51.9	152	46.2	2.0	0.	4	123	62	0.20	0.	0.	C
25	14	15	37.2	59	44.8	153	29.5	150.0	0.	7	89	42	0.10	2.1	6.5	B
25	17	17	1.8	59	56.5	152	60.0	5.0	0.	5	182	54	1.33	416.4	955.5	D
25	22	37	20.6	59	13.6	153	59.2	5.0	0.	5	211	34	3.54	18.2	25.9	D
26	2	25	1.3	60	14.6	152	56.3	5.0	0.	8	113	21	3.06	12.8	26.4	D
26	4	27	4.6	59	52.2	153	20.1	143.9	0.	6	106	51	0.16	4.3	13.4	C
26	8	53	23.7	58	2.1	156	54.7	30.9	0.	7	156	75	0.21	3.9	3.2	D
26	17	18	28.7	60	3.6	153	0.3	5.0	0.	6	176	42	1.26	99.7	250.9	D
26	17	17	35.1	61	39.0	150	58.9	36.1	0.	7	291	167	0.24	16.0	373.5	D
27	19	16	27.9	57	53.1	152	11.8	5.0	0.	7	217	23	1.92	28.0	36.4	D
28	0	45	2.8	59	36.3	152	51.9	124.0	0.	6	106	38	0.16	4.1	8.6	C
28	3	23	16.3	59	49.5	154	8.3	214.5	0.	7	99	67	0.17	4.5	15.8	C
28	6	1	33.8	60	33.5	152	1.5	119.4	0.	6	279	43	0.12	11.1	13.6	D
28	8	47	3.0	58	55.8	154	25.3	96.6	0.	4	232	51	0.03	0.	0.	C
28	19	59	1.3	58	10.7	156	22.8	33.2	0.	8	266	150	1.24	46.5	750.7	D
28	20	16	7.8	58	16.1	151	33.9	27.1	0.	8	224	79	0.31	3.8	2.3	D
29	2	42	24.4	58	47.6	153	53.3	4.1	0.	5	291	27	9.36	825.0	286.5	D
29	22	9	37.8	58	58.1	153	48.3	7.2	0.	5	205	15	0.03	0.8	0.8	C
29	22	55	59.3	61	12.5	150	43.0	38.9	0.	6	286	142	0.15	8.7	234.7	D
30	0	51	58.8	60	17.7	152	33.9	127.0	0.	7	188	17	0.18	4.3	7.1	D

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
JUN	30	1	3	40.1	59	24.7	151	53.1	5.0	0.	5	173	18	0.96	2.1	3.7	D
	30	1	44	39.5	61	26.3	149	52.3	0.8	3.1	14	73	23	22.70	109.6	443.7	D
	30	2	12	55.1	61	30.5	151	36.5	91.0	3.7	15	109	93	0.33	2.5	6.4	C
	30	3	45	24.0	60	7.9	151	56.8	8.5	0.	7	219	55	0.91	13.2	394.7	D
	30	5	20	36.2	58	14.6	151	40.8	20.9	0.	8	219	73	0.58	8.5	6.7	D
	30	11	50	11.1	59	51.9	152	43.7	5.0	0.	6	126	61	1.30	13.3	252.9	D
	30	13	49	30.3	59	25.4	153	30.1	47.8	0.	6	86	10	1.85	26.1	37.5	C
	30	13	50	27.2	56	49.3	155	25.3	4.5	0.	5	303	204	0.30	50.9	21.5	D
	30	15	24	36.6	59	41.5	152	11.8	67.3	0.	5	147	42	0.15	6.5	18.8	D
JUL	1	0	23	52.8	58	44.9	153	13.6	0.1	0.	8	164	28	6.01	63.0	230.7	D
	1	2	19	52.8	58	17.3	153	21.8	83.2	0.	7	206	75	0.15	4.4	6.0	D
	1	2	56	39.8	59	2.9	152	27.9	80.9	0.	8	134	62	0.19	2.3	3.9	B
	1	4	12	49.8	60	4.9	150	33.4	5.0	0.	5	293	89	0.66	66.0	481.3	D
	1	6	35	26.7	59	31.7	151	8.0	53.3	0.	6	288	26	0.03	2.4	1.4	C
	1	8	34	1.2	60	25.2	151	52.6	46.2	0.	5	261	49	0.54	17.3	21.3	D
	1	22	23	47.5	58	46.4	152	36.4	74.0	0.	6	254	56	0.08	4.9	5.8	D
	2	1	6	20.0	60	55.5	153	12.9	1.9	0.	5	232	61	2.20	34.4	24.8	D
	2	1	17	43.7	58	57.3	153	58.2	6.2	0.	7	249	25	0.70	20.4	14.1	D
	2	5	27	36.3	59	31.3	153	0.5	66.9	0.	5	111	25	0.08	1.8	4.3	C
	2	6	44	4.5	59	52.5	152	52.3	5.0	0.	7	117	60	1.84	16.0	809.6	D
	2	16	25	33.9	59	37.6	153	23.8	131.4	0.	8	78	28	0.05	0.8	1.5	A
	3	13	4	47.2	59	4.1	151	56.6	74.1	0.	5	168	49	0.06	1.8	3.1	C
	3	15	38	13.0	59	22.1	152	15.5	4.9	0.	5	193	40	0.93	50.1	102.0	D
	3	23	35	22.2	59	13.6	153	44.0	135.0	0.	10	92	21	0.40	4.6	7.3	C
	4	3	54	31.1	58	55.3	156	13.4	167.1	0.	7	284	155	0.83	58.3	47.7	D
	4	7	45	30.9	57	19.1	151	42.2	5.0	0.	7	314	67	2.15	179.6	57.6	D
	4	11	27	11.8	59	28.8	152	59.0	118.7	0.	6	117	24	0.06	1.6	4.6	B
	4	12	36	55.4	59	53.2	152	27.0	5.0	0.	4	150	62	0.69	0.	0.	D
	4	13	15	54.6	60	2.4	153	14.5	158.7	0.	8	93	49	0.20	3.8	6.3	C
	4	14	21	34.6	59	34.9	152	45.3	108.7	0.	6	112	41	0.04	0.9	3.3	B
	4	20	36	25.6	59	25.6	151	56.5	11.5	0.	4	187	21	0.06	0.	0.	C
	4	22	16	2.4	58	23.8	152	52.3	17.5	0.	6	166	73	0.14	2.3	3.3	C
	4	23	56	23.3	59	54.4	151	39.6	113.1	0.	6	222	48	0.20	15.2	31.1	D
	5	11	44	13.4	60	44.9	151	47.1	133.1	0.	6	299	65	0.04	6.8	7.9	D
	5	15	54	35.6	59	38.5	151	54.2	30.9	0.	4	165	26	0.06	0.	0.	C
	5	21	14	31.7	59	21.9	153	45.3	162.9	0.	5	238	19	0.06	10.3	21.0	D
	6	1	45	10.0	59	58.2	152	39.4	11.9	0.	4	140	50	0.74	0.	0.	D
	6	2	59	46.3	59	47.2	152	31.4	5.0	0.	3	135	63	0.01	0.	0.	C
	9	22	42	20.0	59	43.8	151	55.8	15.2	0.	4	177	34	1.83	0.	0.	D
	10	1	25	38.4	59	7.2	151	48.6	5.0	0.	7	241	41	1.88	63.8	60.8	D
	10	7	52	10.2	60	13.5	152	14.7	91.3	0.	6	210	36	0.23	2.8	5.6	D
	10	9	17	59.7	61	59.1	148	22.9	23.8	2.7	9	129	58	0.21	2.8	2.4	D
	10	9	30	47.9	59	54.9	152	13.5	5.0	0.	4	243	63	0.85	0.	0.	D
	10	18	30	51.3	59	49.2	151	56.4	5.0	0.	4	187	43	2.04	0.	0.	D
	10	21	3	31.8	61	7.4	152	2.4	19.3	0.	7	263	88	1.24	42.5	22.9	D

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
JUL 10	21	42	39.4	60	15.6	153	15.7	194.9	0.	7	179	32	0.13	5.6	15.5	D
11	2	0	12.6	63	14.8	150	45.4	25.8	4.5	6	137	202	0.33	4.1	572.6	D
11	4	46	59.6	59	51.7	152	14.7	5.0	0.	5	165	57	1.49	23.3	330.0	D
11	5	10	13.1	59	57.6	153	35.0	175.8	5.0	13	63	36	0.39	3.7	6.2	B
11	17	52	29.3	60	7.3	152	54.1	170.3	0.	5	122	33	1.47	37.9	105.8	D
11	20	3	33.8	59	14.8	153	6.3	0.2	0.	4	241	19	3.74	0.	0.	D
12	7	6	39.5	60	18.2	153	36.4	0.3	0.	6	212	47	0.24	6.0	18.4	D
12	15	39	53.4	59	32.8	152	8.6	72.5	0.	5	125	33	0.10	4.2	9.7	D
12	17	22	9.6	59	41.9	152	22.5	5.0	0.	5	135	51	2.62	53.8	127.8	D
13	18	43	18.8	60	56.9	149	51.9	34.5	0.	6	297	169	0.68	67.3	184.1	D
13	22	7	25.5	59	50.8	153	5.5	8.9	0.	4	101	55	1.05	0.	0.	D
14	1	10	37.0	60	4.1	152	48.8	122.0	0.	6	130	39	0.08	1.9	4.0	B
14	5	39	49.6	57	50.8	155	59.4	40.5	0.	11	138	103	1.00	8.3	250.7	D
14	6	57	31.0	60	35.4	151	37.5	4.1	0.	4	286	65	0.09	0.	0.	C
14	7	10	44.6	59	39.9	152	32.9	4.5	0.	5	122	56	0.60	6.5	11.8	D
14	7	13	11.2	60	37.6	152	13.9	94.4	0.	5	238	37	0.07	3.1	2.8	D
14	9	14	33.6	58	16.5	153	55.0	35.6	0.	7	204	102	0.77	15.7	23.0	D
14	10	19	54.1	59	45.5	152	31.2	5.0	0.	5	132	62	0.71	10.2	596.6	D
14	17	7	39.4	59	36.2	153	53.9	118.2	0.	8	94	40	0.36	5.0	7.8	C
14	17	55	20.0	60	56.4	145	18.0	5.0	3.9	4	265	137	0.19	0.	0.	C
14	18	12	57.3	57	54.1	153	32.6	106.7	0.	8	224	64	3.61	113.5	209.1	D
14	19	0	53.3	60	0.2	154	46.9	448.2	0.	6	279	31	0.40	70.5	259.1	D
14	23	19	26.8	58	58.5	154	8.1	131.9	0.	8	162	56	0.16	2.6	3.9	D
15	7	37	52.6	60	6.3	150	53.3	21.0	0.	7	280	80	0.11	4.5	1.3	D
15	9	9	45.5	62	41.3	149	39.7	0.2	4.6	9	142	116	0.98	18.0	123.9	D
15	10	42	17.3	58	59.9	152	28.1	5.0	0.	5	222	61	6.65	201.6	840.5	D
15	16	32	21.0	59	21.8	150	53.5	4.7	0.	4	295	41	0.02	0.	0.	C
16	0	18	8.8	59	55.9	150	55.6	31.4	0.	4	278	63	0.02	0.	0.	C
16	1	23	25.3	59	42.7	152	14.3	5.0	0.	4	146	45	2.97	0.	0.	D
16	3	22	11.9	60	4.2	152	18.0	3.7	0.	6	183	46	2.34	15.1	31.1	D
16	3	49	0.1	60	5.3	151	59.8	37.4	0.	7	211	56	0.42	58.2	31.0	D
16	15	7	32.6	59	45.6	154	2.1	161.0	0.	8	92	24	0.20	3.6	8.5	C
16	22	17	34.3	59	34.5	152	29.6	110.3	0.	7	118	53	0.04	0.8	2.0	B
17	3	9	46.2	58	52.9	153	11.6	86.3	0.	7	239	21	0.12	3.4	3.4	D
17	13	39	41.1	58	53.8	152	51.2	106.4	0.	6	231	39	0.09	4.8	6.7	D
17	15	18	58.9	58	20.1	152	55.3	37.4	0.	8	153	70	0.22	3.3	2.2	D
17	15	51	12.4	59	0.2	152	49.2	97.6	0.	6	234	50	0.28	10.7	11.1	D
17	22	17	1.4	59	19.8	153	4.9	97.4	0.	7	132	16	0.01	0.2	0.4	B
17	22	55	29.0	59	55.2	152	54.6	5.0	0.	6	116	56	1.27	13.5	202.0	D
18	2	18	15.1	58	22.7	151	38.8	39.4	0.	8	214	86	2.16	34.4	58.2	D
18	3	49	43.4	59	29.7	153	7.5	123.6	0.	8	111	17	0.07	1.2	2.3	B
18	4	12	2.8	59	28.2	151	57.5	70.0	0.	5	148	21	0.11	6.8	12.1	D
18	5	23	37.3	59	17.2	153	19.4	15.1	0.	6	119	7	0.96	12.1	13.4	C
18	12	27	47.2	59	16.8	152	4.6	97.9	0.	6	194	35	0.01	0.6	1.2	C
18	13	52	19.4	60	5.4	151	54.4	87.7	0.	8	218	60	0.23	5.5	8.5	D

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
JUL	18	20	14	39.6	59	14.8	152	4.3	24.8	0.	5	201	37	4.67	210.3	642.6	D
	18	23	1	32.0	58	55.8	153	31.5	5.8	0.	6	284	2	0.08	3.4	0.9	D
	18	23	44	50.9	60	23.5	152	8.7	2.5	0.	5	248	34	0.91	147.0	188.0	D
	19	0	13	36.8	59	5.0	152	37.3	0.8	0.	7	201	52	3.65	43.9	178.4	D
	19	1	26	43.9	58	9.7	151	26.2	43.5	0.	8	237	77	0.44	64.5	743.1	D
	19	2	4	15.5	60	9.5	153	6.3	148.4	0.	7	142	34	0.08	2.6	6.9	C
	19	5	25	23.2	58	4.3	155	40.6	15.0	0.	5	318	149	1.29	233.8	58.1	D
	19	5	32	4.1	59	37.5	153	27.3	141.1	0.	6	127	29	0.06	2.2	6.8	C
	19	9	43	6.9	61	59.0	146	24.2	2.5	0.	8	170	150	4.45	43.1	166.0	D
	19	19	54	22.7	59	32.0	152	47.9	104.1	0.	6	117	36	0.02	0.4	1.3	B
	20	9	33	23.5	59	31.2	152	55.5	121.1	0.	6	115	29	0.03	0.8	2.2	B
	21	3	38	45.2	60	23.0	152	7.1	100.6	0.	5	231	36	0.04	1.6	1.7	C
	21	19	46	35.0	60	5.6	153	3.7	169.1	0.	5	127	39	0.08	4.2	12.2	D
	22	3	2	36.7	60	12.0	152	6.5	10.2	0.	5	216	44	0.70	16.1	561.3	D
	22	6	7	19.4	60	13.3	153	13.4	5.0	0.	6	166	33	4.64	121.5	260.8	D
	22	10	12	38.6	59	47.6	152	4.6	118.2	0.	6	171	45	0.21	9.7	26.4	D
	22	12	33	32.4	58	33.2	153	34.2	63.5	0.	7	170	44	0.19	2.8	4.5	C
	22	18	19	34.0	59	44.3	152	16.0	90.9	0.	7	148	48	0.14	3.3	9.4	C
	22	18	58	54.5	59	48.2	152	30.0	1.5	0.	5	138	63	1.08	3.3	29.0	D
	23	1	2	13.1	59	14.8	152	25.2	7.7	0.	4	217	53	0.18	0.	0.	C
	23	1	21	12.1	59	28.4	151	34.9	5.0	0.	14	185	0	22.87	606.7	586.9	D
	23	2	37	32.6	59	38.3	152	55.8	114.4	0.	5	116	44	0.05	1.4	6.0	D
	23	2	48	21.5	60	6.0	153	14.0	157.8	0.	6	141	43	0.14	6.5	21.6	D
	23	4	12	25.8	59	5.4	153	46.0	120.5	0.	8	135	20	0.09	2.3	3.6	C
	23	4	14	13.2	59	7.9	152	33.1	91.2	0.	5	238	52	0.05	6.3	8.7	D
	23	9	23	51.1	59	57.4	152	15.4	5.0	0.	6	174	58	1.26	15.1	185.0	D
	23	9	52	22.0	60	4.9	152	48.0	119.5	0.	6	132	37	0.13	3.0	6.1	C
	23	10	7	43.1	59	54.3	153	4.9	5.0	0.	6	103	59	1.34	13.9	314.3	D
	23	15	55	50.6	60	9.6	153	14.9	253.6	0.	5	155	39	0.06	9.9	53.6	D
	23	16	18	48.1	60	8.0	153	7.5	140.3	0.	7	99	37	0.12	2.3	5.1	C
	23	18	44	14.6	59	40.3	154	33.2	111.8	0.	5	293	51	0.08	16.5	15.8	D
	23	21	35	32.2	60	24.0	152	11.1	39.7	0.	6	248	32	0.72	3.1	1.3	D
	24	8	1	54.3	60	23.9	152	20.3	115.1	0.	4	224	24	0.	0.	0.	C
	24	14	40	3.9	58	27.8	155	18.3	0.6	0.	6	301	95	0.85	26.6	42.7	D
	24	14	40	12.5	58	28.1	155	19.1	0.6	0.	6	301	95	0.95	33.4	53.2	D
	24	17	36	43.6	58	11.8	154	20.6	81.1	0.	6	316	101	0.13	30.7	12.3	D
	24	19	47	29.8	59	45.6	152	29.7	5.0	0.	6	134	60	1.04	11.0	798.4	D
	24	20	16	14.3	59	9.4	153	39.2	1.3	0.	4	223	23	0.16	0.	0.	C
	24	20	21	51.9	59	51.9	152	49.4	5.0	0.	8	119	61	1.52	12.0	147.5	D
	25	5	6	12.1	59	13.3	152	54.6	86.7	0.	7	160	30	0.17	3.7	6.4	C
	25	5	18	21.2	58	38.7	152	55.0	72.1	0.	6	262	82	0.15	6.9	6.6	D
	25	8	11	47.6	60	19.1	152	9.9	100.7	0.	8	226	35	0.05	1.2	1.6	C
	25	9	34	10.0	59	21.0	152	21.2	4.5	0.	5	196	46	0.98	10.6	9.8	D
	25	13	19	19.0	60	18.8	152	18.3	113.1	0.	5	222	28	0.01	1.6	3.4	C
	25	18	28	34.0	59	57.6	152	52.8	10.1	0.	6	120	51	1.18	12.7	47.7	D

1976	ORIGIN HR	TIME MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
JUL 25	20	53	30.1	59	54.6	152	49.1	5.0	0.	4	123	56	0.57	0.	0.	D
25	22	16	3.9	59	20.6	154	5.6	8.0	0.	4	117	27	0.27	0.	0.	C
26	2	35	27.6	61	24.4	151	29.8	31.9	0.	9	280	130	0.36	14.4	482.6	D
27	0	0	34.0	59	26.2	152	43.4	98.9	0.	6	159	36	0.10	2.5	5.8	C
27	0	41	44.5	60	15.9	152	29.9	93.3	0.	5	191	22	0.23	0.5	0.9	C
27	6	2	9.4	59	54.2	152	56.1	5.0	0.	6	113	58	1.57	16.0	724.2	D
27	13	1	17.6	58	53.1	154	12.0	122.0	0.	7	248	24	0.12	4.9	5.4	D
27	16	41	22.3	59	18.1	152	41.9	103.8	0.	4	208	38	0.	0.	0.	C
27	17	22	35.3	59	10.7	154	43.1	4.5	0.	5	271	30	6.35	991.5	364.6	D
27	18	26	43.1	59	12.6	152	18.2	84.6	4.2	12	129	50	0.22	1.8	2.8	B
27	20	23	4.2	59	21.5	152	34.2	80.0	0.	14	101	44	0.25	2.0	2.8	B
27	20	44	53.6	58	30.6	152	31.7	0.3	0.	6	302	105	20.38	84.7	913.4	D
28	19	46	20.5	59	7.4	152	57.3	85.4	0.	6	204	35	0.30	8.1	11.4	D
29	0	53	26.6	58	13.9	155	33.5	5.0	0.	8	232	124	1.38	28.5	52.2	D
29	1	16	50.6	57	21.6	149	20.8	2.5	0.	4	293	219	0.08	0.	0.	C
29	5	0	25.5	60	16.0	152	5.1	117.6	0.	10	226	41	0.17	3.2	3.9	D
29	15	35	51.4	59	56.8	152	32.9	125.3	0.	7	147	54	0.10	1.9	3.3	C
30	4	6	36.4	59	21.7	154	16.6	10.7	0.	4	102	29	0.20	0.	0.	C
30	15	9	23.2	58	9.7	153	35.4	51.6	0.	11	88	79	0.30	2.4	13.8	C
31	5	9	33.2	59	20.2	152	6.2	5.0	0.	7	179	33	1.96	36.8	73.0	D
31	8	31	53.0	58	39.1	152	59.6	40.0	0.	8	139	45	0.66	7.3	4.7	D
31	9	35	17.3	58	19.0	154	46.8	182.5	0.	9	132	74	2.41	45.3	119.6	C
31	10	28	54.9	59	22.6	152	11.6	69.0	0.	4	165	36	0.01	0.	0.	C
31	15	16	6.7	59	43.4	151	55.8	40.2	0.	5	176	34	2.22	121.3	101.6	D
31	15	56	12.5	60	21.6	151	6.8	41.0	0.	8	266	91	0.22	7.6	316.1	D
31	16	6	3.9	58	18.8	154	53.5	19.0	0.	5	303	96	0.12	17.9	4.6	D
31	17	45	13.7	59	53.3	153	2.0	5.0	0.	6	106	60	1.25	12.9	173.3	D
31	23	51	3.4	60	11.3	152	14.5	107.1	0.	10	204	39	0.07	1.1	1.5	C
AUG 1	9	27	4.7	60	18.4	153	6.7	154.8	0.	5	113	22	0.17	6.1	11.7	D
1	13	55	4.2	58	58.7	153	24.2	8.8	0.	7	188	7	0.04	0.4	0.2	C
1	13	59	0.5	58	58.1	153	23.3	8.7	0.	5	263	8	0.03	3.2	1.0	D
2	3	24	52.1	59	46.3	152	51.7	2.5	0.	5	111	72	0.32	4.4	713.9	D
2	3	47	36.8	59	38.2	152	59.2	2.5	0.	6	99	78	0.93	9.3	618.5	D
2	16	33	43.9	59	33.9	152	53.8	113.7	0.	4	137	75	0.	0.	0.	C
2	18	25	53.1	59	35.8	152	51.3	5.0	0.	4	133	73	0.09	0.	0.	C
3	5	19	1.2	59	58.7	152	47.5	125.2	0.	4	139	49	0.	0.	0.	C
3	6	4	0.7	58	58.2	154	27.4	127.6	0.	6	225	20	0.12	6.6	9.2	D
3	8	44	30.4	59	32.0	151	25.5	8.7	0.	5	269	11	0.03	2.9	0.8	D
3	9	6	24.8	59	52.7	152	48.9	5.0	0.	7	121	60	1.29	11.2	974.6	D
3	15	13	31.2	60	30.3	152	19.0	44.3	0.	6	271	26	0.72	1.3	0.9	D
3	15	24	60.0	60	8.8	153	11.2	182.9	0.	4	147	38	0.05	0.	0.	C
3	21	58	34.1	59	53.2	151	54.9	0.2	0.	4	197	50	0.06	0.	0.	C
3	22	34	54.8	60	15.7	152	16.9	126.3	0.	4	213	32	0.18	0.	0.	C
4	3	47	23.1	59	16.1	152	60.0	109.2	0.	5	147	25	0.03	1.3	2.3	C
4	11	26	23.1	59	32.0	153	36.4	0.1	0.	8	68	24	9.99	67.3	380.6	D

1976	ORIGIN TIME HR MN	SEC	LAT N DEG MIN	LONG W DEG MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
AUG 4	12 1	53.1	59 49.3	152 45.4	5.0	0.	5	121	66	0.81	11.3	809.5	D
4	14 30	21.6	60 12.1	153 46.1	174.6	0.	6	111	37	0.24	7.0	17.9	C
4	19 14	43.9	59 26.5	152 26.9	97.9	0.	6	143	49	0.19	5.5	15.5	D
4	20 21	8.7	59 59.1	152 40.7	9.2	0.	5	139	48	0.70	10.3	571.7	D
5	3 30	20.3	56 10.0	154 18.0	27.9	0.	4	343	314	0.23	0.	0.	C
5	9 45	42.5	59 45.1	152 39.4	1.3	0.	5	122	63	0.43	2.1	14.6	D
5	10 23	32.9	59 55.1	152 27.6	5.0	0.	6	152	58	0.98	10.7	700.5	D
5	14 9	20.6	59 21.0	151 54.2	57.3	0.	6	191	22	0.06	3.1	4.4	D
5	17 25	10.3	59 15.9	153 46.7	146.0	0.	6	78	30	0.11	4.2	12.2	B
8	2 14	35.7	60 20.4	152 26.0	123.0	0.	5	218	20	0.03	1.2	1.7	C
9	10 20	43.6	58 20.2	151 34.4	20.0	0.	7	220	85	0.22	3.3	2.8	D
18	10 13	53.1	60 1.8	151 27.7	108.8	0.	5	245	42	0.12	13.1	23.3	D
18	15 26	29.5	58 54.8	151 46.9	5.0	0.	6	215	45	0.88	62.2	115.5	D
18	16 26	3.4	59 6.9	152 14.5	84.5	0.	5	143	54	2.36	63.7	240.6	D
18	16 48	54.2	59 33.1	153 2.6	109.3	0.	9	173	15	0.18	2.4	5.7	B
18	19 13	33.1	58 50.8	153 9.0	9.7	0.	11	178	52	0.31	2.4	393.7	D
19	7 1	16.4	58 3.5	153 20.9	92.0	0.	10	170	86	0.42	6.3	12.7	D
19	7 54	53.8	59 28.4	152 34.3	82.2	0.	9	96	42	0.19	2.3	4.9	B
19	8 30	26.9	60 20.0	152 8.0	109.8	0.	13	226	36	0.20	3.2	4.5	D
19	18 45	16.7	58 58.2	152 38.7	62.5	0.	9	112	41	0.20	2.8	5.8	C
20	3 13	4.5	59 57.6	152 59.9	4.5	0.	5	104	52	0.77	2.1	4.6	D
20	14 56	1.5	60 36.3	153 3.1	186.0	0.	6	281	25	0.02	2.5	4.6	C
20	16 52	13.3	59 18.9	153 27.7	121.9	0.	9	88	2	0.09	1.6	3.3	B
20	17 48	40.6	59 2.0	153 21.4	81.5	0.	9	116	13	0.13	1.8	2.5	B
20	20 56	13.3	60 14.6	153 49.2	236.0	2.7	17	99	39	1.30	15.8	32.5	C
20	22 56	41.8	59 53.7	153 2.5	5.0	0.	5	182	60	3.43	67.1	678.5	D
20	22 59	57.9	59 25.6	153 29.1	129.6	0.	8	96	9	0.60	12.4	28.4	C
21	0 20	52.9	59 43.5	151 44.3	94.2	0.	8	181	9	2.41	63.3	102.3	D
22	0 58	45.4	58 51.0	152 34.0	96.6	0.	8	176	27	1.99	53.2	83.6	D
22	1 13	41.2	59 8.4	153 18.9	79.8	0.	9	75	22	0.56	6.9	10.8	C
22	2 1	44.0	59 59.1	153 7.8	145.2	5.5	19	47	37	0.36	2.6	4.3	B
22	2 43	13.2	59 59.1	153 15.3	151.4	0.	9	122	37	0.18	4.2	10.3	C
22	2 44	47.7	59 54.6	153 7.0	114.2	0.	10	104	29	0.44	6.7	16.5	C
22	2 53	57.3	59 7.5	153 43.1	113.9	0.	8	114	21	0.12	2.7	4.8	C
22	9 57	29.6	60 1.4	153 32.0	170.1	0.	10	144	39	0.19	4.0	10.9	C
22	12 11	6.4	60 10.2	152 26.7	98.4	0.	10	175	33	0.23	5.2	10.2	D
22	16 53	7.1	60 31.2	150 26.3	29.4	0.	6	304	117	0.27	62.2	6.9	D
22	16 55	52.8	58 40.8	153 51.4	0.6	0.	8	243	36	0.16	2.7	6.5	D
22	17 13	1.9	59 47.2	153 3.9	111.7	0.	12	87	17	0.21	2.1	4.2	B
22	18 33	35.8	59 0.9	152 50.1	88.4	0.	7	146	49	0.09	1.9	3.2	C
22	19 23	1.6	58 34.4	152 47.4	62.1	0.	10	226	26	0.25	5.7	6.4	D
23	1 19	13.4	59 46.8	153 4.4	13.5	0.	5	186	16	0.	0.	0.1	C
23	4 40	12.3	59 47.4	153 18.8	126.8	0.	11	93	15	0.19	2.5	5.9	C
23	4 42	42.9	58 43.5	153 50.8	90.1	0.	8	216	31	0.10	2.1	2.9	C
23	5 34	13.5	60 0.9	153 16.8	140.1	0.	10	129	40	0.20	4.2	10.4	C

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
AUG 23	9	5	49.3	60	8.4	152	50.1	114.4	0.	7	123	31	0.15	4.2	13.8	C
23	11	9	0.6	59	38.8	153	6.9	109.9	0.	9	96	6	0.22	3.6	7.7	C
23	12	26	15.1	60	16.9	152	38.2	121.2	0.	8	168	17	0.11	3.9	7.6	C
23	16	25	46.4	58	12.8	153	3.9	34.3	0.	10	170	62	0.21	2.6	1.8	D
23	16	35	20.0	58	13.2	153	2.4	33.5	0.	9	177	60	0.15	1.8	1.1	C
24	6	19	21.9	59	49.8	153	31.2	156.4	0.	8	110	25	0.04	1.0	2.4	B
24	7	23	42.3	60	1.5	153	18.9	143.4	0.	7	132	41	0.24	7.4	18.5	C
24	7	33	40.0	60	3.4	153	41.9	162.7	0.	8	162	31	0.15	5.0	12.7	C
24	9	58	41.8	59	50.0	153	44.8	159.8	0.	9	124	30	0.19	5.3	12.1	C
24	10	16	2.5	60	20.8	152	30.3	125.0	0.	7	209	16	0.22	10.9	19.0	D
24	14	32	16.9	60	20.7	152	59.3	116.3	0.	6	209	14	0.10	5.6	10.2	D
25	3	16	23.3	59	59.2	152	35.9	144.9	0.	7	136	49	0.47	13.9	34.1	D
25	3	37	49.8	59	42.5	153	8.7	5.0	0.	6	80	67	1.85	17.7	201.4	D
25	6	21	45.1	59	28.1	152	10.3	54.2	0.	5	196	36	2.18	77.2	129.5	D
25	11	4	17.9	60	32.3	150	3.0	21.1	3.8	15	181	83	0.91	8.2	6.5	D
25	15	6	1.0	59	36.2	153	0.5	111.3	0.	7	77	13	0.26	4.8	11.4	B
25	18	25	20.7	59	57.4	151	31.1	76.7	0.	5	237	34	0.25	20.7	33.0	D
26	6	46	28.1	59	14.1	152	31.1	9.3	0.	6	125	49	4.10	42.9	104.7	D
26	15	8	10.9	60	10.3	153	59.4	5.0	0.	11	103	71	3.42	22.1	290.3	D
27	17	7	24.6	62	12.4	149	26.7	40.2	4.0	12	94	66	0.47	3.9	2.7	C
27	22	20	37.3	60	11.1	150	55.1	69.5	0.	11	267	71	0.38	11.5	8.9	D
28	3	52	0.5	58	8.0	154	55.4	99.4	0.	7	301	115	0.20	20.6	13.8	D
28	9	49	27.6	59	38.1	154	0.3	6.3	0.	5	150	38	0.10	1.5	2.0	C
28	13	32	57.3	59	46.7	152	18.5	87.5	0.	9	189	39	0.23	4.7	8.4	D
28	19	41	33.6	58	57.4	152	24.2	76.0	0.	7	136	36	0.07	1.5	3.6	C
28	20	5	39.2	58	25.6	154	13.3	98.8	0.	10	219	75	0.08	1.6	2.2	C
29	8	1	55.6	60	39.4	152	0.0	37.3	3.0	15	106	113	0.43	2.7	500.6	D
30	5	56	55.2	58	39.1	149	54.2	0.3	0.	7	278	142	2.30	85.3	135.7	D
30	6	5	5.5	59	25.0	151	36.1	75.1	0.	6	195	6	1.20	73.3	125.9	D
30	8	17	40.0	59	50.4	153	16.5	136.1	4.5	18	66	21	0.27	2.2	3.6	B
30	10	1	7.4	61	24.6	151	9.4	153.3	4.1	18	148	73	1.54	15.2	23.0	D
30	10	36	37.0	60	17.4	153	22.1	180.3	0.	7	254	60	0.19	11.8	22.6	D
30	11	12	3.2	59	48.2	152	43.5	22.6	0.	6	225	33	1.76	88.6	185.9	D
30	11	36	35.4	59	53.1	153	23.4	140.7	0.	9	185	27	0.12	3.0	6.4	D
30	15	21	21.8	59	39.7	152	44.0	115.0	0.	8	238	28	0.13	4.4	5.8	D
30	16	53	54.5	59	22.0	153	38.7	121.4	0.	7	106	12	0.13	3.5	6.6	C
30	19	2	42.2	59	39.9	153	16.9	123.7	0.	13	129	3	0.18	1.9	2.9	B
31	2	15	51.3	59	11.6	153	0.9	80.9	0.	12	79	27	0.19	1.6	2.6	B
31	8	6	27.8	59	15.0	151	51.2	5.0	0.	5	263	74	0.20	10.3	456.8	D
31	10	26	25.4	58	31.7	154	20.5	100.3	0.	9	248	64	0.15	4.3	5.4	D
31	12	24	14.8	59	7.9	152	33.9	25.5	0.	12	111	52	3.33	20.0	48.4	D
SEP 1	3	55	5.4	59	22.3	152	10.5	40.7	0.	5	195	35	0.01	0.3	0.2	C
1	8	28	57.4	60	13.1	152	19.6	87.9	0.	6	254	73	0.37	17.0	38.4	D
1	11	31	23.5	58	47.0	154	29.6	9.6	0.	5	284	39	0.22	17.4	488.2	D
1	17	29	34.8	59	0.2	149	58.8	0.9	3.3	13	221	105	1.83	19.8	83.3	D

1976	ORIGIN TIME				LAT N		LONG W		DEPTH	MAG	NO	GAP	DM	RMS	ERH	ERZ	Q
		HR	MN	SEC	DEG	MIN	DEG	MIN	KM			DEG	KM	SEC	KM	KM	
SEP	2	9	26	11.7	59	44.4	153	36.8	160.1	0.	7	149	23	0.15	5.7	12.3	D
	2	10	1	30.9	58	53.6	152	11.9	102.9	0.	4	253	73	1.00	0.	0.	D
	2	11	45	49.6	59	55.9	153	25.5	145.1	0.	6	193	33	0.20	8.5	18.9	D
	2	18	50	9.9	59	43.9	151	36.4	5.0	0.	7	257	8	5.96	119.7	37.9	D
	3	6	8	0.7	59	17.8	153	0.8	102.3	0.	10	99	21	0.11	1.4	2.6	B
	3	7	36	58.4	60	46.1	151	31.3	55.0	0.	6	324	123	0.69	432.4	215.6	D
	3	12	36	42.3	59	6.3	153	34.4	73.9	0.	6	212	26	3.19	82.7	105.9	D
	3	12	43	57.4	56	46.1	152	0.9	1.3	3.2	8	335	112	14.03	726.2	956.5	D
	3	16	49	25.4	58	55.4	152	51.1	77.3	0.	7	146	43	0.37	7.3	17.3	D
	3	20	27	14.8	59	46.7	152	12.7	76.2	0.	7	192	34	0.27	6.5	11.3	D
	3	20	52	52.7	59	27.3	152	12.7	11.1	0.	4	172	35	0.56	0.	0.	D
	4	18	0	11.5	60	7.8	151	48.3	89.6	0.	10	268	53	0.45	16.5	18.1	D
	4	20	16	59.5	59	14.1	146	51.1	24.6	0.	4	338	270	0.63	0.	0.	D
	4	20	59	28.0	59	47.1	152	49.6	98.5	5.4	7	178	27	0.18	4.5	6.8	C
	4	23	23	47.3	62	58.2	150	47.3	34.0	3.7	13	69	154	0.72	4.6	865.4	D
	5	8	36	8.5	58	44.0	152	6.0	29.5	0.	11	211	18	0.28	3.1	2.4	D
	5	11	29	39.2	59	45.3	152	28.3	85.5	0.	8	180	44	0.25	4.8	8.8	C
	5	17	19	43.9	60	4.1	153	2.3	180.9	0.	7	221	47	0.32	15.1	35.2	D
	5	3	45	3.9	60	29.5	152	16.7	120.8	0.	10	229	99	0.19	3.6	6.8	D
	5	9	0	14.9	58	43.3	153	59.8	33.5	0.	4	248	43	0.03	0.	0.	C
	7	0	16	26.0	60	13.6	159	2.7	35.0	4.2	8	273	211	1.43	64.2	18.2	D
	7	8	57	21.5	60	8.0	152	0.8	86.2	0.	5	257	56	0.10	7.6	8.4	D
	8	2	52	19.1	56	19.4	153	26.2	5.0	0.	5	336	312	5.16	607.2	224.3	D
	8	4	18	26.3	58	36.0	152	37.4	50.8	0.	5	221	16	0.04	2.5	2.6	C
	8	6	55	16.1	58	59.5	152	32.7	62.4	0.	7	130	42	3.51	29.4	67.1	C
	8	12	5	42.9	60	23.5	152	19.8	102.5	0.	6	238	24	3.51	217.1	371.5	D
	9	7	57	27.0	58	31.3	154	6.3	5.0	0.	7	272	64	1.48	49.4	264.2	D
	9	15	28	14.4	61	20.5	150	10.8	36.2	3.2	13	92	35	0.59	4.4	3.2	C
	9	22	4	14.9	58	55.6	153	25.8	7.1	0.	4	293	6	0.46	0.	0.	D
	10	2	1	1.7	59	29.9	153	54.5	4.1	0.	8	77	32	5.71	35.3	54.8	D
	10	6	24	33.7	60	15.4	150	57.6	5.0	0.	7	281	76	0.42	17.1	640.4	D
	10	13	56	29.2	60	26.3	152	46.9	9.5	0.	12	208	2	12.17	32.6	18.7	D
	10	18	34	39.4	59	26.7	153	30.0	123.6	0.	10	98	7	0.10	1.7	3.4	B
	11	2	31	2.7	60	9.1	153	14.3	177.2	0.	9	152	39	0.18	6.0	15.2	D
	11	6	20	20.0	60	19.0	152	29.6	52.4	0.	5	201	19	0.42	7.8	12.4	D
	11	12	2	11.9	59	18.5	152	16.4	71.9	0.	9	118	43	0.16	1.8	4.3	B
	11	18	1	15.6	59	52.5	153	23.9	146.3	0.	9	108	26	0.20	4.3	11.1	C
	11	18	42	51.0	59	48.7	151	59.8	97.7	0.	8	163	26	0.16	4.2	9.6	C
	11	22	21	42.7	57	43.2	151	39.7	83.6	0.	10	272	49	2.03	74.0	70.8	D
	11	22	55	52.7	59	20.6	153	42.7	142.1	0.	7	111	16	0.07	2.0	4.4	B
	12	2	38	9.1	57	37.8	151	13.0	34.6	0.	8	319	129	1.36	292.5	608.6	D
	12	4	41	28.8	58	52.1	153	7.2	11.5	0.	9	172	52	3.16	25.5	242.0	D
	12	6	10	17.7	60	28.5	152	28.3	44.2	0.	6	264	17	1.05	16.5	11.8	D
	12	10	18	46.6	59	49.3	153	37.8	7.0	0.	4	126	29	0.	0.	0.	C
	12	15	24	40.8	59	39.0	153	45.6	173.5	0.	5	178	29	0.15	9.3	22.3	D

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
SEP 13	23	35	11.9	59	26.7	152	51.3	105.4	0.	8	81	31	0.26	3.5	9.5	B
14	19	30	34.9	59	17.2	153	7.3	7.6	0.	9	72	18	2.59	16.8	22.1	D
15	1	28	55.7	59	26.8	153	40.2	13.1	0.	10	64	9	4.91	32.9	54.9	C
15	2	49	22.9	57	57.2	154	10.4	34.9	0.	6	284	127	0.11	6.6	183.3	D
15	6	17	36.2	58	38.8	152	54.9	61.2	0.	7	211	33	0.10	3.4	4.7	D
15	7	41	6.2	60	4.1	152	57.6	142.1	0.	7	162	40	0.56	17.6	41.7	D
15	14	25	33.2	59	53.4	152	21.1	84.1	0.	5	145	47	0.21	6.6	14.4	D
15	16	44	31.1	61	10.0	150	40.9	49.5	4.0	16	113	61	0.42	3.3	11.3	C
15	19	9	47.3	61	1.9	150	10.8	4.5	0.	8	292	157	3.89	205.6	188.1	D
15	22	53	48.1	59	59.1	152	12.0	41.1	0.	7	173	48	1.38	58.7	40.7	D
16	0	18	34.4	61	18.1	150	51.5	31.2	0.	11	286	143	0.34	13.5	431.9	D
16	6	50	2.3	62	55.3	150	37.0	5.0	0.	5	315	301	0.29	81.9	650.8	D
16	18	38	33.2	59	41.4	153	24.7	137.9	0.	7	169	11	0.28	7.2	16.7	D
16	19	17	4.7	59	33.2	152	3.4	11.8	0.	5	144	26	0.69	11.2	540.4	D
17	5	31	34.7	60	26.6	152	42.2	173.4	0.	4	272	4	0.09	0.	0.	C
17	6	44	27.9	59	55.1	153	26.0	190.3	0.	7	188	31	0.29	11.4	30.7	D
18	10	46	2.2	59	45.7	154	25.9	412.6	0.	4	310	68	0.01	0.	0.	C
18	19	57	13.6	59	1.5	152	29.9	53.4	0.	5	256	63	0.48	4.5	6.8	D
18	21	2	19.0	59	13.0	152	34.3	9.2	0.	7	116	50	1.71	14.4	615.7	D
19	9	14	33.2	63	3.2	151	7.5	40.0	3.3	11	133	169	0.46	3.4	575.6	D
19	9	20	17.2	60	5.3	152	35.8	5.0	0.	5	147	38	1.70	12.7	32.5	D
19	9	52	28.6	59	6.5	153	11.8	22.7	0.	7	189	28	3.87	57.4	145.8	D
19	12	3	37.8	62	9.2	149	22.9	36.5	3.0	12	92	61	0.51	4.9	3.8	C
19	19	33	15.7	59	32.4	152	50.8	98.8	0.	10	77	25	0.17	1.9	5.0	B
20	4	42	54.2	59	52.2	154	14.1	4.7	0.	6	134	10	1.17	16.9	24.2	D
20	14	11	38.7	59	45.3	153	36.4	170.7	0.	5	187	24	0.01	0.8	2.1	C
21	2	59	47.4	56	56.7	150	22.2	5.0	0.	8	319	156	3.55	213.9	481.6	D
21	3	1	2.1	57	33.9	151	51.0	34.6	4.5	11	294	43	2.83	334.8	69.8	D
21	3	6	31.9	57	34.4	151	56.5	29.2	0.	8	295	38	0.22	9.1	2.0	D
21	3	29	56.4	57	50.7	152	7.3	4.5	0.	5	234	24	0.78	98.3	140.2	D
22	1	44	53.6	59	20.3	152	49.2	104.0	3.0	14	96	34	0.19	1.6	2.4	B
22	7	21	54.1	60	11.3	151	56.1	115.1	0.	5	226	52	0.21	17.5	37.9	D
22	14	23	33.2	60	16.0	152	16.7	4.5	0.	5	211	32	1.52	790.5	380.6	D
23	22	9	37.4	59	48.2	152	47.2	5.0	0.	4	135	66	2.39	0.	0.	D
23	23	50	41.8	59	52.7	153	20.3	5.0	0.	4	178	67	5.41	0.	0.	D
24	1	41	27.1	60	5.6	153	49.7	2.5	0.	4	227	68	6.22	0.	0.	D
24	5	48	12.4	59	55.1	152	42.6	9.1	0.	5	132	41	1.97	30.4	404.8	D
24	14	3	12.5	59	47.1	152	42.6	2.3	0.	4	140	32	4.72	0.	0.	D
24	16	45	47.8	59	49.7	151	28.8	5.0	0.	4	248	97	1.45	0.	0.	D
24	20	45	53.2	59	27.2	152	18.8	75.0	0.	5	122	44	0.10	2.6	5.6	D
25	4	52	11.5	59	59.4	153	33.5	157.3	0.	8	138	37	2.03	59.0	176.3	D
25	8	51	5.1	59	41.7	152	8.9	98.4	0.	9	121	28	0.12	1.6	2.6	B
26	6	23	25.1	59	37.9	153	21.2	146.5	0.	7	99	7	1.78	46.6	137.3	C
26	9	25	43.4	61	43.8	151	57.9	34.1	4.0	13	115	110	0.58	4.1	697.0	D
26	9	28	56.0	61	28.8	151	49.9	36.9	3.4	13	107	105	0.52	3.7	628.7	D

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976		ORIGIN HR	TIME MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
SEP	26	18	14	56.1	58	33.7	154	36.9	86.1	0.	4	281	64	0.26	0.	0.	C
	27	8	48	10.1	58	13.3	154	20.5	38.6	0.	4	249	98	0.08	0.	0.	C
	28	5	40	19.2	59	15.5	153	0.3	110.0	0.	5	138	25	0.05	2.2	4.4	C
	28	9	27	5.9	58	23.1	154	48.2	0.3	0.	6	304	87	5.87	652.3	815.7	D
	28	10	29	50.9	60	2.5	152	31.3	88.3	0.	4	149	44	0.	0.	0.	C
	28	11	28	27.1	60	26.3	152	39.6	53.5	0.	5	256	6	0.93	36.7	35.0	D
	28	11	36	39.2	58	51.7	153	58.4	141.8	0.	7	229	27	3.21	148.7	213.6	D
	28	18	13	17.6	59	56.4	152	56.6	206.0	0.	4	153	35	0.	0.	0.	C
	29	3	28	13.5	58	36.1	153	29.5	61.0	0.	10	175	39	0.45	5.7	7.7	D
	29	7	12	40.9	60	16.7	152	41.4	119.5	0.	4	156	16	0.	0.	0.	C
	29	12	10	26.3	60	13.2	151	4.3	411.3	0.	4	279	70	0.23	0.	0.	C
	29	14	17	43.9	62	16.1	151	8.6	22.0	4.0	10	137	129	0.56	5.5	7.2	D
	30	3	11	29.9	60	30.8	151	30.7	152.5	0.	8	258	70	4.56	167.4	184.2	D
	30	5	57	25.3	59	28.6	152	6.5	63.8	0.	5	136	33	0.78	20.5	40.6	D
	30	13	9	4.2	60	9.6	152	19.1	89.4	0.	7	187	38	4.41	121.9	220.1	D
	30	15	43	2.9	60	56.1	151	52.7	111.9	0.	6	305	75	0.08	13.8	10.3	D
	30	20	29	16.6	58	12.8	151	26.5	0.3	0.	6	306	146	4.92	83.8	129.9	D
OCT	1	0	20	3.9	58	56.1	152	46.3	70.1	0.	6	138	42	0.17	4.0	8.3	C
	1	11	34	23.1	60	9.5	152	49.4	119.8	0.	5	125	29	0.12	5.7	12.3	D
	1	13	6	42.5	59	8.0	152	39.0	5.0	0.	5	119	58	0.34	4.8	757.9	D
	2	0	56	13.8	59	47.2	152	6.1	66.5	0.	4	147	29	0.	0.	0.	C
	2	1	34	33.3	59	15.2	154	30.9	0.1	0.	5	238	24	0.07	2.3	9.2	D
	2	23	14	11.6	59	37.8	152	46.2	251.7	0.	4	188	26	1.33	0.	0.	D
	3	17	0	30.0	59	11.3	152	31.3	65.5	0.	5	141	63	0.07	1.8	4.9	C
	3	18	5	9.6	59	35.1	152	50.1	96.0	0.	5	123	23	0.03	0.8	1.8	C
	3	19	57	43.6	62	47.0	149	36.9	27.3	3.3	8	200	127	0.20	3.4	2.7	D
	3	23	30	43.7	60	37.6	152	22.8	119.3	0.	5	285	31	0.12	16.2	19.2	D
	4	5	6	1.3	59	50.3	152	49.1	5.0	0.	4	111	64	0.85	0.	0.	D
	4	9	45	8.3	60	33.6	155	36.8	170.0	0.	4	316	156	1.61	0.	0.	D
	4	15	38	45.9	59	54.5	152	56.5	5.0	0.	4	151	57	0.65	0.	0.	D
	4	22	35	33.6	63	19.4	149	23.8	31.5	0.	7	163	188	0.23	3.7	357.0	D
	5	1	42	29.8	59	59.3	153	9.6	7.6	0.	8	117	37	5.91	46.2	65.6	D
	5	15	6	9.1	59	9.2	152	27.9	2.0	0.	4	134	58	0.67	0.	0.	D
	5	15	39	20.1	59	8.4	152	39.7	0.8	0.	5	117	59	0.68	4.7	43.4	D
	5	16	5	57.3	61	2.1	154	2.8	1.3	0.	5	310	97	77.73	20.4	831.7	D
	5	21	15	4.0	59	1.0	154	8.3	110.5	0.	4	227	10	0.05	0.	0.	C
	6	7	24	22.0	58	55.5	153	12.4	5.0	0.	4	165	59	0.13	0.	0.	C
	6	7	39	26.3	59	6.2	152	23.4	1.0	0.	4	143	53	0.49	0.	0.	D
	6	11	1	42.1	59	25.6	153	22.7	5.0	0.	4	157	59	0.32	0.	0.	D
	6	11	36	53.9	59	53.7	152	45.0	3.6	0.	4	114	58	0.39	0.	0.	D
	7	2	20	26.9	59	41.6	153	51.9	31.9	0.	5	129	36	3.45	57.1	136.1	D
	7	12	27	28.5	59	17.6	152	9.3	69.0	0.	5	153	49	0.05	1.4	3.2	C
	7	20	33	57.9	59	21.3	153	6.3	85.5	0.	5	143	34	0.03	0.7	1.4	C
	8	0	52	4.2	58	57.8	153	34.8	85.1	0.	8	176	3	0.24	5.2	7.5	D
	8	6	27	54.3	59	54.7	154	6.2	96.5	0.	6	123	9	3.85	132.5	199.1	C

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
OCT	8	10	29	15.5	59	45.9	153	15.4	114.7	0.	4	207	12	0.	0.	0.	C
	8	12	3	13.2	59	59.3	153	44.3	182.0	0.	5	213	47	0.15	11.1	24.5	D
	8	12	42	23.2	59	24.8	152	58.9	100.4	0.	4	151	30	0.	0.	0.	C
	8	18	20	3.8	61	7.7	150	52.1	67.5	3.2	14	114	71	0.64	5.7	13.5	C
	8	22	15	23.0	58	45.9	153	59.5	99.1	0.	9	200	34	0.26	5.1	5.7	D
	8	23	12	13.2	57	34.0	152	27.0	28.0	0.	6	318	20	0.29	16.4	2.7	D
	9	0	37	17.1	60	0.1	152	2.6	39.3	0.	4	191	44	0.	0.	0.	C
	9	6	56	21.0	60	18.1	153	36.0	0.2	0.	4	211	47	0.14	0.	0.	C
	9	14	55	50.0	60	36.8	157	32.2	145.7	0.	4	328	262	1.08	0.	0.	D
	10	2	25	60.0	57	54.0	150	0.7	56.9	0.	7	289	148	3.45	37.7	114.6	D
	10	14	53	41.6	59	49.6	153	27.1	128.1	0.	4	117	23	0.	0.	0.	C
	11	6	46	42.7	60	3.0	152	50.7	65.4	0.	5	117	41	4.49	23.3	72.4	D
	11	20	23	52.8	59	55.1	152	50.1	2.0	0.	4	110	56	0.50	0.	0.	D
	12	6	58	56.6	63	4.8	152	41.9	37.9	0.	4	317	267	1.68	0.	0.	D
	12	8	10	49.3	59	57.4	152	12.8	86.1	0.	4	167	46	0.	0.	0.	C
	12	8	30	2.1	58	55.8	152	19.7	5.0	0.	5	158	90	1.45	22.9	241.2	D
	12	15	43	33.7	60	13.2	146	19.9	5.0	0.	3	329	303	0.28	0.	0.	C
	12	20	1	16.6	59	41.2	152	41.2	115.7	0.	9	96	58	0.24	2.9	5.8	C
	12	21	16	24.4	59	54.3	153	13.3	140.9	0.	5	104	57	0.81	24.3	58.5	D
	13	2	36	15.4	59	8.6	153	55.4	91.6	0.	6	131	16	1.06	25.3	39.5	C
	13	8	36	35.7	53	51.6	154	51.0	135.0	0.	5	250	46	0.03	2.5	2.1	D
	13	10	40	53.7	59	20.8	152	38.7	86.3	0.	7	109	51	0.12	1.7	5.4	C
	13	15	11	13.7	57	51.7	154	50.1	39.1	0.	6	273	139	0.21	11.8	363.7	D
	13	18	7	10.1	60	25.0	151	34.2	12.4	0.	4	273	66	1.11	0.	0.	D
	14	2	45	57.3	60	4.1	152	41.1	1.0	0.	5	135	39	0.36	9.5	84.5	D
	14	7	51	57.5	58	56.7	152	12.6	5.0	0.	7	165	36	4.61	48.4	82.4	D
	14	9	3	56.6	59	35.3	153	59.1	194.0	0.	5	149	43	4.54	378.5	250.1	D
	14	9	16	54.4	61	38.6	149	42.5	35.4	0.	12	83	9	0.31	2.5	1.2	B
	14	10	5	49.8	60	33.4	154	49.0	7.6	0.	4	290	113	2.91	0.	0.	D
	14	20	45	43.4	58	59.2	153	33.9	5.0	0.	5	134	38	5.33	1.9	4.1	D
	15	2	12	44.9	57	46.2	147	27.4	5.0	0.	3	319	299	0.07	0.	0.	C
	15	2	16	10.6	59	41.2	152	0.2	75.0	0.	8	126	20	0.27	4.5	7.7	C
	15	9	9	14.6	57	43.9	155	46.9	10.9	0.	8	272	178	0.96	35.2	37.7	D
	15	15	27	3.1	59	39.1	153	13.5	5.0	0.	4	154	82	0.90	0.	0.	D
	15	22	13	45.9	59	39.4	152	36.7	94.7	0.	8	94	54	0.20	2.5	5.7	C
	15	23	8	3.6	59	54.8	153	29.0	160.2	0.	9	76	42	0.23	3.5	6.3	B
	16	6	20	40.0	57	27.7	150	27.7	18.4	0.	8	300	125	0.27	17.6	5.9	D
	16	14	41	3.4	59	57.5	152	49.6	4.5	0.	4	113	40	4.71	0.	0.	D
	17	0	7	34.3	60	17.6	152	16.7	107.1	0.	6	216	30	0.09	4.5	7.0	D
	17	2	11	11.9	59	57.5	152	19.0	105.2	0.	7	158	50	0.25	5.8	10.3	D
	17	5	21	25.9	60	11.0	152	46.4	119.1	0.	6	133	26	0.38	14.8	29.9	C
	17	6	34	3.6	59	28.0	152	53.9	82.9	0.	7	88	27	0.06	0.7	1.4	A
	18	0	36	10.0	61	40.4	149	29.0	0.4	1.7	17	83	20	22.05	21.5	55.0	D
	22	12	45	20.7	59	8.0	154	6.8	130.6	0.	6	182	38	0.06	1.8	4.1	C
	22	18	2	1.7	58	31.3	155	0.0	97.9	0.	6	180	31	5.98	311.0	695.4	D

1976		ORIGIN HR	TIME MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
OCT	22	18	35	24.5	56	3.8	153	8.4	26.3	0.	20	267	85	0.52	13.1	4.7	D
	22	19	41	39.5	56	19.5	153	1.6	1.3	0.	12	276	76	1.48	33.6	66.1	D
	22	20	33	45.6	59	0.4	152	7.6	73.0	0.	6	166	44	0.23	7.0	17.3	D
	22	21	7	51.6	58	38.4	153	47.1	4.1	0.	8	158	38	1.13	9.0	13.4	D
	23	0	26	27.1	58	45.0	153	51.1	5.0	0.	3	157	29	0.	0.	0.	C
	23	2	27	45.8	60	6.8	153	26.8	193.9	0.	13	159	47	1.13	24.3	39.7	D
	23	4	46	34.6	60	29.6	152	37.8	166.6	0.	8	243	11	4.89	146.6	141.1	D
	23	9	27	12.7	57	33.8	152	40.7	10.0	0.	5	263	16	0.08	3.9	1.2	D
	23	10	18	1.7	58	31.0	157	9.4	38.9	0.	4	269	216	2.10	0.	0.	D
	23	16	8	44.6	57	10.0	153	42.8	0.3	0.	7	296	162	23.47	529.4	601.0	D
	24	3	39	21.0	60	8.7	154	8.0	203.0	0.	11	229	21	0.76	22.4	31.3	D
	24	6	42	31.7	58	8.3	153	57.4	4.1	0.	15	89	43	17.09	80.0	140.8	D
	24	8	36	12.5	58	5.3	153	31.0	31.8	4.1	26	50	21	1.13	4.2	4.1	C
	24	9	31	51.9	58	2.9	153	20.1	47.2	0.	6	135	10	0.06	1.0	1.1	B
	24	9	37	34.2	61	52.9	151	33.3	39.9	0.	10	299	175	0.52	47.7	675.2	D
	24	10	1	39.3	59	27.7	153	2.2	87.9	0.	6	161	63	0.07	1.3	2.3	C
	24	12	42	35.3	58	2.9	153	19.6	47.3	0.	5	134	9	0.03	1.0	0.9	C
	24	17	19	54.3	62	35.6	149	10.7	37.7	4.8	11	101	111	0.29	2.5	369.6	D
	24	21	26	29.8	60	6.8	150	55.2	159.6	0.	8	278	80	3.44	171.2	177.2	D
	25	1	49	24.5	59	57.7	152	37.8	2.3	0.	9	141	48	7.33	70.2	105.3	D
	25	5	43	57.1	57	3.9	150	48.6	26.1	0.	9	298	135	0.19	13.9	4.6	D
	25	12	26	47.2	59	43.0	153	58.8	170.3	3.4	26	87	30	0.47	3.1	4.6	B
	25	17	27	43.0	56	36.4	153	40.9	33.3	0.	7	235	31	0.14	3.3	1.2	D
	25	21	57	1.8	58	19.2	153	47.3	59.1	0.	11	86	46	0.34	2.7	7.5	B
	26	1	4	43.4	57	45.0	157	27.8	169.8	0.	16	152	53	0.30	3.4	4.6	D
	26	8	42	37.9	60	25.9	152	21.0	193.5	0.	6	251	23	2.14	129.2	211.2	D
	26	-1	59	59.3	59	45.6	154	26.5	5.0	0.	4	213	118	0.53	0.	0.	D
	27	3	43	40.0	61	49.8	151	27.4	29.0	3.7	10	291	172	0.27	13.5	350.2	D
	27	8	56	15.4	59	34.1	153	43.3	251.5	0.	8	175	29	1.09	33.5	80.6	D
	27	9	15	2.9	59	15.2	152	4.8	73.7	0.	15	143	37	4.23	34.4	60.7	D
	27	13	25	52.6	59	58.8	153	20.9	139.5	0.	13	87	37	1.73	20.6	30.9	C
	27	22	32	36.7	60	30.4	155	12.5	29.6	0.	10	159	70	2.90	45.6	55.5	D
	28	7	50	41.6	60	16.9	153	52.9	274.0	0.	9	235	63	0.75	33.9	66.8	D
	29	0	51	47.3	59	27.5	154	44.3	5.0	0.	6	191	62	4.79	65.4	293.2	D
	29	1	44	9.4	60	5.9	152	15.8	38.7	0.	10	190	45	5.61	37.2	20.9	D
	29	1	56	45.8	58	55.6	151	44.7	373.2	0.	6	246	48	5.38	498.2	139.0	D
	29	18	35	59.7	62	5.4	151	47.2	237.6	0.	4	303	193	0.78	0.	0.	D
	29	18	58	38.8	58	4.5	153	43.6	39.4	0.	5	233	98	6.14	209.9	674.6	D
	29	19	40	39.2	59	26.2	151	54.8	5.0	0.	5	219	93	3.70	91.8	274.2	D
	30	1	2	49.4	59	13.3	154	58.2	138.7	0.	6	237	88	5.16	43.8	40.2	D
	30	1	24	32.3	63	8.8	150	27.4	26.5	3.6	9	83	169	0.37	3.2	492.9	D
	30	6	5	59.8	58	8.0	155	46.8	123.0	0.	11	140	34	0.23	4.4	3.5	C
	30	13	16	21.2	60	2.8	151	54.9	5.0	0.	4	238	63	0.21	0.	0.	C
	30	15	9	51.7	59	20.1	153	41.9	187.4	0.	10	109	15	0.95	17.3	38.1	C
	30	16	28	51.6	61	0.7	151	44.7	119.1	3.0	18	112	86	4.50	31.5	71.3	C

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
OCT	30	17	7	46.4	59	39.3	153	39.2	187.8	0.	11	103	23	2.13	32.6	64.6	C
	31	12	58	58.5	58	56.6	153	43.4	177.9	0.	9	121	11	0.95	18.0	38.6	C
	31	13	28	14.2	59	28.5	151	34.0	61.5	0.	7	238	0	0.15	3.7	4.4	D
	31	17	21	39.0	59	46.8	153	24.0	5.0	0.	6	171	79	3.81	47.5	590.3	D
	31	19	38	20.6	59	49.6	153	3.1	5.0	0.	5	154	67	0.63	10.0	406.1	D
	31	22	59	26.2	60	5.4	155	34.1	23.2	0.	8	260	75	1.48	28.3	18.1	D
	31	23	13	44.3	59	47.7	153	14.4	154.9	4.6	24	48	15	1.25	7.9	11.6	C
NOV	1	6	52	10.7	58	46.2	154	56.3	301.3	2.0	4	298	83	0.38	0.	0.	D
	1	7	54	53.6	59	30.0	153	58.9	180.8	2.2	11	73	36	0.38	5.4	11.3	C
	1	8	37	38.9	57	52.1	153	43.5	41.6	2.2	7	254	109	0.78	22.7	196.5	D
	1	10	52	13.0	59	55.2	151	54.6	5.0	1.7	4	231	73	0.38	0.	0.	D
	1	11	23	58.3	59	0.4	152	47.3	1.5	1.3	5	168	43	2.15	0.4	2.5	D
	1	19	44	17.7	59	54.8	152	40.1	91.9	1.8	7	135	42	0.22	3.8	9.1	C
	1	22	1	27.6	60	3.3	152	1.9	136.5	2.1	8	204	57	2.85	72.4	129.7	D
	2	12	48	34.3	56	44.7	157	24.5	59.2	3.4	16	182	12	4.16	41.5	45.0	D
	2	14	9	19.3	59	54.1	152	10.4	9.8	2.2	11	175	58	6.49	48.7	356.6	D
	2	21	14	28.2	61	14.5	150	43.3	34.9	2.7	6	287	144	0.39	26.6	682.7	D
	3	-1	59	39.9	59	38.7	152	33.3	397.6	2.4	9	182	38	2.88	135.8	250.4	D
	3	7	49	0.1	61	36.4	147	19.0	36.0	3.4	3	339	323	0.	0.	0.	C
	3	8	7	19.9	58	52.5	152	30.6	135.9	0.	26	123	29	3.82	23.3	37.6	C
	3	12	47	51.9	56	42.6	154	34.4	12.2	3.3	15	200	29	17.08	95.6	105.4	D
	3	13	14	34.4	58	34.7	154	18.1	11.8	2.1	9	199	58	0.43	4.7	8.6	D
	3	16	33	57.0	59	52.1	153	34.1	35.6	2.1	12	76	30	34.25	211.4	184.4	C
	3	16	40	46.9	63	7.9	151	2.5	37.9	4.1	10	74	175	0.64	5.0	832.3	D
	3	18	25	0.8	59	27.1	152	36.7	98.1	1.5	6	175	41	0.14	6.1	10.9	D
	3	18	39	39.8	58	40.7	153	5.8	55.9	1.7	6	209	39	3.42	112.6	151.8	D
	3	22	16	15.5	59	36.9	152	20.2	35.5	2.2	10	98	39	5.51	33.6	35.2	C
	4	12	43	56.1	61	25.8	147	18.2	5.0	3.7	3	338	317	0.03	0.	0.	C
	4	14	48	46.9	58	41.8	153	49.4	2.3	1.7	4	239	33	0.	0.	0.	C
	5	0	25	56.8	59	39.9	153	4.9	120.9	2.2	11	93	8	0.31	3.6	6.7	C
	5	6	35	38.8	59	55.4	152	48.9	101.6	2.1	10	112	38	0.30	4.1	10.2	C
	5	13	19	23.5	59	36.5	151	53.0	5.0	2.0	8	223	76	3.09	43.5	371.7	D
	5	13	50	8.2	59	39.6	151	40.9	5.0	1.5	5	200	21	0.86	4.2	6.6	D
	5	17	2	15.2	60	42.6	151	2.2	27.0	2.4	5	324	100	0.53	486.5	23.7	D
	6	0	8	9.6	59	52.3	153	35.6	244.1	2.4	14	76	31	1.66	22.6	45.2	C
	6	0	29	26.7	60	48.0	153	32.8	5.0	1.8	5	208	60	1.29	33.9	894.5	D
	6	9	38	23.5	59	10.2	155	56.8	5.0	2.3	6	265	100	9.00	466.8	36.2	D
	6	9	42	29.8	59	34.0	153	23.8	138.8	2.3	14	70	21	3.22	30.2	50.1	C
	6	23	18	36.5	59	51.1	153	19.8	144.3	2.1	4	160	51	0.14	0.	0.	C
	6	23	51	59.7	60	41.4	155	6.7	119.1	2.0	4	174	54	1.03	0.	0.	D
	7	5	33	7.8	57	56.1	154	40.6	39.3	2.6	11	88	90	6.21	43.9	783.1	D
	7	10	3	36.7	59	56.9	150	25.7	96.9	3.0	9	296	75	0.19	16.9	11.7	D
	7	13	10	12.5	60	0.9	153	19.2	165.0	2.0	7	131	51	0.11	3.1	10.2	C
	7	21	13	54.5	59	46.5	152	13.1	110.5	2.0	6	156	49	0.16	6.4	19.7	D
	8	0	26	39.2	59	1.9	152	8.6	5.0	2.3	6	231	58	0.86	19.0	494.2	D

1976		ORIGIN HR	TIME MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
NOV	8	2	40	13.8	59	43.4	153	2.5	1.6	1.8	6	98	43	2.34	4.2	26.1	D
	8	5	48	19.4	60	20.2	152	24.6	120.7	2.0	8	218	22	0.25	5.7	8.6	D
	8	7	56	8.8	59	51.5	152	48.2	115.3	2.2	8	120	62	0.08	1.3	3.0	B
	8	9	47	1.8	59	30.1	152	17.8	32.4	1.8	8	134	40	3.47	36.5	119.0	C
	8	12	32	33.6	58	47.8	152	23.0	12.2	1.8	8	177	68	6.34	50.7	335.3	D
	9	1	16	4.7	60	6.7	151	30.3	5.0	2.0	5	247	71	0.67	22.3	508.0	D
	9	16	29	31.3	59	54.6	151	45.6	5.0	1.8	3	213	50	0.	0.	0.	C
	9	16	58	55.1	59	28.8	152	5.1	76.9	2.0	9	143	28	4.72	84.0	144.9	D
	10	4	13	25.3	59	25.8	151	59.3	65.3	1.7	7	160	23	0.15	3.9	6.7	C
	10	8	31	4.2	61	37.8	149	58.6	0.5	2.7	7	301	202	0.79	38.5	76.2	D
	16	5	58	8.8	59	45.8	153	53.3	91.8	1.8	7	125	29	1.90	42.9	61.8	C
	16	17	18	7.1	58	56.6	158	26.0	25.4	2.7	6	285	244	2.17	171.0	753.0	D
	17	0	45	46.3	59	12.2	151	10.1	32.2	2.1	8	239	93	6.26	139.1	71.6	D
	17	9	54	25.3	59	16.0	152	27.7	1.3	2.3	8	109	52	4.73	31.0	140.7	D
	17	17	4	41.4	60	17.7	153	7.1	145.1	2.4	8	110	23	0.30	5.9	11.8	C
	18	0	56	32.6	60	21.8	153	11.4	38.3	2.5	9	133	23	3.98	38.7	23.9	C
	18	21	57	9.4	59	46.3	152	1.2	5.0	1.9	4	173	41	1.93	0.	0.	D
	18	23	32	50.1	59	50.8	153	25.9	169.9	1.7	5	207	53	0.05	3.5	10.9	D
	19	3	33	15.8	61	6.7	150	47.8	2.0	2.8	7	283	132	0.35	16.9	17.6	D
	19	3	42	43.9	59	31.9	152	59.9	107.3	2.0	9	88	26	0.08	1.1	2.0	B
	19	4	36	22.7	59	27.0	152	14.4	99.0	1.8	4	249	63	0.10	0.	0.	C
	19	5	43	53.8	58	43.6	153	40.9	0.4	1.9	8	127	27	0.41	3.5	21.4	C
	19	9	8	12.9	62	50.1	150	56.8	32.5	3.4	10	108	143	0.23	2.2	299.6	D
	19	9	27	11.4	60	3.7	150	3.3	4.5	2.0	4	308	108	0.19	0.	0.	C
	19	12	12	43.4	59	50.2	152	57.2	5.0	2.0	6	109	56	1.58	16.1	743.5	D
	19	19	35	39.8	59	47.2	153	5.6	107.6	1.7	5	174	53	0.25	9.9	26.7	D
	20	12	3	41.6	59	39.8	152	55.1	41.3	1.9	4	162	78	0.31	0.	0.	D
	21	17	0	56.0	58	52.1	151	50.1	5.0	2.5	6	264	68	1.42	47.3	452.8	D
	22	1	7	9.6	60	0.3	153	1.9	107.2	1.9	4	176	40	0.	0.	0.	C
	22	14	6	31.1	60	5.5	152	46.3	123.2	2.1	9	136	36	0.19	2.8	5.0	C
	23	3	46	34.7	60	11.9	153	3.1	149.1	1.8	7	144	29	0.09	3.4	9.3	C
	23	4	14	20.5	61	20.7	146	6.8	18.4	3.7	7	185	84	0.21	2.8	3.8	D
	23	7	47	22.9	59	57.7	153	23.9	110.5	1.9	7	124	35	5.96	92.6	199.2	C
	23	11	45	33.6	60	2.3	146	28.2	41.6	3.7	4	341	293	0.22	0.	0.	C
	23	13	55	27.3	60	18.4	153	30.4	197.8	2.7	9	207	42	0.18	9.2	21.0	D
	23	17	38	11.0	57	28.6	147	32.8	32.3	3.2	3	341	310	0.15	0.	0.	C
	23	20	19	15.5	60	51.8	152	47.6	162.6	2.3	7	296	49	0.31	57.6	71.9	D
	24	0	37	53.0	59	45.0	153	21.8	112.2	2.3	9	72	13	1.29	15.7	30.8	C
	24	2	29	54.8	60	55.2	151	51.6	118.9	2.6	7	304	74	0.15	22.0	17.9	D
	24	3	1	47.3	57	51.8	153	25.4	39.2	2.7	9	191	56	1.52	20.7	20.8	D
	24	3	39	22.1	60	52.7	151	21.4	19.4	2.4	7	308	92	0.44	47.8	9.7	D
	24	3	54	20.1	60	26.4	152	42.0	138.3	2.1	5	266	4	0.23	23.1	46.6	D
	24	7	6	31.1	58	51.3	153	33.3	9.4	2.1	10	192	11	0.76	6.8	4.6	D
	24	8	6	21.0	59	37.0	152	58.4	118.1	2.6	15	79	15	0.64	5.5	9.1	C
	24	8	23	51.9	59	19.6	153	56.4	134.8	2.3	12	124	29	0.21	2.8	3.9	C

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
NOV 24	10	20	6.9	58	51.3	152	58.4	87.3	2.5	13	88	34	0.97	7.4	14.1	C
24	11	34	55.7	59	50.4	152	50.5	5.0	2.1	6	103	59	1.03	9.9	788.5	D
24	19	7	39.0	59	44.7	153	23.7	5.0	2.1	4	200	82	0.27	0.	0.	C
24	20	56	35.8	59	48.8	150	58.4	0.8	2.2	7	278	41	4.62	182.8	244.5	D
24	21	22	22.3	59	54.2	152	36.6	9.7	1.8	5	139	44	2.07	31.3	615.4	D
24	23	29	23.8	58	48.4	153	12.0	160.6	2.0	6	199	25	3.09	192.2	307.8	D
24	23	51	18.1	59	51.3	154	33.7	117.3	2.6	7	268	21	5.29	257.1	334.9	D
25	2	53	13.0	57	55.4	155	23.6	177.3	2.5	8	297	158	1.45	107.5	109.9	D
25	3	13	40.2	59	33.6	152	50.0	125.3	1.7	6	163	24	0.31	9.7	18.8	D
25	3	45	45.7	59	46.8	151	27.5	5.0	2.2	3	293	100	0.06	0.	0.	C
25	15	9	43.9	58	53.2	152	43.4	22.6	2.2	9	98	36	3.84	26.7	50.0	C
25	16	8	59.8	58	58.2	152	32.8	3.6	2.1	10	119	39	2.52	16.3	26.5	D
25	17	50	57.8	59	55.4	152	51.1	95.6	1.9	4	200	36	0.	0.	0.	C
25	19	6	0.9	58	37.4	150	14.5	16.5	2.5	10	269	121	4.61	129.7	44.4	D
25	23	4	3.7	59	7.1	154	40.0	86.5	2.4	10	231	26	3.37	70.4	65.0	D
25	23	7	40.1	59	8.2	152	26.9	83.8	1.5	6	121	56	0.10	2.1	6.1	C
26	0	29	54.1	58	17.3	153	31.8	119.1	2.1	9	182	33	3.26	81.9	137.9	D
26	1	21	41.7	60	48.8	149	20.7	5.0	2.6	5	318	192	0.47	9.5	6.8	D
26	1	51	43.2	60	11.7	152	38.9	96.5	2.3	8	152	25	0.14	3.7	7.5	C
26	2	13	26.5	60	12.2	152	37.3	148.8	2.5	11	157	25	0.53	8.3	14.0	D
26	13	6	39.0	59	59.8	152	58.9	141.0	2.3	4	113	40	0.	0.	0.	C
26	16	46	35.6	59	26.7	152	29.0	115.1	2.4	4	108	51	0.	0.	0.	C
26	21	36	45.2	59	47.9	152	51.5	90.1	2.4	7	99	26	0.21	3.2	7.0	C
27	4	25	59.7	59	47.4	152	40.6	98.7	2.4	5	124	34	0.22	7.3	23.2	D
27	5	21	34.5	60	24.2	151	43.3	5.0	2.8	5	264	58	1.00	51.6	243.8	D
27	7	35	25.7	60	7.4	153	18.7	162.9	2.2	6	152	44	0.25	12.5	35.8	D
27	8	25	40.5	60	12.3	152	24.8	43.9	2.5	4	185	31	0.39	0.	0.	D
27	11	12	12.6	59	5.5	152	56.0	76.9	2.3	12	86	37	0.19	1.5	2.9	B
27	13	7	43.0	58	51.6	152	34.1	48.1	2.3	8	114	28	0.20	2.1	4.2	B
27	9	9	41.9	60	52.2	151	42.8	85.9	3.1	8	260	76	0.28	8.9	7.4	D
27	14	26	45.8	60	22.8	152	54.9	61.4	2.3	8	184	9	3.43	116.7	141.3	D
27	16	0	19.8	59	34.3	152	49.9	90.3	2.0	7	82	24	1.32	18.2	49.8	C
27	18	16	51.0	60	25.2	154	4.0	243.6	2.4	5	260	52	0.09	15.7	30.5	D
27	19	6	47.7	59	57.1	151	32.9	39.9	2.2	5	234	33	4.01	303.6	182.4	D
27	19	30	42.1	60	0.9	152	43.8	105.9	2.6	8	126	45	0.24	4.7	9.6	C
27	23	2	11.1	59	33.6	152	9.6	151.3	2.0	5	122	31	1.80	41.8	131.7	D
28	0	24	23.8	59	58.7	152	4.1	162.6	2.7	4	184	42	0.	0.	0.	C
28	1	1	24.8	59	26.4	151	55.7	75.8	2.4	6	115	20	0.16	4.3	7.1	C
28	2	54	5.8	59	46.5	153	2.6	113.9	2.5	10	88	17	0.32	3.6	6.2	B
28	3	31	11.5	59	46.3	152	21.1	84.8	2.5	7	126	41	3.43	62.7	158.3	C
28	7	2	59.0	59	39.8	153	27.4	123.0	2.2	5	206	12	0.10	5.8	12.4	D
28	12	17	41.8	57	10.7	155	25.5	61.1	3.8	12	260	66	0.64	16.6	14.4	D
28	15	33	45.7	60	13.5	153	10.2	177.3	2.5	4	162	30	0.	0.	0.	C
28	15	48	7.4	59	28.2	152	37.3	112.1	2.8	14	81	39	2.67	23.5	41.9	C
28	21	47	43.9	60	1.9	152	48.0	123.9	2.7	11	121	43	0.30	3.8	5.9	C

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
NOV 29	2	22	45.6	58	37.9	154	4.2	0.6	2.3	7	182	47	3.00	29.1	123.9	D
29	2	25	23.0	58	43.7	153	50.6	2.9	2.6	9	161	31	0.32	2.5	3.4	C
29	3	28	47.7	60	26.0	151	59.3	45.7	2.6	6	259	43	0.72	19.0	21.4	D
29	6	45	58.7	60	30.8	152	0.8	104.1	2.3	4	272	43	0.04	0.	0.	C
29	8	27	9.0	58	50.7	152	37.9	112.7	2.1	9	105	29	2.50	35.9	62.1	C
29	11	31	47.7	60	7.2	153	4.5	153.6	2.0	6	196	37	0.12	6.1	12.5	D
29	14	5	2.2	59	18.2	152	10.5	5.0	2.3	5	203	71	3.01	83.0	719.3	D
29	16	26	20.6	60	21.6	151	18.7	5.0	2.7	6	274	80	0.99	42.8	708.7	D
30	6	22	35.2	59	49.7	153	22.5	144.5	0.	18	74	21	0.31	2.7	4.3	B
DEC 1	8	5	29.3	59	33.3	152	20.5	61.1	1.9	7	123	41	5.38	81.2	184.1	C
1	9	22	57.4	59	54.1	153	21.6	136.4	2.3	12	76	28	0.16	1.8	3.3	B
1	11	43	46.5	59	12.1	151	53.0	5.0	2.3	7	213	69	1.53	23.4	329.2	D
1	23	39	33.0	53	23.8	151	29.2	28.1	2.5	11	222	56	1.74	22.6	12.1	D
2	11	4	43.7	58	45.6	154	55.1	135.4	2.1	8	266	56	0.15	7.4	7.1	D
2	6	56	5.2	59	47.7	151	57.3	69.3	2.2	8	183	41	0.23	3.9	7.8	D
2	8	6	54.6	60	1.4	153	16.6	241.3	2.2	12	90	41	2.13	43.0	75.8	C
2	11	21	53.9	59	43.2	152	55.3	100.8	1.8	4	159	18	0.	0.	0.	C
2	15	7	21.1	58	38.7	152	30.2	6.9	2.0	8	90	9	0.47	4.5	5.1	C
2	17	50	10.2	60	8.9	151	26.0	5.0	2.2	3	254	75	0.01	0.	0.	C
2	20	2	16.8	59	26.3	150	13.1	5.0	3.0	3	307	172	0.08	0.	0.	C
2	23	25	52.2	59	42.4	151	26.1	50.2	2.3	6	240	27	0.12	6.9	7.7	D
3	4	27	33.2	60	2.2	152	41.1	122.5	2.0	5	142	42	0.04	1.8	5.0	D
5	7	45	35.7	58	40.2	152	33.8	101.5	2.1	7	189	13	2.99	162.5	248.4	D
5	14	49	53.3	59	30.5	152	48.3	72.7	2.3	6	92	69	0.40	5.8	16.1	C
5	20	3	25.5	59	54.9	155	11.7	2.5	2.8	5	294	216	7.26	638.4	234.4	D
6	0	57	50.7	60	19.2	153	12.2	160.4	2.5	10	122	26	0.24	4.0	6.7	C
6	2	16	14.4	59	28.0	152	35.1	94.7	2.4	6	134	44	0.07	1.7	4.7	B
6	4	55	10.7	59	42.6	153	39.4	154.6	2.0	7	135	41	0.23	7.8	18.8	D
6	13	55	55.4	59	42.1	153	12.6	123.3	2.2	8	104	64	0.28	4.7	12.8	C
6	14	13	59.1	60	15.0	150	58.1	113.5	2.3	5	281	76	0.06	22.0	22.4	D
7	2	45	16.0	58	53.5	153	53.9	92.1	2.2	8	196	22	0.19	3.9	3.8	D
7	2	45	45.8	59	4.3	152	9.8	67.1	2.8	6	224	55	0.01	0.6	0.9	C
7	4	57	22.9	59	38.4	153	21.6	107.4	2.9	13	68	30	1.57	12.8	21.9	C
7	6	9	44.2	59	38.7	153	3.1	31.6	2.8	11	79	35	4.61	27.4	35.4	C
7	7	23	17.6	58	44.1	154	21.9	96.0	2.4	7	230	41	0.13	4.0	4.3	D
7	9	28	40.5	59	4.5	151	22.4	9.6	2.1	4	242	45	0.26	0.	0.	C
7	10	24	14.0	58	16.0	153	29.3	74.0	2.6	10	182	30	0.09	1.3	2.0	C
7	11	51	34.3	58	26.1	154	33.4	2.5	2.3	8	244	77	0.50	10.5	30.9	D
7	11	52	49.4	59	47.9	152	52.2	5.0	2.3	6	91	69	2.59	24.9	485.1	D
7	14	37	1.7	56	21.4	158	31.2	35.4	3.8	3	323	375	0.29	0.	0.	C
7	17	29	21.6	58	21.8	154	8.0	67.2	2.8	9	206	66	0.23	3.5	6.0	D
20	32	59	59.3	59	31.1	150	2.7	0.3	2.9	4	290	165	1.62	0.	0.	D
8	12	9	45.4	59	31.5	151	49.8	166.1	1.7	6	141	15	2.57	103.4	214.2	D
8	13	37	3.4	61	59.9	150	23.2	33.9	3.1	6	303	217	0.48	47.9	830.3	D
8	16	20	57.5	59	54.5	152	51.8	5.0	2.4	8	107	57	1.42	10.4	12.9	D

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976		ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
DEC	8	17	8	18.9	58	17.5	152	15.3	23.3	2.5	10	177	37	3.07	27.9	30.8	D
	8	17	44	5.2	59	51.4	153	4.8	5.0	1.8	8	102	56	4.62	36.1	530.0	D
	8	18	35	21.8	55	57.8	150	30.4	5.0	3.8	3	349	232	1.07	0.	0.	D
	9	4	24	17.6	58	6.9	152	10.0	40.0	2.2	5	213	45	0.20	5.8	3.1	D
	9	4	56	7.4	59	45.0	152	43.8	36.9	2.5	9	101	54	2.61	18.2	20.6	C
	9	7	50	55.4	59	51.7	152	50.4	5.0	2.0	4	110	62	0.71	0.	0.	D
	9	22	30	54.2	58	7.3	151	49.6	20.0	2.5	7	218	57	0.52	8.8	11.4	D
	10	3	53	34.1	59	26.5	151	8.9	5.0	2.2	4	257	113	3.84	0.	0.	D
	10	6	57	5.5	59	48.4	153	29.8	149.6	2.5	9	117	44	0.25	3.7	6.6	C
	10	11	19	21.3	59	52.6	153	42.7	59.1	1.8	4	137	30	4.61	0.	0.	D
	10	18	14	58.1	59	35.5	153	12.3	36.2	2.2	6	111	70	0.68	7.2	10.3	C
	10	22	49	54.6	59	10.0	153	29.6	5.0	2.1	6	164	89	4.04	47.4	994.6	D
	11	2	5	45.9	57	59.1	152	32.6	44.6	2.2	5	155	26	1.04	5.9	10.7	D
	11	7	33	35.2	59	57.3	152	13.4	29.3	1.7	4	166	46	0.75	0.	0.	D
	11	9	58	14.9	59	45.2	153	10.9	5.0	1.8	4	218	77	0.17	0.	0.	C
	12	7	44	51.5	62	58.9	151	30.0	5.0	3.5	4	315	293	0.28	0.	0.	C
	12	11	36	26.9	61	6.7	151	26.7	87.9	2.8	8	272	105	0.40	16.7	13.5	D
	12	13	30	37.8	59	47.4	152	30.6	11.0	2.1	4	172	50	0.33	0.	0.	D
	12	14	56	52.8	59	7.0	152	32.3	90.1	2.5	9	115	54	0.17	1.8	3.7	B
	12	16	37	51.8	59	2.6	153	55.0	0.7	2.0	4	192	42	0.	0.	0.	C
	12	19	0	1.2	60	21.7	151	55.6	183.9	2.4	8	251	47	2.31	116.0	191.2	D
	12	20	30	43.2	59	40.7	152	0.3	34.3	2.1	7	124	20	0.17	1.9	1.5	B
	13	1	25	29.6	60	31.1	147	15.3	5.0	3.5	4	326	303	1.30	0.	0.	D
	13	7	25	9.2	57	47.4	152	23.7	35.8	2.4	5	216	7	0.11	3.5	2.1	D
	13	7	33	55.4	58	17.1	151	26.9	19.3	2.6	7	227	63	0.41	7.4	6.5	D
	13	17	57	52.4	60	15.4	152	3.1	117.2	2.6	6	227	43	0.14	8.8	18.9	D
	13	8	57	34.8	61	22.0	151	1.0	91.3	2.9	5	285	142	0.60	69.1	68.1	D
	13	12	29	0.6	59	43.0	153	36.9	30.4	2.7	5	219	91	0.35	13.4	16.0	D
	13	17	28	13.0	60	7.5	152	35.5	5.0	2.7	6	155	34	0.34	10.4	18.8	D
	14	9	52	13.2	59	53.1	152	41.6	5.0	2.1	3	142	59	0.	0.	0.	C
	14	13	54	12.8	59	34.6	152	16.3	5.0	2.2	3	199	70	0.	0.	0.	C
	14	19	12	25.5	60	0.4	153	39.8	168.9	2.3	6	235	67	0.11	5.9	8.8	D
	14	19	49	49.2	58	41.2	153	46.7	0.3	2.9	7	186	74	14.14	211.9	971.9	D
	14	20	14	57.8	59	18.3	157	2.1	26.3	3.4	6	260	205	1.65	68.3	861.4	D
	14	21	9	44.0	58	35.3	152	3.9	16.7	1.9	4	239	17	0.	0.	0.	C
	15	0	57	21.8	60	12.8	152	33.2	402.6	2.9	7	168	25	1.59	95.5	224.3	D
	15	5	35	34.7	60	2.8	152	8.1	31.2	2.3	7	188	51	3.39	41.7	48.0	D
	15	5	37	34.3	60	2.6	152	33.3	11.9	2.2	6	146	43	1.15	12.3	990.3	D
	15	9	42	46.7	60	38.9	151	52.4	5.0	2.0	3	290	55	0.06	0.	0.	C
	15	9	51	23.0	61	49.4	149	16.3	35.2	3.8	7	333	245	0.14	73.9	212.9	D
	15	10	57	34.4	60	16.8	152	15.6	5.0	1.8	5	215	32	0.75	51.0	91.8	D
	15	13	2	16.8	59	57.7	152	42.1	3.3	2.0	4	116	60	1.25	0.	0.	D
	15	14	23	33.5	58	42.8	151	41.6	185.1	1.9	5	228	39	1.10	81.7	133.5	D
	15	16	2	45.0	58	5.0	152	45.8	5.0	1.0	3	135	23	0.	0.	0.	C
	16	5	11	55.9	59	34.1	153	8.0	106.7	2.4	7	93	25	0.38	6.9	17.3	C

1976	ORIGIN TIME HR MN	SEC	LAT N DEG MIN	LONG W DEG MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
DEC 16	7 52	35.2	59 8.6	152 39.4	146.8	2.2	6	165	48	2.84	81.1	172.9	D
16	9 8	13.5	60 13.7	152 46.4	5.0	1.4	4	135	21	3.52	0.	0.	D
16	11 50	23.6	61 59.2	150 43.6	31.1	3.3	7	300	206	0.43	33.6	651.3	D
16	13 42	25.0	59 10.4	152 1.6	75.3	2.6	8	152	41	0.16	2.0	3.8	C
14	26 59	52.1	59 14.1	152 30.9	70.3	2.4	9	108	50	0.20	1.9	3.8	B
16	19 51	14.0	59 12.0	152 59.2	5.0	2.0	5	170	73	0.42	6.8	930.9	D
16	22 23	53.4	60 0.1	152 33.6	4.1	2.2	6	141	47	0.65	12.7	29.5	D
17	0 54	57.9	59 37.7	152 59.3	5.0	2.2	3	154	79	0.01	0.	0.	C
17	1 1	42.3	60 23.5	153 31.4	207.5	2.5	10	141	41	0.30	5.8	11.5	D
17	5 23	57.2	59 51.9	152 40.0	5.0	1.9	6	139	61	1.20	12.4	80.6	D
17	6 31	27.2	59 19.0	153 21.0	5.0	2.4	3	232	95	0.	0.	0.	C
17	9 3	4.3	59 26.5	152 59.6	2.5	2.1	5	152	80	0.58	8.9	285.7	D
17	11 53	44.1	60 43.1	153 52.2	1.3	2.6	8	184	68	6.08	63.4	461.2	D
17	13 29	40.0	59 59.9	153 1.1	134.0	2.5	10	100	48	0.18	2.5	4.0	B
17	13 44	40.6	60 9.5	152 45.8	119.9	2.2	8	133	29	0.25	4.3	6.9	C
17	13 55	9.9	58 47.4	152 33.8	53.9	2.4	9	118	21	0.37	3.7	6.0	C
17	17 20	0.3	58 13.6	151 14.2	27.7	2.8	10	243	79	0.64	10.8	5.2	D
17	19 20	24.4	59 30.9	153 24.3	131.6	2.5	11	92	16	0.23	2.6	4.3	C
17	18 33	9.4	59 42.2	151 59.1	86.5	2.7	11	133	19	6.22	66.9	97.6	C
17	19 57	59.7	59 31.8	152 42.8	5.0	2.2	5	131	62	0.41	6.1	926.4	D
18	1 55	17.5	59 25.0	153 6.3	118.7	2.0	8	120	15	0.19	2.9	5.8	C
18	5 4	56.4	60 9.2	152 45.8	130.6	2.5	10	132	29	0.33	4.9	7.6	C
18	6 34	13.1	59 37.7	152 46.9	5.0	1.9	3	256	64	0.24	0.	0.	C
18	7 29	34.9	60 7.3	152 5.9	90.6	2.8	10	202	49	3.74	62.0	91.8	D
18	7 51	52.0	59 28.4	154 1.0	363.9	2.0	6	199	55	1.27	37.7	112.0	D
18	8 42	32.4	59 31.0	152 53.5	94.3	1.6	4	141	74	0.	0.	0.	C
18	9 16	35.6	59 53.3	152 18.1	4.5	2.0	5	148	45	3.85	6.6	9.7	D
18	12 39	59.9	59 19.4	152 32.0	77.5	2.9	10	99	47	0.23	2.1	4.3	B
19	0 47	11.2	59 43.5	153 4.4	5.0	2.4	7	83	70	1.07	8.4	629.6	D
19	15 59	10.8	59 50.8	152 24.8	10.9	2.0	4	145	49	0.02	0.	0.	C
19	16 36	23.0	60 3.1	152 20.7	4.0	2.2	4	168	47	0.52	0.	0.	D
19	17 35	45.7	61 12.9	151 39.9	59.9	2.6	4	272	107	0.	0.	0.	C
19	20 8	32.4	59 59.1	154 48.4	5.0	2.4	4	233	122	0.14	0.	0.	C
19	20 39	13.5	58 57.0	153 4.4	5.0	2.2	5	147	99	7.65	123.1	82.5	D
20	0 4	16.8	59 45.9	153 3.4	5.0	2.4	7	86	69	1.15	9.1	764.1	D
20	2 24	53.2	60 11.4	152 1.3	1.3	1.9	4	219	48	0.85	0.	0.	D
20	3 12	38.3	58 59.5	152 9.0	86.2	2.4	8	165	42	10.46	149.0	277.5	D
21	2 41	11.0	61 43.2	148 8.8	177.2	3.3	3	337	288	0.04	0.	0.	C
21	7 28	25.0	62 11.3	151 52.2	5.0	3.2	5	298	203	0.33	52.9	63.2	D
21	13 4	3.6	59 57.8	151 47.8	70.3	2.4	7	213	35	0.24	8.3	11.8	D
21	14 31	46.7	58 21.0	154 9.5	109.8	2.7	7	275	65	0.19	12.0	12.3	D
21	15 55	27.0	59 11.8	152 36.7	5.0	2.1	5	146	65	1.19	17.8	663.8	D
21	18 49	59.3	58 47.0	152 34.5	7.5	2.2	4	214	21	0.12	0.	0.	C
21	21 58	25.3	59 51.5	152 29.7	11.0	2.3	4	147	52	0.44	0.	0.	D
22	3 38	44.8	59 52.7	152 36.4	5.0	2.6	6	123	59	0.67	6.6	164.0	D

COOK INLET-WESTERN GULF OF ALASKA EARTHQUAKES

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
DEC 22	5	39	55.6	59	24.2	150	15.3	54.4	2.8	6	319	75	0.15	41.6	8.1	D
22	10	1	34.2	60	15.5	152	14.6	106.1	2.8	10	212	34	0.20	3.4	4.8	D
22	13	37	54.2	60	24.9	153	2.6	159.8	2.7	10	149	15	0.24	4.1	7.0	C
22	14	49	18.8	59	37.5	151	52.4	5.0	2.2	5	223	93	4.90	127.8	956.8	D
22	20	3	55.7	59	51.6	153	24.2	142.5	1.9	4	127	47	0.	0.	0.	C
23	6	37	29.5	61	24.2	151	49.0	105.4	3.2	9	276	121	0.25	9.7	9.0	D
23	6	11	21.3	58	51.1	153	31.2	41.5	1.9	4	175	90	0.97	0.	0.	D
23	6	37	28.8	61	23.7	151	48.3	118.9	3.2	9	276	120	0.72	28.2	26.1	D
23	11	35	51.8	60	3.2	152	1.1	101.6	2.6	5	200	48	0.21	11.2	15.0	D
23	12	23	15.5	59	38.4	153	6.9	5.0	2.5	6	79	72	1.31	12.4	265.4	D
23	15	44	20.1	58	10.5	152	5.1	37.4	2.7	7	247	52	0.15	4.2	1.3	D
24	1	50	23.8	62	50.6	151	55.5	5.0	3.9	5	312	273	0.30	56.8	520.9	D
24	1	56	47.3	60	54.0	153	27.0	5.0	2.1	4	224	65	1.62	0.	0.	D
24	3	16	25.6	58	32.4	152	32.8	21.1	2.3	6	186	64	1.44	19.1	21.9	D
24	8	42	36.3	59	50.5	153	35.2	139.4	1.8	6	105	38	0.17	6.6	17.4	C
24	10	6	23.8	59	48.2	152	32.7	132.4	2.3	7	119	53	0.18	3.9	10.0	C
21	14	38	33.2	60	28.9	152	3.8	22.3	3.0	9	236	39	1.08	17.3	10.3	D
24	15	28	4.9	60	42.2	149	18.9	39.6	3.0	4	322	173	0.08	0.	0.	C
24	18	27	53.6	60	7.1	152	57.5	59.2	1.9	5	121	35	0.40	29.9	69.0	D
24	21	45	48.1	58	25.5	152	34.5	21.2	2.1	4	194	53	0.30	0.	0.	C
25	3	20	46.0	59	30.3	152	51.9	81.9	2.6	6	117	71	0.21	3.9	10.6	C
25	7	39	24.2	60	8.6	152	49.5	106.0	2.3	8	124	30	0.23	5.5	10.6	C
25	11	8	15.0	61	32.6	155	50.7	2.3	3.1	7	321	49	5.22	116.7	44.5	D
25	19	47	50.7	59	59.7	152	56.7	132.7	2.1	6	108	41	1.40	33.0	64.6	C
25	20	21	22.2	59	59.6	150	37.4	10.9	2.2	4	291	68	0.02	0.	0.	C
25	23	41	32.6	59	56.3	153	23.2	162.2	2.0	5	120	33	0.13	8.5	29.2	D
26	0	16	23.7	58	26.2	152	47.9	37.7	2.0	8	261	33	0.22	7.4	1.7	D
26	3	17	42.2	60	3.9	152	33.2	125.0	2.3	7	149	41	0.15	4.3	12.2	C
26	7	4	32.3	58	19.9	151	48.4	15.0	2.7	8	296	45	0.60	40.4	11.1	D
26	9	0	34.2	59	58.9	152	16.1	84.9	2.9	10	166	50	0.24	3.1	5.7	D
26	10	48	48.6	59	56.8	152	52.6	0.5	2.1	4	109	38	4.38	0.	0.	D
26	15	39	3.7	59	21.2	153	35.5	117.6	1.8	6	101	9	0.06	1.7	2.8	B
27	0	16	0.9	59	12.5	150	50.1	2.3	2.8	4	314	144	2.95	0.	0.	D
27	2	44	57.7	59	47.9	153	8.2	111.2	2.2	6	179	49	0.15	4.4	11.2	C
27	5	27	35.7	58	39.7	152	31.2	5.0	2.4	5	266	105	0.24	13.2	544.3	D
27	12	4	45.4	62	57.2	149	13.0	5.0	4.2	3	321	339	0.09	0.	0.	C
27	22	59	43.5	59	12.1	152	6.4	424.0	2.3	4	260	42	2.63	0.	0.	D
27	17	25	16.5	58	29.2	152	17.1	25.9	3.0	6	281	116	0.20	57.7	3.3	D
28	9	39	40.4	59	50.2	153	27.8	148.5	2.0	5	213	52	0.08	5.8	12.1	D
28	10	2	42.8	58	31.6	154	55.4	17.3	3.0	5	313	76	0.15	36.1	12.2	D
28	19	29	56.4	59	39.6	152	45.0	131.0	2.6	7	119	46	0.09	2.9	18.1	C
28	22	24	46.1	59	20.2	153	7.1	90.0	2.6	9	96	13	0.17	2.1	3.6	B
28	22	40	42.6	60	27.3	150	26.6	0.7	2.9	4	302	111	0.83	0.	0.	D
28	22	41	41.7	60	19.4	152	45.8	133.5	2.4	6	143	10	0.13	11.7	30.3	D
28	23	18	15.6	60	6.6	152	59.8	204.0	2.4	6	124	36	0.22	17.4	102.8	C

1976	ORIGIN TIME HR	MN	SEC	LAT N DEG	MIN	LONG W DEG	MIN	DEPTH KM	MAG	NO	GAP DEG	DM KM	RMS SEC	ERH KM	ERZ KM	Q
DEC 29	0	35	4.6	58	52.1	152	8.9	0.8	2.2	6	178	29	0.97	25.7	207.8	D
29	9	34	3.1	59	55.4	152	59.8	5.0	2.7	7	99	56	1.29	10.6	975.1	D
29	10	34	43.3	59	56.4	152	40.3	82.6	2.5	5	125	53	0.04	1.7	10.9	D
29	17	25	34.8	59	19.8	153	5.9	89.2	2.0	5	120	18	0.09	2.7	5.3	D
29	18	2	11.7	60	0.5	152	59.0	92.1	2.0	4	138	47	0.37	0.	0.	D
29	18	7	17.3	60	25.0	150	18.6	84.1	2.7	4	304	112	0.03	0.	0.	C
29	21	22	32.2	59	31.4	152	42.4	78.2	2.3	6	78	46	0.21	3.3	9.9	B
29	21	39	44.9	58	56.0	152	43.1	5.0	2.3	7	170	40	1.25	48.0	111.1	D
30	4	21	10.1	62	9.9	151	54.2	1.3	2.9	6	297	200	0.57	59.0	117.8	D
30	7	55	21.8	60	0.7	152	33.3	2.7	2.2	4	142	47	0.35	0.	0.	D
30	16	57	29.7	60	4.2	151	14.7	117.6	2.5	4	261	51	0.10	0.	0.	C

Appendix 3

Cumulative and Monthly Plots of Epicenters of Earthquakes in the Lower Cook Inlet, Kodiak, and Alaska Peninsula Areas February through December 1976

This appendix shows cumulative and monthly plots of epicenters. Triangles with three-letter codes show the locations of seismic stations. The one-letter code shows the epicenter location with the following depth code:

A	$0 \leq 25$
B	$26 \leq 50$
C	$51 \leq 100$
D	$101 \leq 125$
E	$126 \leq 150$
F	$151 \leq 175$
G	$176 \leq 200$
etc.	

The following is a list of figures:

Figure	Caption
A3-1	Cook Inlet, all events
A3-2	Cook Inlet, class 1 events
A3-3	Kodiak-Alaska Peninsula, all events
A3-4	Cook Inlet, all events, depth $\leq$ 50 km
A3-5	Cook Inlet, all events, depth > 50 km
A3-6 through A3-16	Cook Inlet, monthly plots, all events

Class 1 events have the following quality parameters (see Appendix 2 for definition):

RMS $\leq$ 1 sec
ERZ $\leq$ 10 km
ERH $\leq$ 10 km
NP > 5

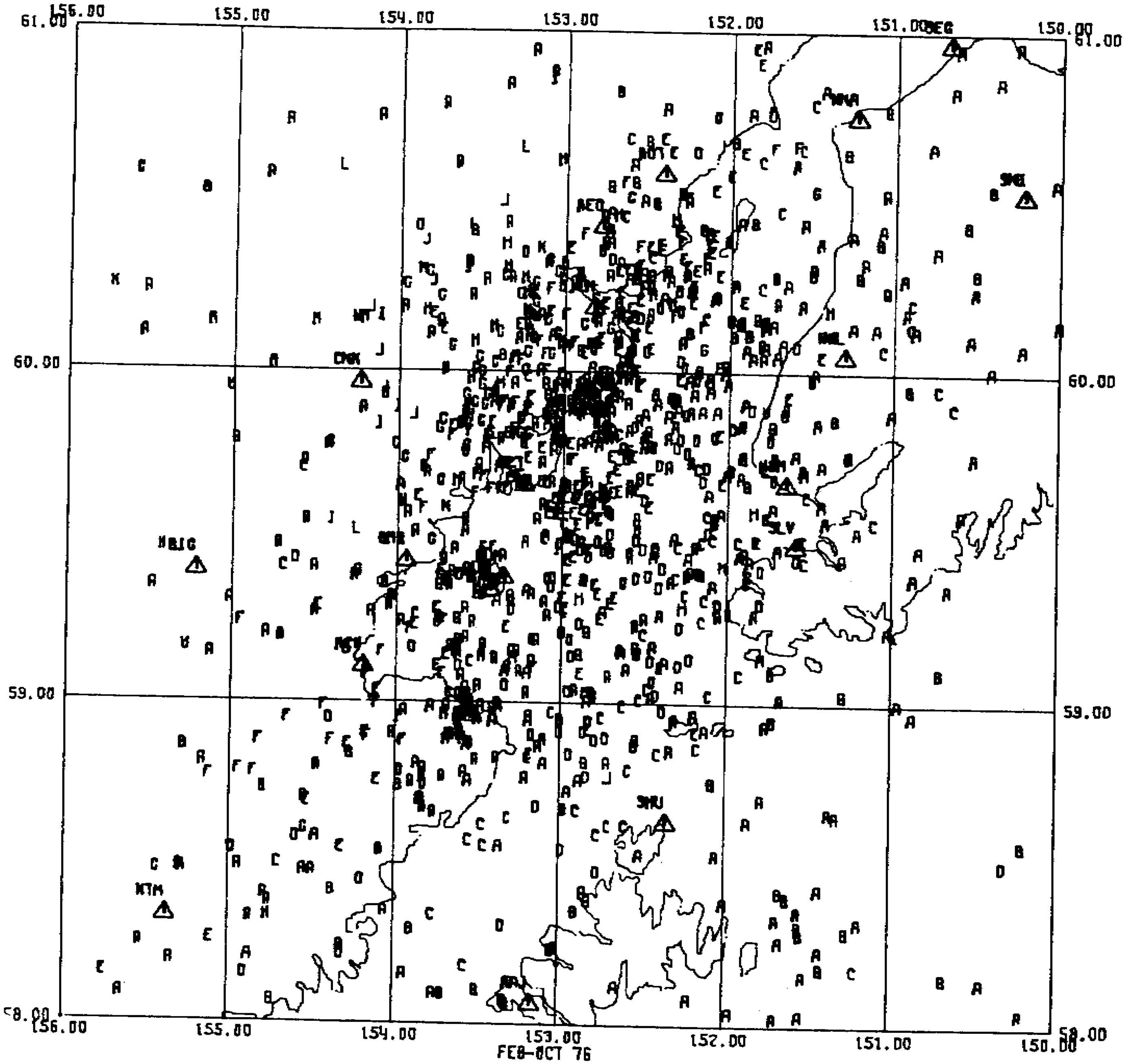
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Figure A3-1

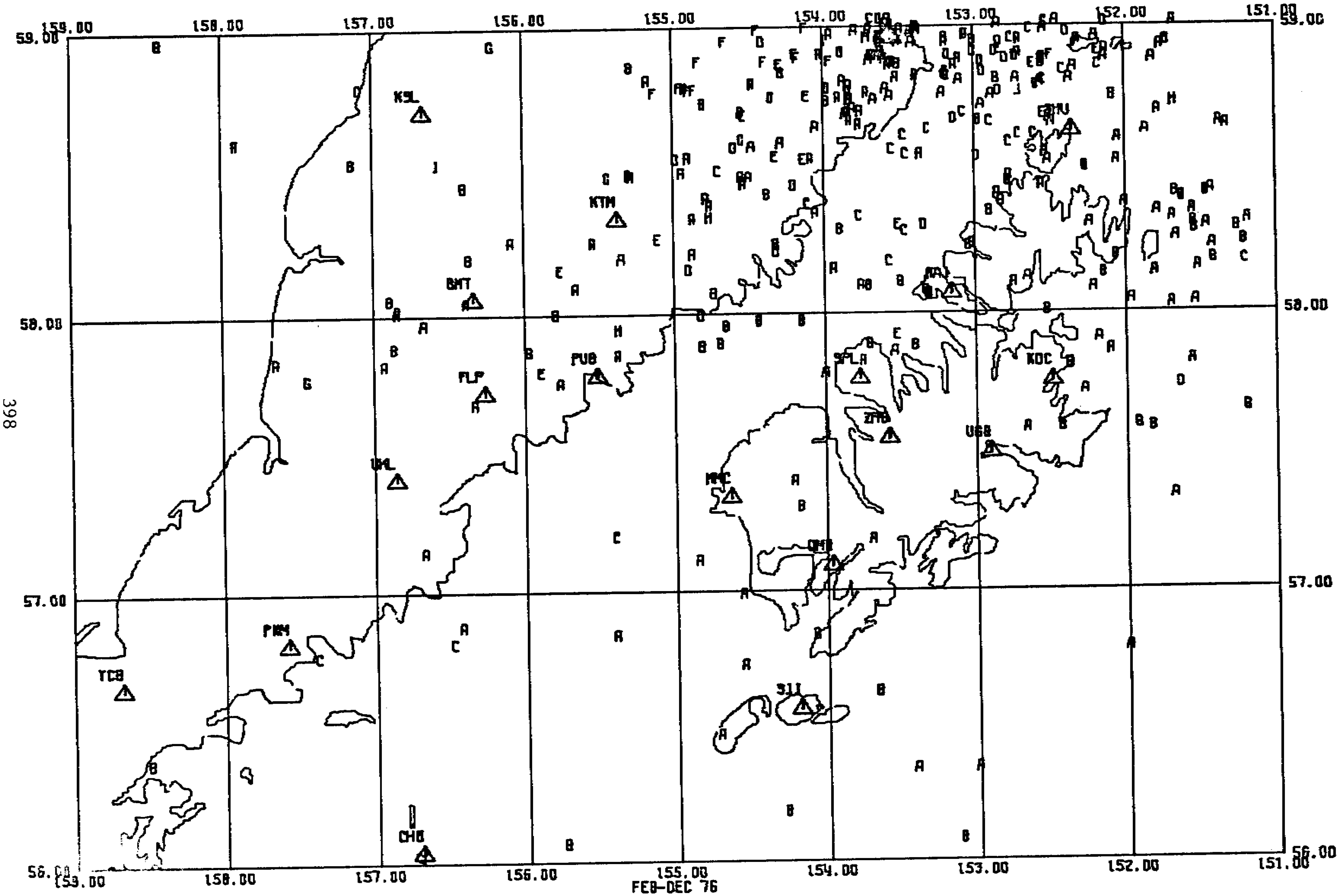
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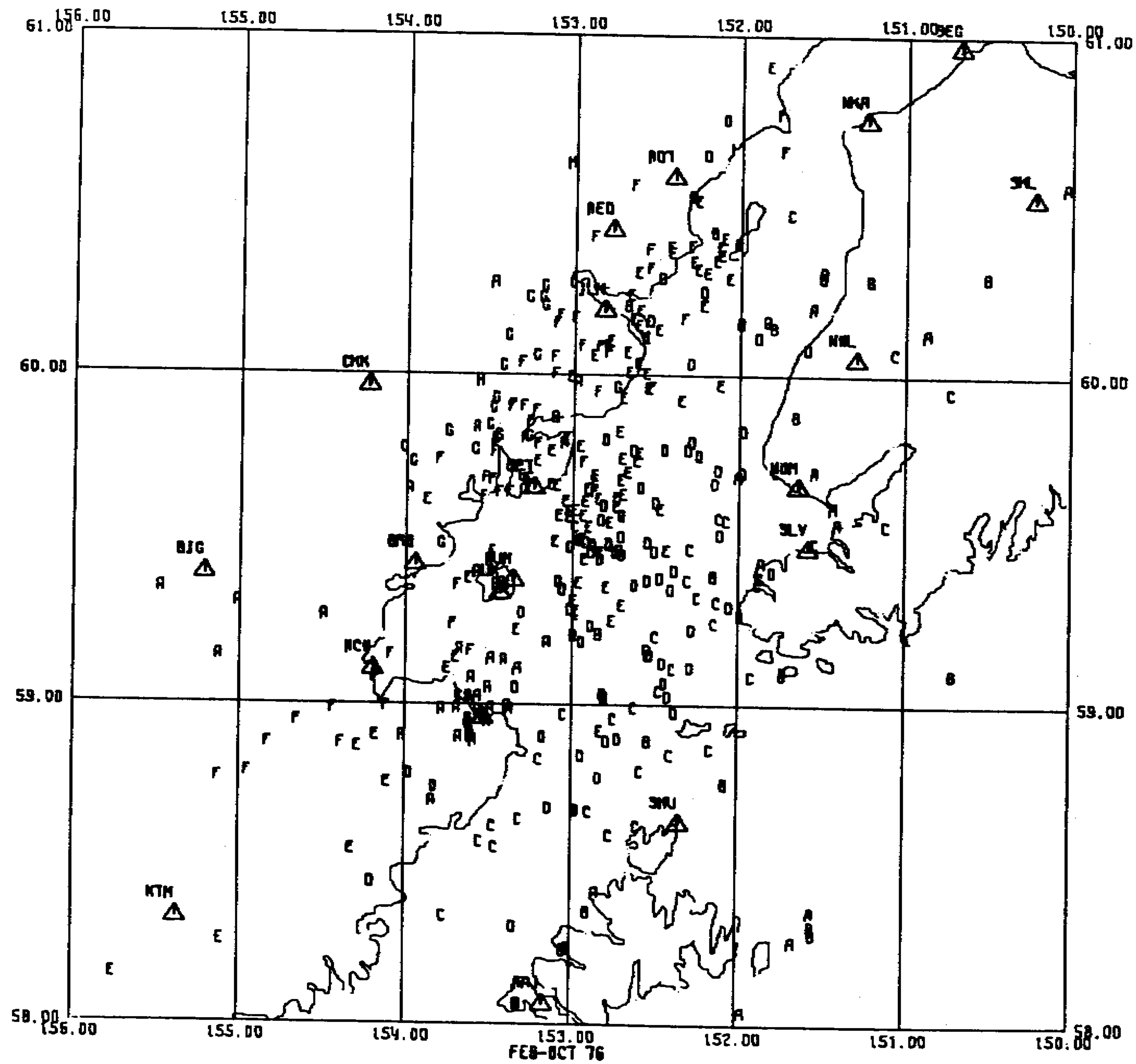
Figure A3-2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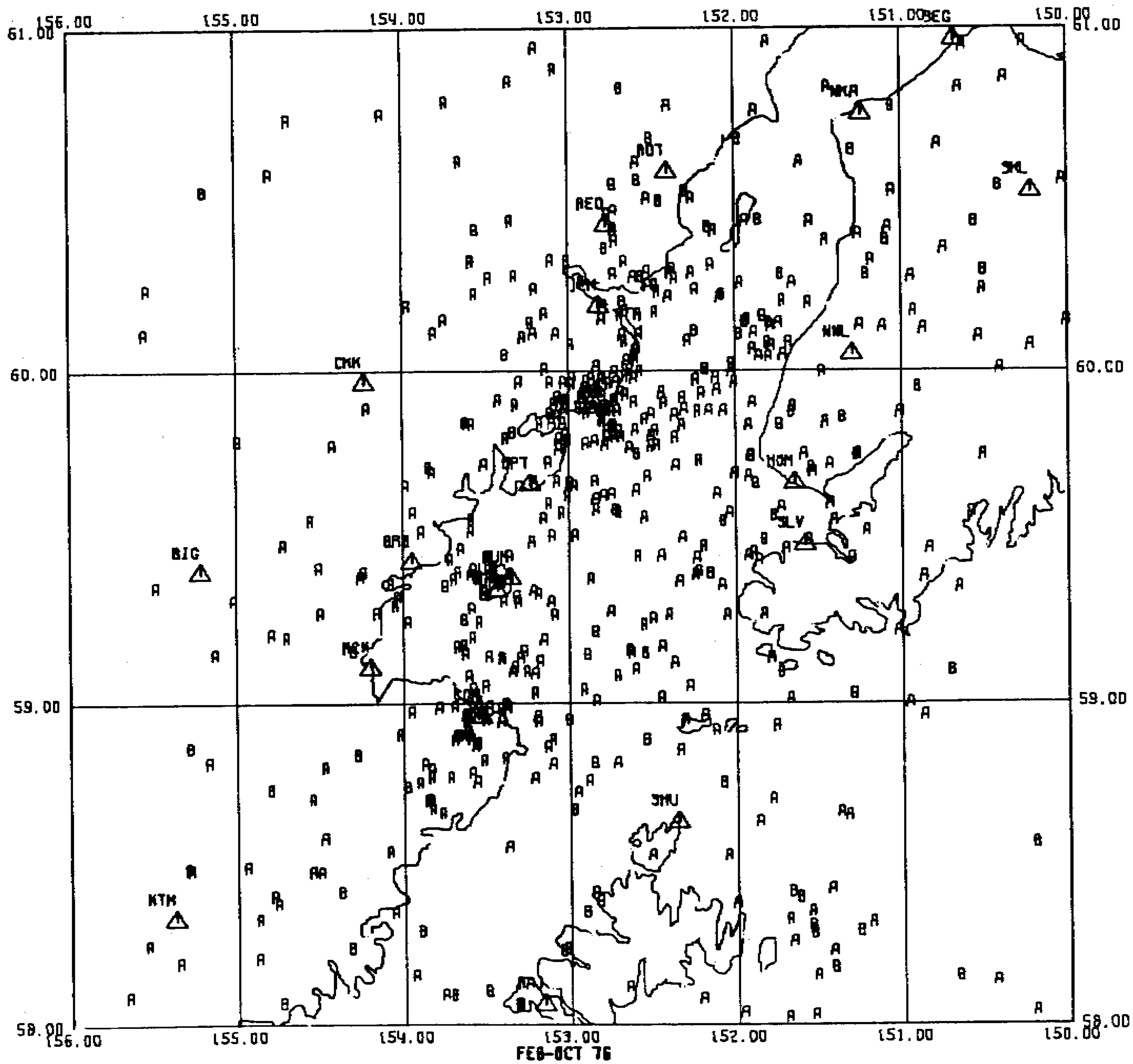
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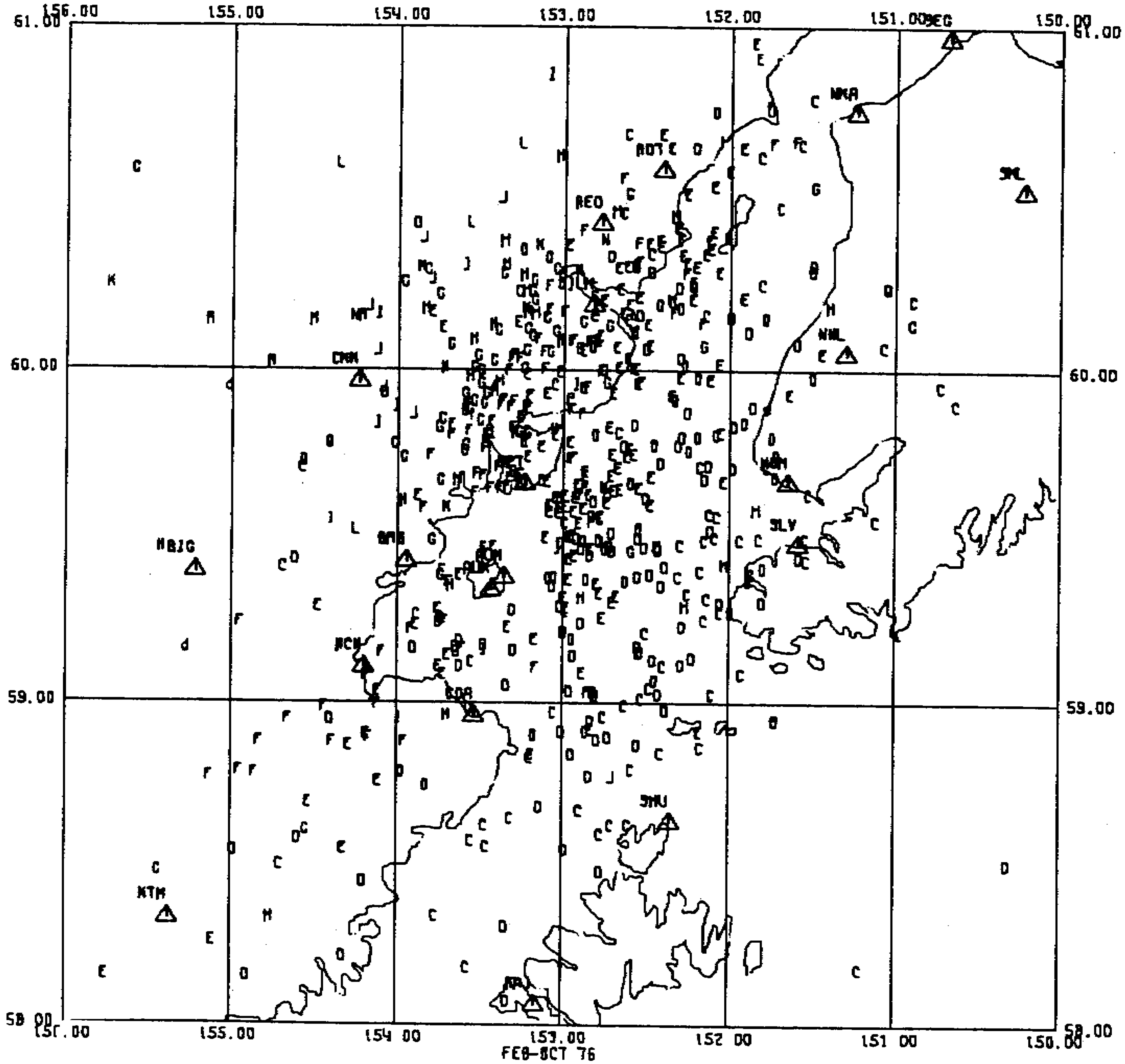
Figure A3-4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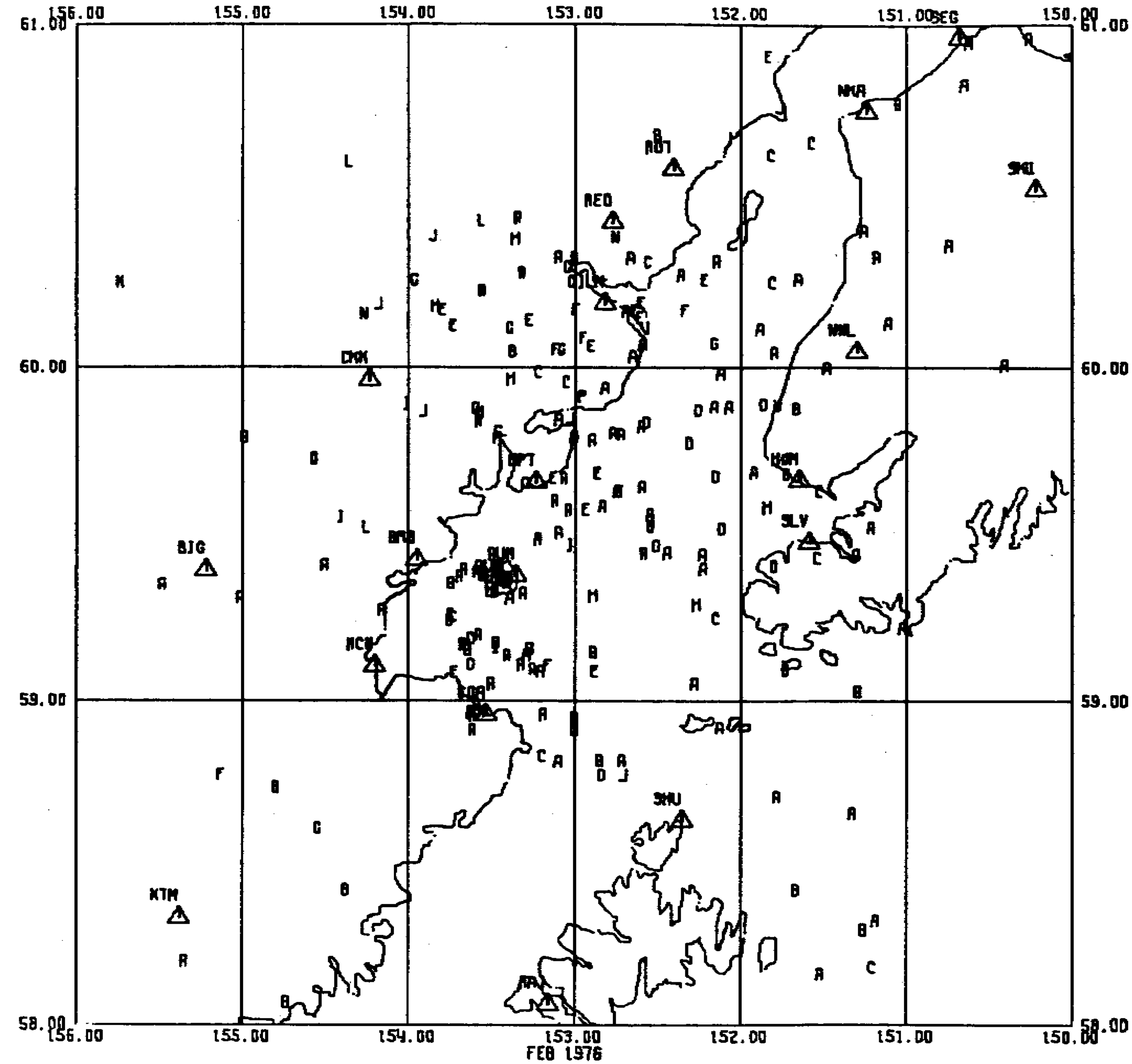
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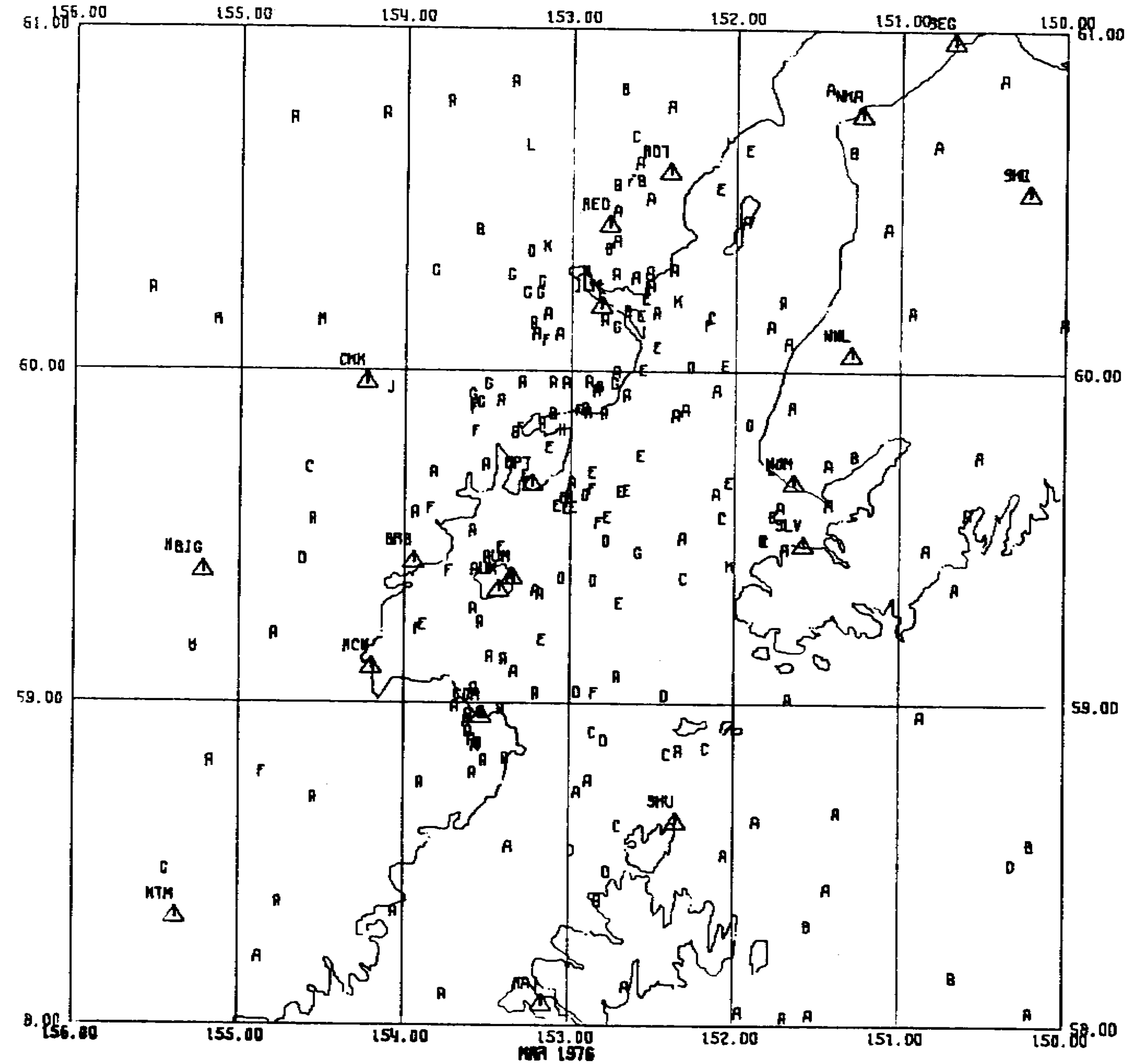
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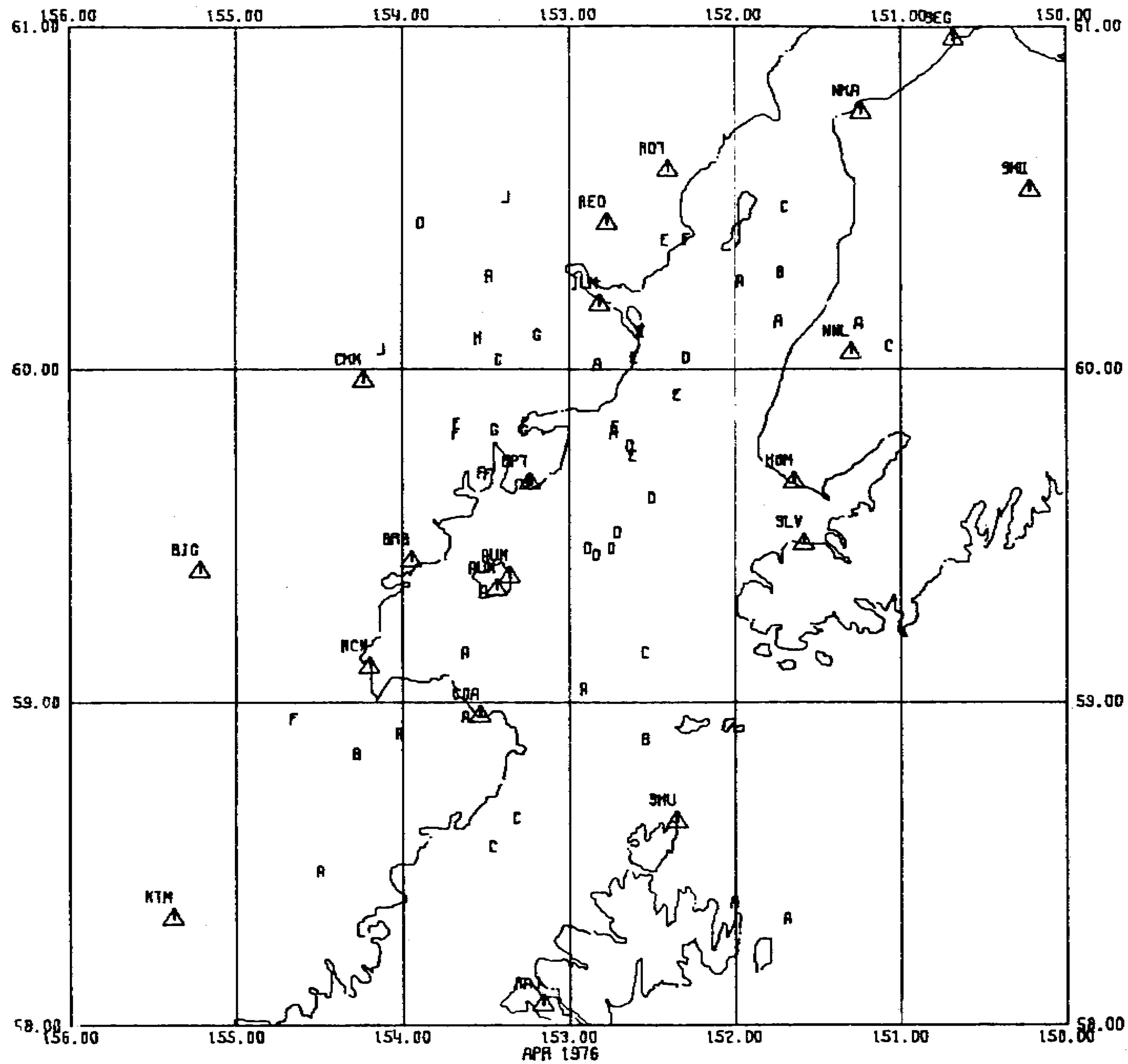
Figure A3-7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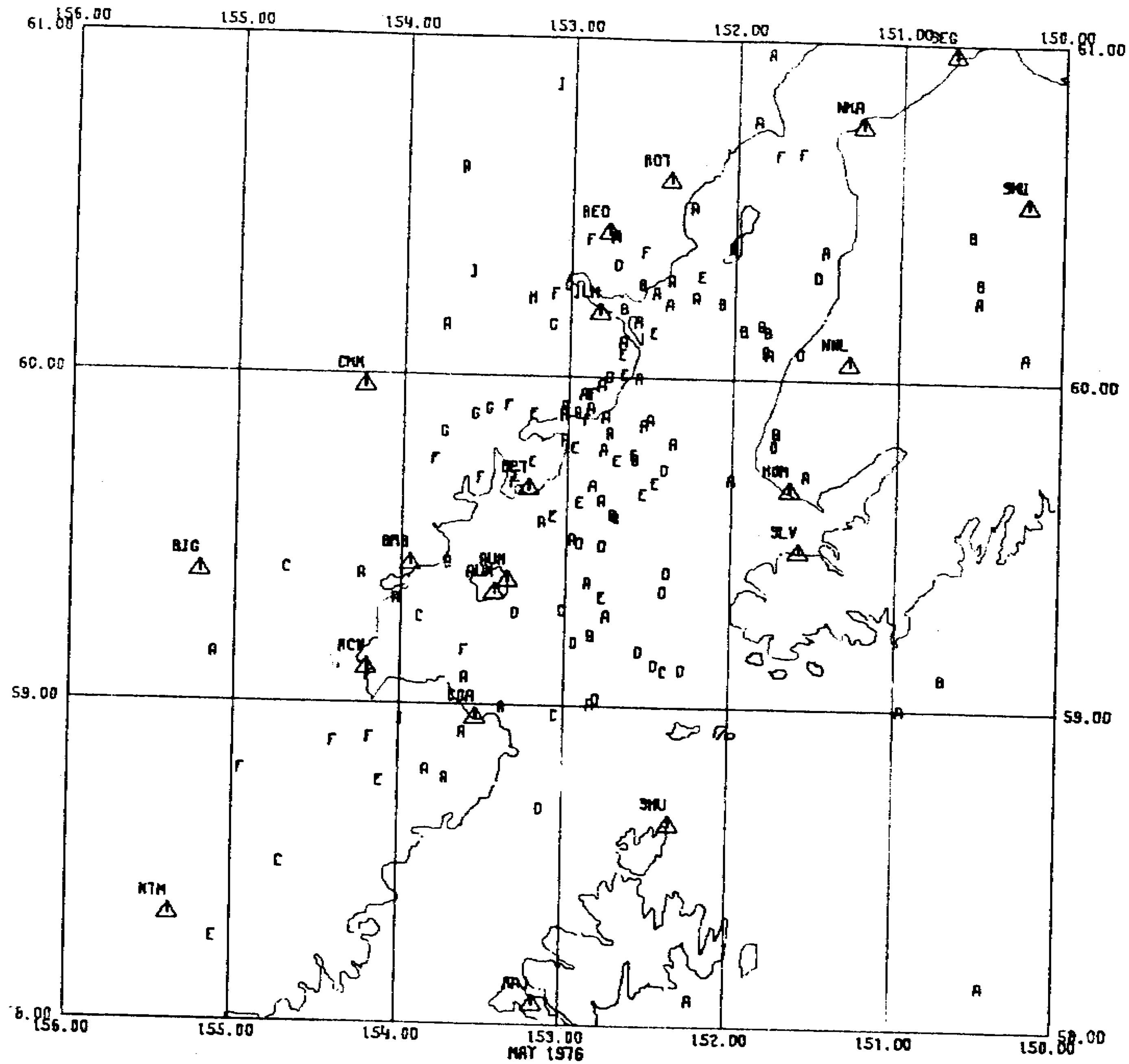
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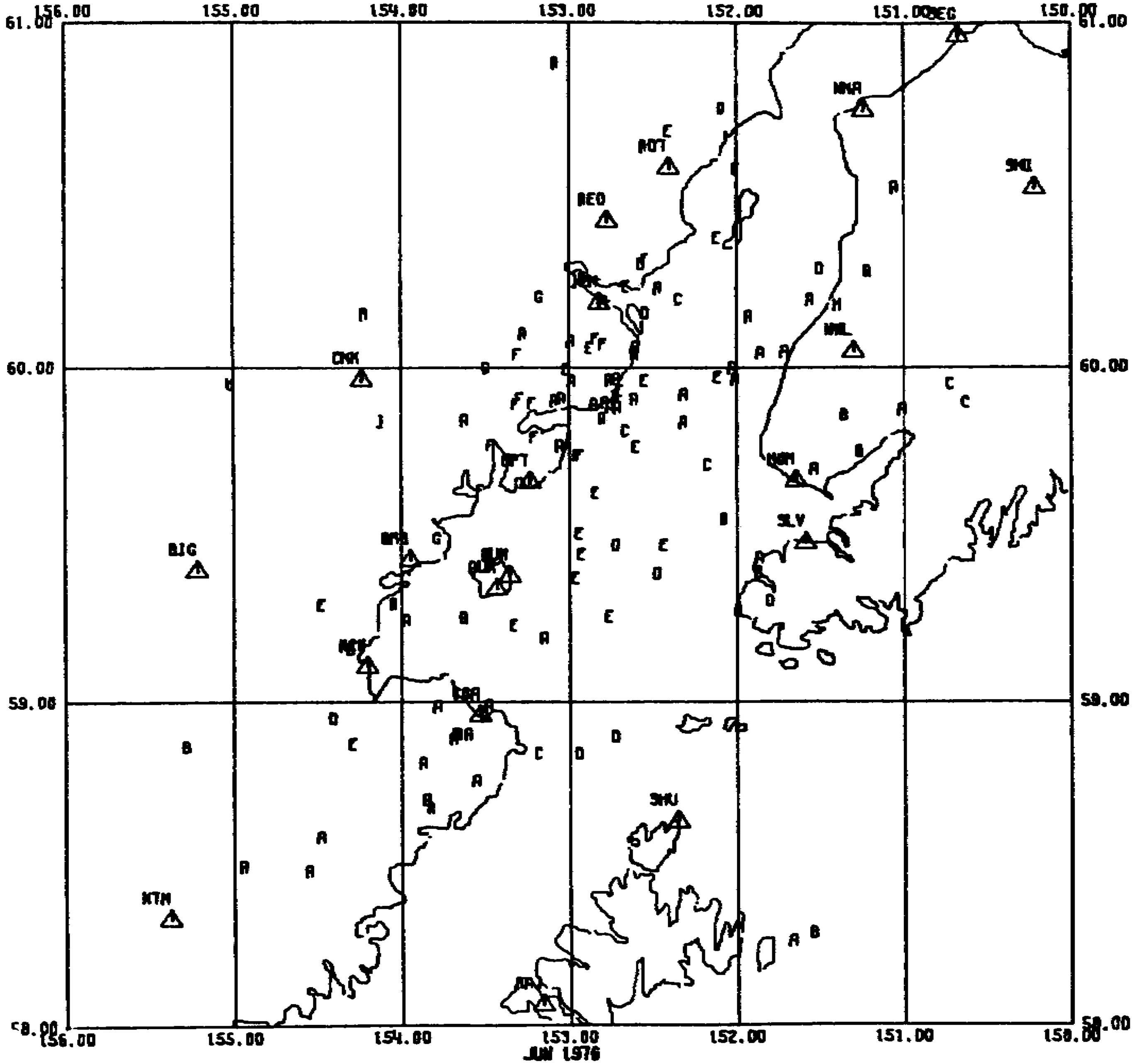
Figure A3-9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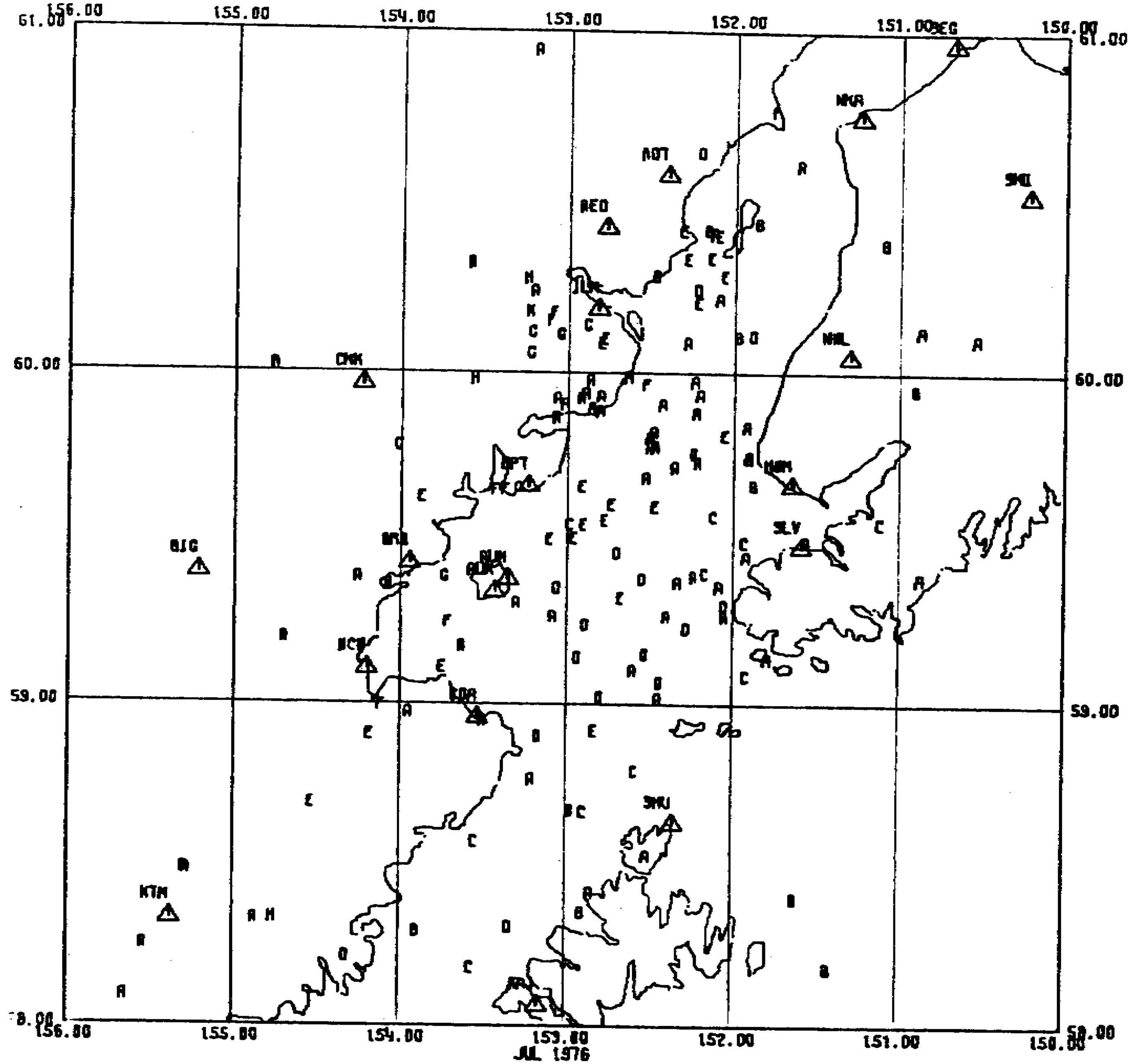

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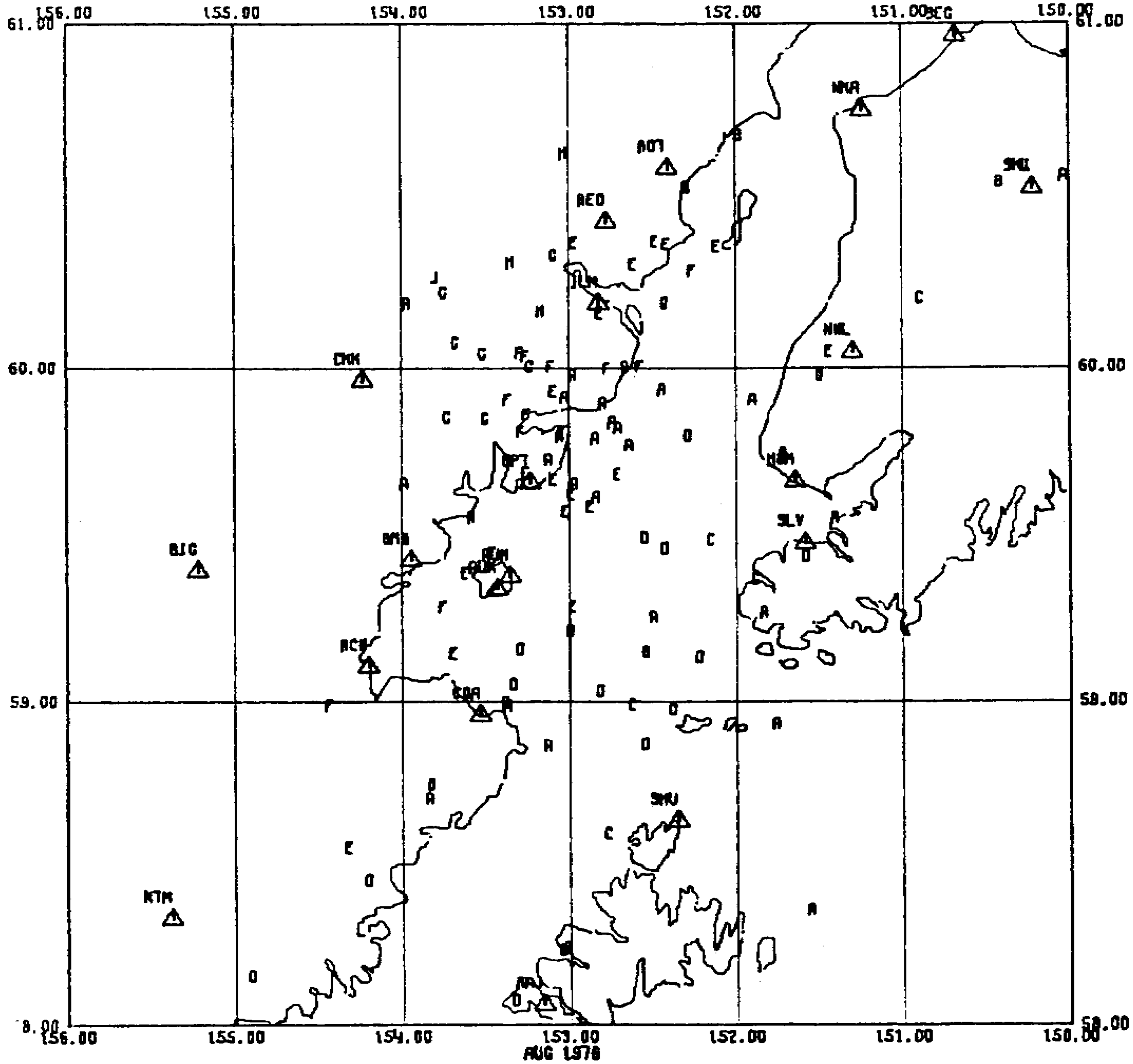

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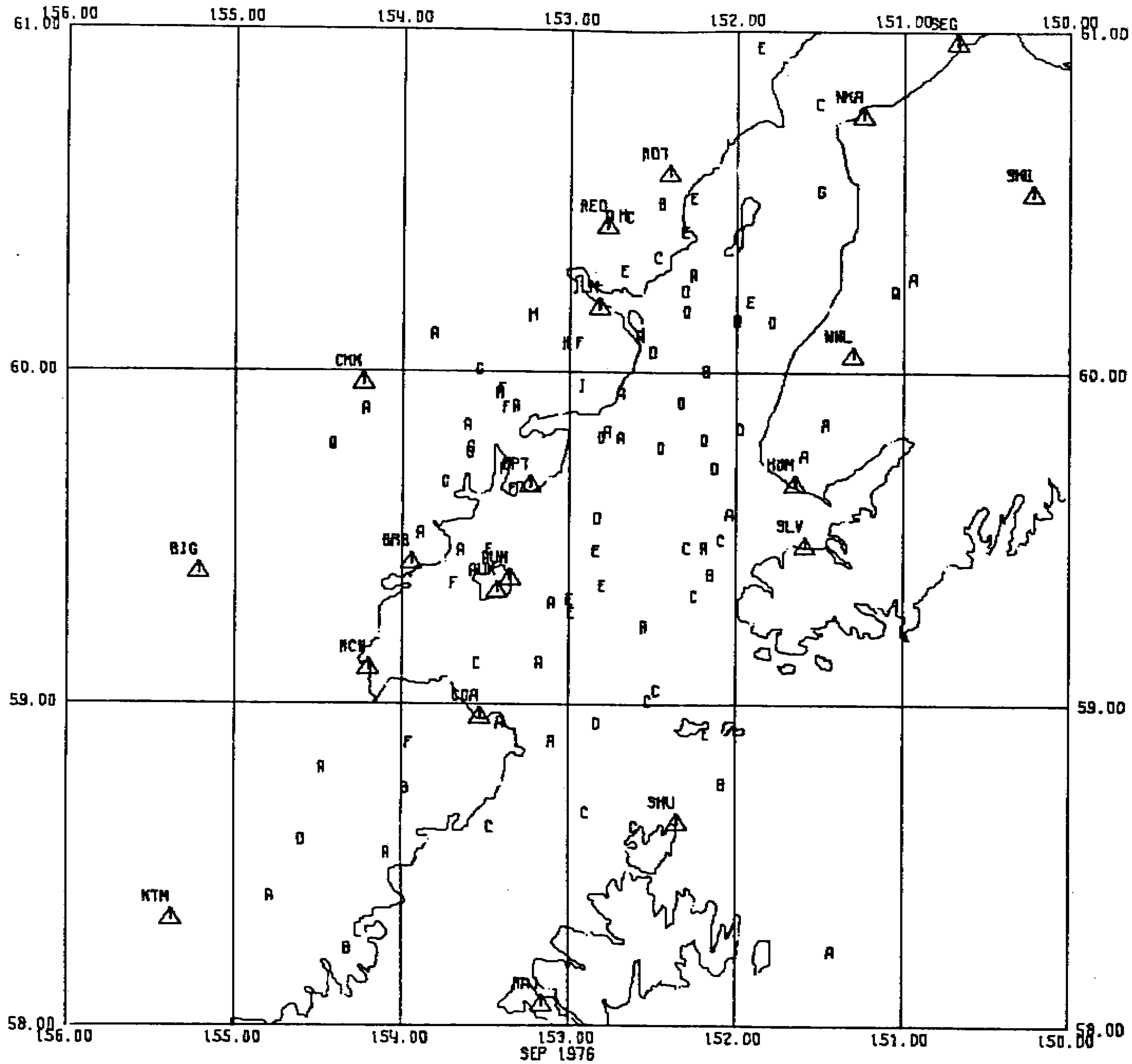

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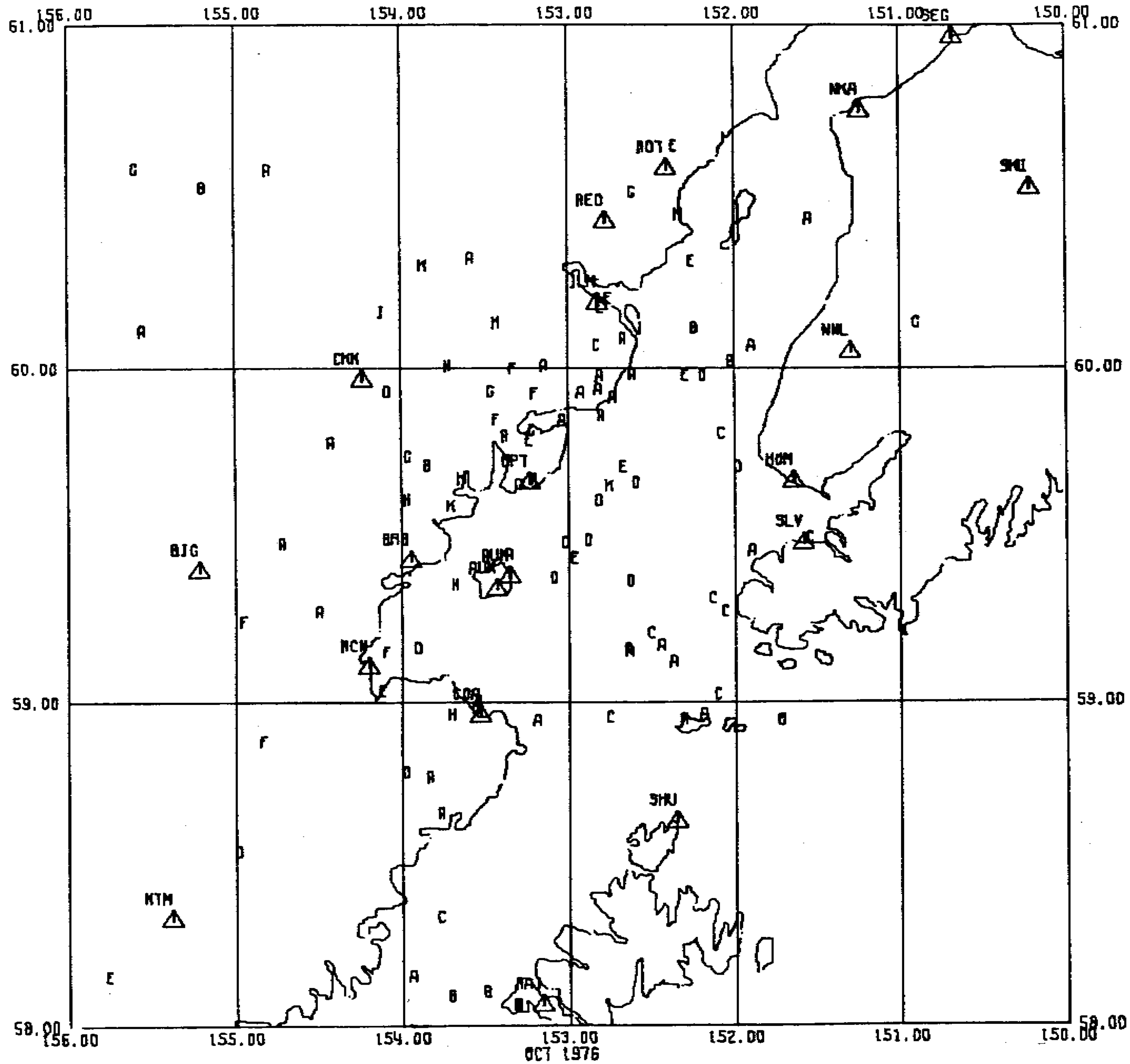

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Figure A3-14

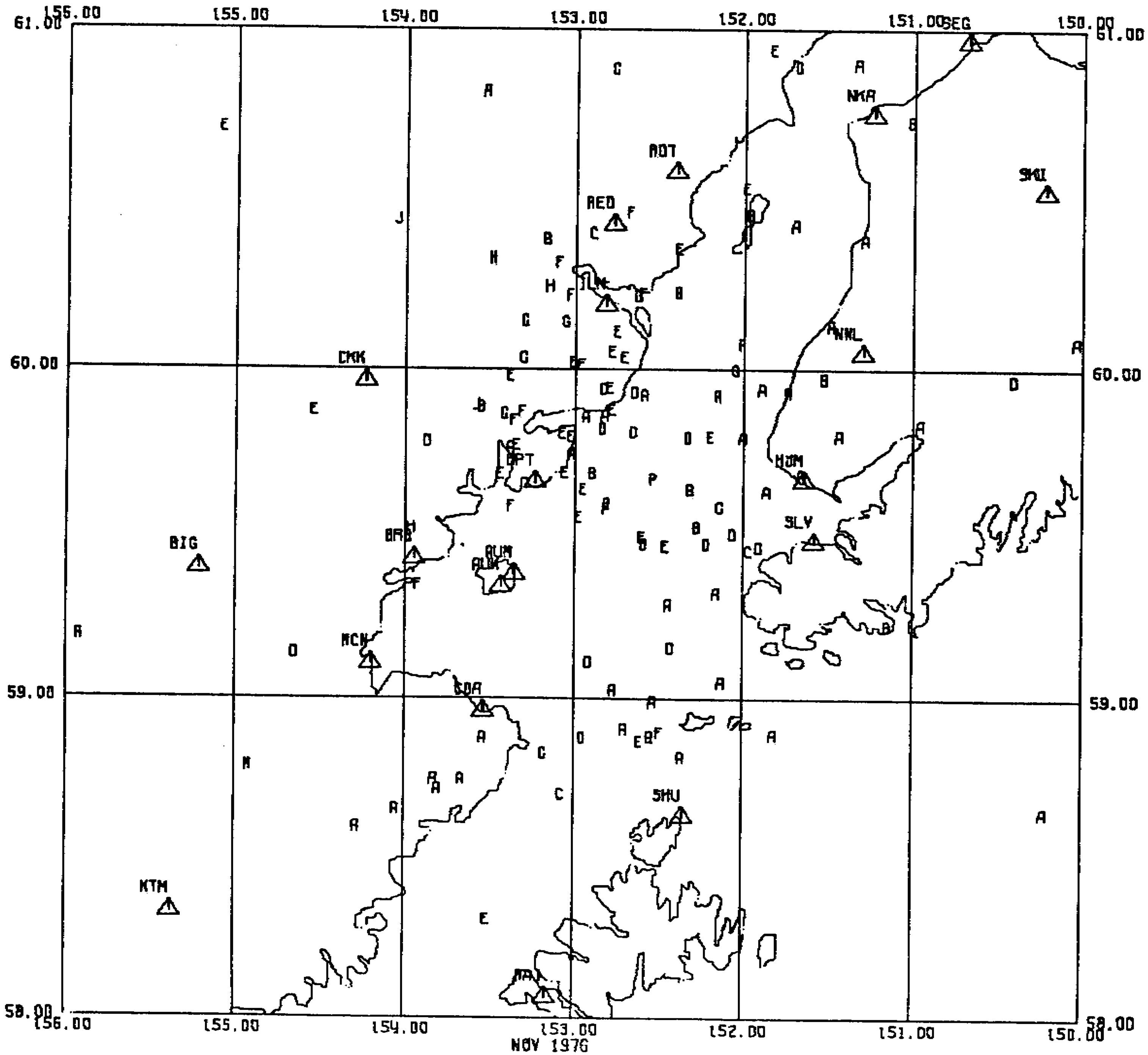
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Figure A3-15

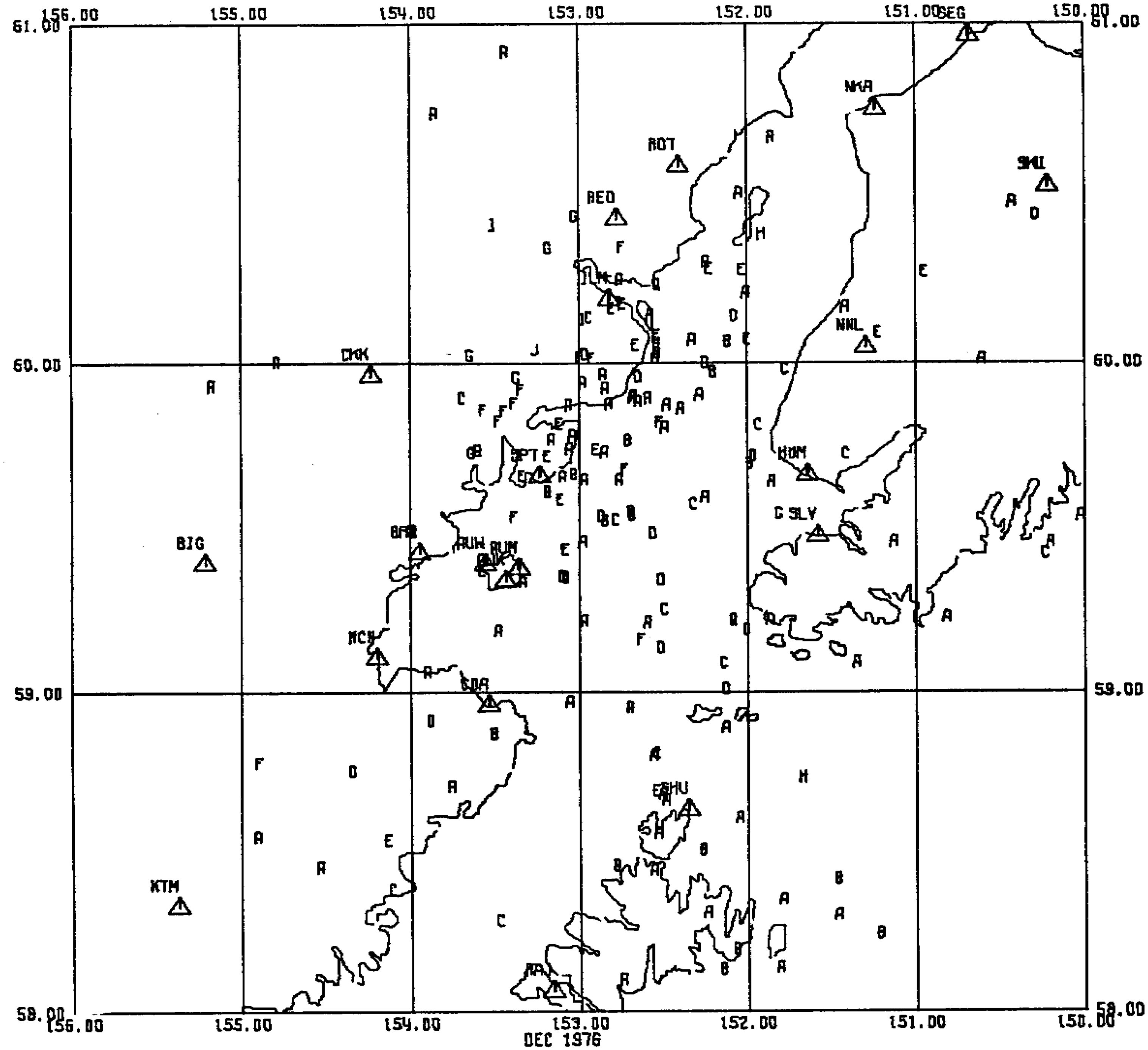
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Figure A3-16

Appendix 4

Preliminary Augustine Island Hazard Evaluation

This appendix lists the following:

Table I. Summary of events in historic eruptions of Augustine Volcano.

Table II. Summary of onshore and offshore hazards accompanying eruptions of Augustine Volcano.

Table III. Summary of current hazards at Augustine Volcano (1977).

TABLE I: SUMMARY OF EVENTS IN HISTORIC ERUPTIONS OF AUGUSTINE

ERUPTION	PRECURSORS	EXPLOSIVE PHASE INITIAL	CLIMAX	LATER PHASE	OTHER COMMENTS
1812	?	Ash deposited in Skilak Lake, Kenai Peninsula, 200 km NE of Augustine		?	Reported activity is from DOROSHIN, 1870.
1883	Steam visible in August, 1883; frequent earthquakes felt on island days before eruption.	tephra eruptions one or more days prior to climax ?	October 6, 1883: violent explosion, nuee ardente extends >8.6, <12.5 km down north side, impacts Inlet creating tsunami. Nuees continue onall flanks. Summit crater formed, ash deposited in Kodiak and on Kenai Peninsula.	Active lava fountaining continues for more than 2 months, creating 400 foot summit cinder cone. Crater at end of eruption is breached to the north.	3 tsunamis struck English Bay 25 minutes after eruption; first wave was 30 feet high, was followed at 5-minute intervals by waves 18 and 15 feet high.
1935	?	March 13 through April 3: ash deposited at least as far as Skilak Lake (200 km NE); ash-flows emplaced on north and west flanks of cone, reaching the shore.		Two lava domes emplaced within summit crater	
1963-64	?	October 10, 1963: ash eruptions with clouds to 4 km, quickly subsided; November 17, 1963, July 5, 1964, August 19, 1964: explosions occurred. Ash deposited in Skilak Lake (200 km NE); ash-flows emplaced on N, S, E, and SW flanks.		Former summit crater filled by new lava dome, reaching height of 4300 feet.	

ERUPTION	PRECURSORS	EXPLOSIVE PHASE INITIAL	CLIMAX	LATER PHASE	OTHER COMMENTS
1976	July, 1975: no visible precursors: no change in aeromagnetic field between summer, 1972 and August, 1975; fumarolic emissions at 95° C. or less, consist of meteoric water. Steam issues from margins and flank of 1964 lava dome. October 23, 1975: began increased intermittent shallow seisms; October 27, 1975: first steam explosions in summit region; ca. December 20, 1975: seismic network on island ceased to operate; January 21-22, 1976: seismicity increased on off-island seismic net.	January 22, 1976: small explosions at 7:59, 16:30, 22:19 AST. Eruption clouds to 4-5 km; first ash-fall at Lake Iliamna evening January 22. Large seismic swarm from 8:00 to 22:00 AST, January 22. Summit crater formed in initial explosions?	Major eruptions: January 23: 6:58, 7:40, 16:18; January 24: 8:38; January 25: 4:56 AST, plus several more smaller explosions; eruption columns to 14 km. Ash-flows deposited on all flanks, especially north side, where ash-flows extended a short distance beyond the shoreline. Ash-fall on Iliamna area, Kenai Peninsula, Anchorage area, Valdez, and minor ash in Sitka. Quiescent January 26 to February 6; starts again February 6 with ash-fall on Kenai Peninsula plus new ash-flows on all flanks, reaching shoreline to northeast. Explosions continue with decreasing intensity through late February.	Lava dome appears in summit crater February 10; growth of dome continues through late February, accompanied by incandescent block and ash avalanches. After ca. 1½ months quiescence, minor explosions occur in summit region, mid-April during new growth of lava dome and more block and ash avalanches. Lava flow is extruded in summit caldera through late July.	Summit crater formed at beginning of eruption was breached to the north, and controlled emplacement of subsequent block and ash avalanches. Nuees ardentes in January were accompanied by devastating high temperature, high velocity shock waves that advanced more than 1½ km beyond the ash-flow basal avalanche deposits.

TABLE II: SUMMARY OF ONSHORE AND OFFSHORE HAZARDS ACCOMPANYING ERUPTIONS OF AUGUSTINE VOLCANO

HAZARD	DANGERS ANTICIPATED	AREAS ENDANGERED
Summit ash explosions	Sudden, rapid growth of turbulent, ash-charged eruption cloud.	Extends vertically to 14 km or more and laterally 25-50 km away from the vent. Hazard to aircraft travelling along airways G8, V436, V321.
Ash eruptions	Ejection of bombs of dangerous size.	Danger exists everywhere on the island and for an unknown distance offshore (probably less than 25 km); depends upon prevailing winds and direction of blast (controlled by shape of vent).
	Dissemination of ash into atmosphere: ash may abrade and damage exposed surface and engine parts of aircraft flying, landing, or taking off through ash; ash may clog air intake ducts.	Ash distribution depends upon wind direction and speed, height of the eruption column. These can be evaluated during the course of the eruption to give accurate warning of ash distribution, which may extend several hundred kilometers or more from the vent in significant amounts.
	Ash-fall: may foul surface and other uncovered water supplies.	Water contamination can occur within the zone of ash fall for several days to months after an eruption, depending upon the chemistry of the ash, the volume of ash, the melting of ash-laden snow, and post-eruption rainfall.
	may reduce visibility.	During the 1976 eruption visibility at Iliamna airport fell to less than 100 feet (30 m) and at Anchorage dropped from 20 to 2½ miles at the time of peak ash-fall.
	may cause eye or respiratory irritation; prolonged exposure may lead to moderate acid burns, irritation of mucous membranes, respiratory ailments, and even blindness, particulary in animals.	Hazard is generally not severe, except during exceptionally long duration eruptions, in areas of extreme ash-fall and/or blowing ash.
	may abrade engines or other moving machinery, including cross-country skis.	Hazard persists in areas of visible fallout, and may be significant in hydroelectric plants if water is ash-laden.
	may interfere with radio and microwave communication, radar, and aircraft navigation systems dependent upon radio beacons.	Ash cloud is opaque to radio, microwave, and radar signals and will block line-of-sight transmission; this hazard exists within a 50 km or larger radius of the island and in regions of intense ash-fall during eruptions. Military

		microwave transmission from Diamond Ridge (near Homer) to Igiugig (on Iliamna Lake) will be blocked over Augustine, as will any aircraft radio navigation along V436, G8, and V321 or other line-of-sight paths to beacons at Iliamna, Big Mountain, King Salmon, Homer, etc. (Consult aeronautical charts for alternate navigation aids).
	may, in exceptional cases, sicken or endanger wildlife or domestic grazing animals by contamination of grasslands.	Depends upon chemistry of individual eruption's ash, volume of ash present, and post-eruption precipitation. Due to distance of Augustine from grazing lands, this is not a serious hazard.
	collapse of ash-covered structures.	Due to its relatively high density, ash of more than several inches depth may exert substantial pressure on the roofs of buried structures, much more than an equivalent depth of snow.
	post-emplacement sliding of ash.	In unusually thick ash deposits on steep slopes small ash avalanches may occur after ash-fall. Except in unusually large eruptions this poses little threat except on the upper slopes of the volcano itself.
	lightning accompanying ash-clouds.	Lightning commonly occurs within the eruption cloud over the volcano, and can occur between the ash-cloud and ground structures during heavy ash-fall.
	Acid rains.	May accompany ash-fall, including imperceptible ash-fall; acid may also be produced by contact of ash with skin or other moisture. May damage clothing, tarnish metal, and damage some plants, but poses little danger to people or animals.
Pyroclastic flow eruptions	High temperature (up to 600 to 1000° C) and high velocity shock waves able to surmount and flow around barriers, and to cross water.	Direct ash-flow hazard exists in all quadrants of the island and for at least 10-20 kilometers offshore: the October 6, 1883 ash-flow travelled more than 8.6 km but less than 12.5 km from the vent; prehistoric debris flows forming West Augustine and a deposit on the Inlet floor off the SE corner of the island travelled more than 8.6 and 7.8 km respectively. The shock wave/heat wave hazard extends an unknown distance beyond

		the debris deposits, probably another 5-10 km. The 1976 ash-flows devastated a cabin located behind a ridge at Burr Point, more than 1½ km beyond the limits of the deposit of the ash-flow that inflicted the damage.
	Post-emplacement explosions on the ash-flow surface, due to trapped subdeposit water or explosion of incorporated blocks.	Hazard exists anywhere on the ash-flow surface and for a distance away of several hundred meters, for several days after emplacement.
	Fires.	Fires may be ignited in the alder on the low E, S, and W slopes of the volcano, particularly if previous ash fall has killed the vegetation. Fires were reported in the 1963 eruption, but were not widespread.
	Post-emplacement emission of toxic gases.	Toxic gas levels may be relatively high directly on the ash-flow deposits and immediately adjacent for days after eruption, and in local areas for weeks or months, but the hazard is minimal.
	Associated flood or mudflow activity.	Floods and mudflows commonly proceed from the toes or surfaces of ash-flow deposits immediately after or within hours of emplacement. (See discussion of these hazards below).
	Generation of tsunamis by impact of debris flow onto Cook Inlet waters.	October 6, 1883: 3 tsunami waves struck English Bay (85 km E) at 5 minute intervals with amplitudes of 30, 18, and 15 feet, in that order. Traversed inlet in 25 minutes. Were formed by impact of more than 1.3 million cubic meters of debris on the shallow waters north of the island. Two prehistoric debris flows of comparable magnitude are known to have occurred on the west and southeast sides of the cone, probably forming tsunamis. (See discussion of these hazards below).
Mudflows	May travel as high-velocity turbulent debris-laden streams; may inundate areas, damage structures on impact, and displace water on impact with sea creating tsunamis.	Common on flanks of volcano prior to, during or after eruptions, especially accompanying ash-fall and ash-flows. Exceptionally large mudflows might generate tsunamis by impacting the Inlet; Generally follow stream channels.

Floods	May inundate large areas; may follow stream courses as high velocity floods carrying coarse debris and causing rapid erosion.	Broad sheet floods may occur onsteep slopes and flanks of the volcano, especially following ash eruptions accompanied by snowmelt or heavy rains. Except for exceptionally large eruptions, no particular flood danger exists off of the island.
Rockfall, avalanches	Direct hazard of rock impact; exceptionally large avalanches may be preceeded by shock waves, and may create tsunamis upon reaching the surrounding waters.	Rock fall hazards exist on all slopes, especially below steep sided domes in the summit region; avalanche hazard is more extensive: includes all slopes to sealevel; Air cushion avalanches (capable of travelling long distances) are most likely on the south flanks of the volcano, where steep slope breaks are present to permit "launching", the potential for impact on Cook Inlet waters is also greatest on the south slopes, where the runout distance is also shorter.
Lava Flows	Direct hazard due to lava inundation is minor because of slow rate of movement of lava flows. Secondary hazards include: avalanching of debris from toe and margins of flow;	Most flows have ponded within the summit crater; one known prehistoric flow advanced down the NW slope to 700 foot level. Avalanche and rock fall hazard off of advancing flows may extend hundreds of meters downslope, depending upon path and position of flow.
	steam explosions at the toes and margins of of flows that contact water or wet sediments;	Steam explosions are unlikely except for flows of greater extent than any thus observed, but are most likely if a flow reaches the ponded waters and tidal flats on the north and southwest flanks of the volcano.
	ignition of brush fires.	Fire hazard exists on the alder covered lower slopes E, S, and W of the vent.
Poisonous Gases	Asphyxiation or burning, due to the presence of SO_2, H_2S, Cl, HCl, HF, NH_3, CO, CO_2, and/or absence of oxygen; damage to plants. (Note that industrial gas masks that do not supply oxygen may generally be inadequate for safe operation within hazardous zones on Augustine.)	Gas concentrations or paucity of oxygen are likely to be hazardous only within the summit region, especially within a crater or other depression where heavy gases may collect, and near high temperature fumaroles on young ash-flow deposits. Damage to plant life is likely only on the island, and will probably be much less than the damage produced by pyroclastic flows and ash-fall. Even though gas odors may be noticeable off the island no danger due to toxic gases exists elsewhere.

Tsunamis	Wave impact and wave inundation: destruction or damage of structures and vessels, including near shore navigational aids; rupturing of oil storage tank on Homer Spit and subsequent fire hazard.	Hazards are severe near the shores of Augustine; throughout Kamishak Bay, within V-shaped bays opening towards Augustine (especially Kachemak Bay, English Bay, Port Graham Inlet, and several unpopulated or sparsely populated inlets off Kamishak Bay), in shallow waters along the shores of Cook Inlet south of Kenai, along the shores of the Barren Islands and north facing shores of Afognak Island. Particular danger exists for the Homer spit, especially near Lands End. There the presence of a vulnerable oil tank adds to the hazard. Many navigation aids located at or near sea level are also likely to be endangered, creating a subsequent hazard to ship and boat travel. Deep water wave heights may be insignificant (less than 6 feet for a wave comparable to that formed in the 1883 eruption), except in the vicinity of the island near the impact point. The initial decay of the impulsive wave produced upon impact will occur within a few kilometers of the impact site, and waves will not grow again until shoaling occurs.

TABLE III: SUMMARY OF CURRENT HAZARDS AT AUGUSTINE VOLCANO (1977)

HAZARD	DANGERS ANTICIPATED	AREAS ENDANGERED
Mudflows	May move rapidly as turbulent debris-laden streams or move slowly as viscous lobate flows; may inundate areas, damage structures on impact, and displace water on impact with Inlet, creating tsunamis.	Likelihood of damaging mudflow is minimal during the present quiescent period. Any mudflows formed are likely to occur within stream channels following heavy precipitation. There is very little likelihood of an extremely large tsunami-producing mudflow at the present time.
Floods	May inundate large areas; may follow stream courses as high velocity floods carrying coarse debris and causing rapid erosion.	Floods accompanying heavy precipitation are relatively likely, and rapid erosion of ash from lower slopes is also likely. The dangers posed by these conditions are not extreme, however, and are greatest within stream valleys, particularly on the east and west flanks of the volcano.
Rockfall, avalanches	Direct hazards of rock impact; exceptionally large avalanches may be preceeded by shock waves waves, and may create tsunamis upon reaching the surrounding waters.	Current hazard due to rockfall is extreme on the upper slopes of the volcano, especially on the 1976 lava dome and on the exposed north face of that dome, in the gully below that face, and within the 1976 crater rim. A continuing hazard exists for large avalanches anywhere on the upper flanks of the cone, especially on the north side of the cone, where a large avalanche is likely to run out before reaching the shoreline. A rockfall hazard exists also beneath the steep rock faces on all sides of the volcano, especially after rapid changes in temperature (freezing and thawing cycles). DUE TO THE EXTREME ROCKFALL HAZARD IT IS NOT ADVISABLE TO ATTEMPT TO CLIMB ON THE MOUNTAIN, PARTICULARLY THROUGH THE NORTHERN APPROACHES.
Poisonous Gases	Asphyxiation or burning, due to the presence of SO_2, H_2S, Cl, HCl, HF, NH_3, CO, CO_2, and/or the absence of oxygen. NOTE THAT GAS MASKS THAT DO NOT SUPPLY OXYGEN MAY BE INADEQUATE WITHIN THE SUMMIT REGION OF THE VOLCANO.	At present gases are being emitted from high temperature fumaroles on the ash-flow deposits on the north side of the volcano, where they are quickly dissipated and pose little direct danger, and from high temperature fumaroles on the flanks of the summit lava dome, where they are not as quickly dissipated, and may

		be dangerous, especially in sheltered depressions where heavy gases may accumulate to the exclusion of oxygen. Steam emissions also reduce visibility in the summit region, increasing the danger of operating in the summit region.
Tsunamis	Wave impact and wave inundation: Destruction or damage of structures and vessels, including near shore navigational aids; rupturing of oil storage tanks on Homer spit and subsequent fire hazard.	In its current configuration, with a northward breached summit crater, avalanching from the new dome will most likely be contained [illegible] will escape down the north flank where the run out distance is relatively great and the likelihood of forming an air cushion avalanche is small. Thus, the potential for creating a tsunami by impact of a large volume of material is small.

ANNUAL REPORT

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OFFSHORE PERMAFROST - DRILLING, BOUNDARY CONDITIONS, PROPERTIES, PROCESSES AND MODELS

DELINEATION OF MOST PROBABLE AREAS FOR SUBSEA PERMAFROST IN THE CHUKCHI SEA FROM EXISTING DATA

SUBSEA PERMAFROST: PROBING, THERMAL REGIME AND DATA ANALYSIS

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T. E. Osterkamp

Geophysical Institute
University of Alaska
Fairbanks, Alaska 99701

March 31, 1977

I. SUMMARY OF OBJECTIVES, CONCLUSIONS AND IMPLICATIONS WITH RESPECT TO OCS DEVELOPMENT

The objectives of this study are to determine the distribution and properties of subsea permafrost in Alaskan waters, in cooperation with other OSCEAP investigators. Besides direct measurements, our program includes an effort to understand the basic physical processes responsible for the subsea regime, as a basis for predictive models. Further details are given in Section II.

The conclusions based on the work completed since our last annual report are reproduced from Section VIII, CONCLUSIONS, as follows:

1. Existing data suggest that permafrost may be largely absent in the southern Chukchi Sea except in near-shore areas.

2. Ice-bearing subsea permafrost soil is mechanically bonded by the ice in some situations but not in others.

3. Permafrost temperatures on land at Prudhoe Bay suggest a lower mean temperature over the past year or so than the recent average.

4. Seasonal variations and mean annual sea bed temperature at Prudhoe Bay have been studied. Mean temperature shows a fairly smooth (but non-linear) increase with water depth up to about 3 m, and a slight decrease for greater depths. Extremely cold temperatures may be found in very shallow water. At Prudhoe Bay for depths between 2 and 3 m there seems to be a change in the flushing regime under the sea ice. At greater depths normal sea water salinity is maintained and the sea bed temperature remains at about $-1.7^{o}C$ during months of ice cover. Higher temperatures may be found before breakup.

5. Probing measurements have identified a seasonally active permafrost layer under the sea bed in near shore areas.

6. Application of a crude thermal model suggests that ice-bearing permafrost may be found well out on the Beaufort Sea shelf.

7. Theoretical developments (including a better understanding of heat and salt transport processes), together with accumulating data, make it feasible to use more sophisticated models.

In addition to this list of reasonably definite (except for number 1) conclusions, some tentative but more global statements about the general nature and distribution of subsea permafrost are summarized in Section VIII.

A general discussion of the implications of subsea permafrost for offshore petroleum development is given in Section II, C, and in a recently published paper (Osterkamp and Harrison, 1976 B), included as Appendix A. Basically the problems are analagous to those encountered on land. However, in some cases they may be more serious because subsea permafrost is easily disturbed, since it is relatively warm and may contain salt.

The specific implications for petroleum development of the work carried out since our last annual report are as follows: Conclusions 1 and 6 above bear on the problem of the large scale distribution of subsea permafrost. In particular, the former suggests that subsea permafrost may be absent over most of the proposed Hope Basin lease sale area. Conclusions 4 and 7 also bear on the problem of large scale distribution of subsea permafrost, since the former represents an important boundary condition for a predictive model, and the latter bears on the development of the model itself. The tentative but global statements in Section VIII lend some perspective to the problem of subsea permafrost distribution and properties. Conclusions 2 and 5 are important for the construction of offshore structures and pipelines; the former is also important in interpreting the results of seismic studies of soils.

II. INTRODUCTION

A. General Nature and Scope of Study

This work is part of a study of the distribution and properties of permafrost beneath the seas adjacent to Alaska. The study involves coordination of the efforts of a number of investigators (RU 204, 271, 253, 255, 256, 473, 105, 407) and synthesis of the results.

B. Specific Objectives

The specific objectives of our particular project are:

1. To investigate the properties and distribution of subsea permafrost at Prudhoe Bay through a drilling program and associated interpretation and laboratory analysis, as reported in our last annual report.

2. To investigate boundary conditions at the sea bed relevant to the subsea permafrost regime, as described here.

3. To study heat and salt transport processes in subsea permafrost, in order to develop models to describe and predict properties and distribution. Most of this work is supported by NSF and Sea Grant. A description of its status and some preliminary results are given here.

4. To survey existing data to obtain information about the existence of permafrost beneath the Chukchi Sea, as described here.

5. To extend the area of subsea permafrost field study using simple probing techniques to determine temperature, depth to any ice-bonded boundary, and possibly other quantities. Preparations for this work are in progress and the results will be described in later reports.

C. Relevence to Problems of Petroleum Development

(Part of this section was prepared in cooperation with CRREL (RU 105).)

Experience obtained in the terrestrial environment has indicated the necessity for careful consideration of permafrost during development activities. Both the National Academy of Sciences review of offshore permafrost problems and Canadian studies suggest that the consequences of errors in planning or design of facilities are potentially greater offshore than on land in terms of loss of human life, environmental damage, and costs.

The primary problem in any new activity in this environment will be lack of data on:

1. The horizontal and vertical distriubtion of subsea permafrost and the properties of this complex material.

The importance of this information is indicated below in relation to various development activities. This is based on a compilation of data from several sources (Hunter and others, 1976; Osterkamp and Harrison, 1976A; 1976B; OCSEAP reports of Chamberlain and others, 1977 (Ru 105) and the National Academy of Sciences Report 1976).

2. Differential thaw subsidence and reduced bearing strength due to thawing of ice rich permafrost.

(a) Thaw subsidence around well bores causing high down-drag loads on the well casing.

(b) Differential settlement associated with hot pipelines, silos in the sea bed, and pile and gravity structures causing instability.

(c) Differential strain across the phase boundary between bonded and unbonded permafrost.

3. Frost heaving

(a) Well bore casing collapse due to freeze-back.

(b) Pipelines - differential movement.

(c) Gravity structures - local heaving causing foundation instability.

(d) Pile structures - differential stress in pile founded structures.

(e) Silos - differential stress on structure.

4. Seismic data interpretation - Data can be misinterpreted and can lead to improper design of offshore production and distribution facilities.

5. Excavation - (dredging - tunneling - trenching)

(a) Increased strength of material associated with bonded sediment.

(b) Over-consolidated sediment can influence excavation rates and approach.

(c) Thaw can be induced in deeper sediment by removal of material at the sea bed.

(d) Highly concentrated and mobile brines can be found in the bonded sediment.

(e) Insufficient data on engineering properties for design of excavation equipment and facilities.

6. Gas hydrates

(a) Blowouts - can result from gas hydrate decomposition during drilling operations.

(b) Fire danger.

7. Corrosion - Fluids (brines) with concentrations several times normal sea water are common in shallow water (< 3m).

To develop proper precaution against these potential problems, we must obviously define the horizontal and vertical distribution of subsea permafrost. This is no easy task in view of the $>2 \times 10^3$ km coastline subject to potential subsea permafrost problems. It should be emphasized that drilling data exist only at Barrow and Prudhoe Bay and that extrapolations to other areas must be highly speculative.

The exact precautions to take in preventing the above problems (2-7) can not be specified at present due to a lack of data and the obvious site specific nature of these problems. However, precautions will probably involve:

(1) An adequate casing seal to drill safely through permafrost.

(2) A drilling programme designed to minimize the thermal disturbance to permafrost and gas hydrates.

(3) An adequate casing seal to control hydrate decomposition and other high pressure fluids from greater depths.

(4) Adequate assurance of the structural stability and integrity of silos and other structures.

(5) Protection against casing collapse should the well be suspended over a season.

For the present the concerns are for the safety of exploratory drilling, but the eventual objective is not only to find, but to produce hydrocarbons. At that stage, permafrost and hydrate conditions will be even more important since hot fluids in the well-bore are unavoidable. Thus, it is very important to maximize the derived downhole information at the initial stage of exploratory drilling.

Because of the great variability of offshore conditions, extensive preliminary programs will be necessary at each drill site prior to the actual drilling of the well. Without such site specific information it may be difficult to assure a safe drilling program. A partial list of potential accidents is as follows:

(1) Ruptured well casings

(2) Ruptured pipelines

(3) Damage to the drilling structures

(4) Damage to the production structures

(5) Casing collapse

(6) Corrosion and resulting weakening of metals in structure, pieplines, etc.

(7) Blowouts

(8) Fires on rigs

These potential accidents could result in the loss of human life, environmental damage and considerable cost to industry in correcting the problems.

III. CURRENT STATE OF KNOWLEDGE

(Part of this section was prepared in cooperation with CRREL (RU 105).)

Regional details concerning the areal distribution and thickness of permafrost are unknown in the Beaufort Sea, although several local studies have established its existence and local properties (Hunter and others, 1976; Osterkamp and Harrison, 1976 A; Lewellen, 1976; Rogers and others, 1975; and the OCSEAP reports of Rogers and Morack, 1976 (RU 271); Chamberlain and others, 1977 (RU 105); Sellmann and others, 1976, (RU 105). These studies are restricted to three sites along the $>2.3 \times 10^3$ km coastline from the Bering Straits to the Mackenzie Delta; one additional borehole also exists in the Chukchi Sea near Barrow, (Lachenbruch and others, 1962). Even though the sites cover a very limited area they are situated in three distinctly different geological settings. The Canadian study area off the Mackenzie Delta is unique since it is situated in an area exposed to year around river discharge. The two Alaskan Beaufort Sea sites are distinctly different, with the Barrow area primarily fine-grained sediments while the Prudhoe Bay area is predominately coarse-grained material. These contrasts in grain size alone should have a dramatic influence on the distribution of bonded and unbonded permafrost. These differences in material types are anticipated to be somewhat representative of the conditions found along the Beaufort Coast. The Barrow sediments are similar to those between Barrow and the Colville River, while the Prudhoe Bay site would be more like the sediment types found to the east of the Colville River.

Some data are available from direct observations that can help establish some ideas of subsea permafrost limits. The data from the drilling programs supported by NOAA at Prudhoe Bay and the Navy program at Barrow indicate that permafrost (as defined by temperatures colder than $0^{o}C$ throughout the year) is present in every hole from near the sea bed to depths at least as great as 80 meters, which is the maximum depth of the exploratory holes. However, seismic data indicate the absence of continuous ice bonding in some of these holes. One additional industry hole at Prudhoe Bay on Reindeer Island suggests bonded permafrost exists in two zones from 0 to 20 and 90 to 125 m from the surface, although this hole was never thermally logged. A collection of all the thermal data from the holes is provided in Figures 1, 2 and 3. These data indicate permafrost is present 17 km from shore as seen in hole PB-2 at Prudhoe and 11 km at Barrow at hole B-2. Hole locations are given by Lewellen (1976); Harrison and Osterkamp (1976 A); and the OCSEAP reports of Sellman and others (1976).

Considerable data on the extent and distribution of subsea permafrost have been obtained by Canadian government and industry studies in the Mackenzie River region. Drilling and thermal data have confirmed the presence of permafrost and information on the upper limit of the bonded permafrost was obtained based on a study of industry seismic investigations (Hunter, et al., 1976). Additional information concerning ice-bearing permafrost can be inferred from the thermal data shown earlier. Most of these records have negative thermal gradients, a suggestion of ice-bearing permafrost at depth.

The studies conducted by Osterkamp and Harrison (1976 A) near Prudhoe Bay across the land/sea transition established the depth of bonded permafrost along this single line out to the 2 meter water depth. Lewellen's (1973) work at Barrow also indicates that bonded permafrost is very near the surface in the zone along the coast where the sea ice annually freezes to the seabed. From Pt. Barrow to Herschel Island the area from the beach to the 2 m water depth is about 3400 km^2. In this zone the limited data from the two study sites indicate that bonded permafrost will be near the surface, probably within 20 meters, the greatest depths occurring farther offshore and in the coarser-grained material. This may not apply to areas near major deltas where the environment is anticipated to be modified by warmer waters during periods of discharge.

Permafrost distribution in areas other than the shallow water environments is implied from results of the drilling efforts mentioned above as well as from negative bottom water temperatures which would suggest permafrost can exist on most of the Beaufort Sea shelf (Lewellen, 1973).

Thawing at the sea bed in the presence of negative sea bed temperature has been found by Lewellen (1973) and Osterkamp and Harrison

(1976 A). This has been attritued to the infiltration of salts into the sea bed. The distribution of these salts in the thawed sediments has been determined by Osterkamp and Harrison (1976 A) (RU 253) and by CRREL (RU 105).

Preliminary study of seismic, sea bed temperatures and other data imply that bonded subsea permafrost is probably absent in most of the southern Chukchi Sea in the deeper waters although it may still survive in shallow nearshore waters (OCSEAP 1976 fourth quarterly report of Harrison, Dalley and Osterkamp, 1976 (RU 253, 255, 256)).

The following is a list of the general types of data available from Barrow and Prudhoe Bay.

(1) Depth to bonded permafrost near Prudhoe Bay along one line to a water depth of 2 meters; estimates can also be made from data obtained at greater water depths.

(2) One hole on Reindeer Island providing information on permafrost to depth (but on island).

(3) Thermal and seismic data from Barrow offshore and on islands.

(4) Thermal data from Prudhoe Bay.

(5) Geophysical data at Prudhoe Bay (seismic and oceanographic).

(6) Engineering data from core analysis and probing at Prudhoe Bay.

(7) Chemical data from Prudhoe Bay.

(8) Data from several industry studies, in addition to the Reindeer Island hole. These include the deep hole on Gull Island, studies to the west of the new causeway, soil investigations for the new causeway and for the old causeway and the approaches to it. Most of these data with the exception of the causeway studies are proprietary.

IV. STUDY AREA

The main study area has been the Beaufort Sea, with field work so far concentrated at Prudhoe Bay and Barrow (Section III). We plan to carry out reconnaissance probing measurements at one additional coastal site in the Beaufort Sea this spring.

Work has also begun in the Chukchi Sea with Hopkins' (RU 473) shoreline studies and our survey of existing data, both reported in our last OCSEAP quarterly reports. We also plan reconnaissance probing measurements at two coastal sites in the Chukchi Sea this spring.

Another potential area of interest, although not included in our original study plan, is Norton Sound. We have received an inquiry about the possibility of subsea permafrost there in connection with the interpretation of oceanographic measurements, and other areas may also merit attention.

V., VI. and VII. METHODS, RESULTS AND DISCUSSION

A. Chukchi Sea

Some existing data, such as water temperature, seismic velocities, and regional geology have been examined for information about the possible existence of permafrost beneath the Chukchi Sea. Some simple thermal calculations have also been carried out. The results of this survey were submitted with the last OCSEAP quarterly report and are also included with this report as Appendix II. Most of this survey has been concentrated on the southern Chukchi Sea because it is the site of the proposed Hope Basin lease sale area.

Permafrost must have formed over essentially the entire area now covered by the Chukchi Sea when it was exposed during times of Wisconsin and earlier glaciations. However, seismic measurements at several sites in the southern Chukchi Sea seem to indicate the presence of unconsolidated, and therefore ice-unbonded sediments there to depths of at least 200 to 700 m at present. A simple thermal calculation, for which the assumptions cannot be justified, may also lend some support to the absence now of ice-bonded sediments beneath the southeastern Chukchi Sea, at least where the present water depth is of the order of 45 m. However, subsea permafrost is probably widespread in near-shore areas. These tentative conclusions are quite similar to those reached independently by Hopkins (RU 473) in his last quarterly report.

It also seems that the present mean annual sea bed temperature in the southeastern Chukchi Sea is positive, and that ice-bearing permafrost in near-shore areas is probably overlain by a thawed layer except in areas of very shallow water (less than 2 m deep). Further details are given in Appendix II, together with relevant maps. It should be borne in mind that these conclusions are based on a small study consisting only of a literature survey, which is not complete, and rudimentary thermal calculations.

B. Beaufort Sea

1. Further Interpretation of 1975 Drilling Results

Our previous annual report contained a preliminary report on the spring 1975 Prudhoe Bay drilling project, and the final report (Osterkamp and Harrison, 1976 A) was submitted with a later quarterly report. Two features of that data have been noticed subsequently.

In the hole 481 m from shore the electrical conductivity of the interstitial water (Figure 13 of that report), from which the freezing point can be estimated, and the temperature near the sea bed (Appendix F of that report) together indicate that a significant fraction of the interstitial H_2O there, perhaps 50%, must have been in the form of ice. This is consistent with the drill logs (Appendix A of that report), where the first meter or so below the sea bed is noted to be "frozen." However, this material could not be considered to be ice bonded, because of the ease with which Shelby tubes could be pushed into it, and because of the penetration test (Figure 6 of that report). It therefore is obvious that one must make a distinction between "ice-bonded" and "ice-bearing" permafrost, because of its vastly different mechanical properties. The degree of "ice-bonding" is probably variable. The term "frozen" should be avoided. Ignorance about the existence of these different kinds of subsea permafrost, and the problem with terminology can probably account for some of the apparent paradoxes in which a driller reports material to be "frozen", but no fast seismic layer can be found. Examples are Reindeer Island, and the Beaufort Sea drilling site near Barrow.

As a sideline to this 1975 drilling experiment, an analysis of the major ions in several samples was done (Table IV of the report), although some difficulties in interpreting the results were noted. We have now come to doubt the entire chemical analysis, since the numbers of equivalents of positive and negative ions seem to be significantly different. The most important measurement, the total salinity as determined by the electrical conductivity, is correct.

2. Mean Temperature and Thermal Diffusivity on Shore

A hole on land (designated -226 in Osterkamp and Harrison, 1976 A) was drilled in May 1975 and logged for temperature five times subsequently over the following year (Table 1 and Figure 4). The thermal disturbance due to drilling is judged to be fairly small over this period; other errors are similar to those described by Osterkamp and Harrison (1976 A). From this work the mean annual temperature for that period, and the thermal diffusivity of the ground can be deduced. The former is between -10 and -11°C, the latter is roughly 45 ± 15 m^2 a^{-1}. Both of these numbers can be refined after more complete analysis of the data is performed. The mean ground temperature is somewhat colder than the recent value of about -9°C (Gold and Lachenbruch, 1973), which suggests a cooling trend over the last year or so that is also evident in meteorological records at Barrow (Mock, personal communication). The annual temperature variation at 0.4 m depth, which is about the same as the depth of the active layer, exceeds 22°C.

3. Offshore Temperature Measurements

Offshore temperature measurements were made at Prudhoe Bay to help define the appropriate sea bed temperature boundary condition to be used in theoretical models of subsea permafrost. These measurements were made in 1975 and 1976 and are in addition to those made in the holes drilled in spring 1975 (Osterkamp and Harrison, 1975 A); they are along the same line between North Prudhoe Bay State #1 well and Reindeer Island. The July 1975 data were obtained by an observer either wading or in a small boat. During November 1975, five pipes at distances from shore of 23, 99, 162, 302 and 1600 m were installed to depths of 3 m in the seabed and logged for temperature subsequently. Other measurements were made through holes in the ice.

The results are given in Table II. Some of the sea bed temperatures there were obtained by interpolation of the measurements made inside the pipes. Additional sea bed temperature data from the holes drilled in spring 1975 are given by Osterkamp and Harrison (1976 A). Evidently the low sea bed temperatures under thick ice in shallow water are due to poor mixing. At

Prudhoe Bay where the depth is greater than about 2 to 3 m the salt rejected during freezing of the sea ice seems to be efficiently removed, normal sea water salinity is maintained, and the freezing temperature of normal sea water exists under the ice.

As noted earlier, the purpose of these measurements was to determine the annual variation in temperature at the sea bed, since this is an important boundary condition controlling the evolution of subsea permafrost. The annual variations are not completely determined by these few measurements, but taken together with deeper measurements from the drilling experiments, the data seem to be adequate to place reasonable constraints on sea bed annual temperature models. The analysis required to develop these models has not yet been done, but the magnitude of the temperature variations is immediatly evident in Figure 5.

Mean annual sea bed temperatures are easily estimated from the drilling data at Prudhoe Bay (Osterkamp and Harrison, 1976A; OCSEAP reports of CRREL-USGS (RU 105 and 204)). The dependence on water depth is shown in Figure 6. Also included in Figure 6 are data from the Tapkaluk Islands region in the Beaufort Sea near Barrow (Lewellen, 1976). These data seem to indicate an increase in mean temperature T with depth x for depths less than about 3 m; in this region a reasonable description is

$$T = T_o e^{-ax} \qquad (x \lesssim 3 \text{ m})$$

where $T_o = -9^oC$, $a = 0.903 \text{ m}^{-1}$. This does not hold for greater water depths where the trend is reversed and colder temperatures are found.

4. An Active Subsea Permafrost Layer

Probing experiments show the existence of seasonal variations in the location of a bonded-unbonded subsea permafrost boundary in shallow water (Figure 7). The November 1975 data were obtained with a light hand-driven probe, and it is possible that the boundary is either slightly deeper or poorly defined. This changing subsea layer is analagous to the active layer on land. The distribution of ice in it may be complicated, and considerable liquid phase may be present because of salt. Probably active layers consisting of ice-bearing but ice-unbonded subsea permafrost also exist.

5. Development of Experimental Techniques

Techniques for driving and jetting probes into the sea bed with light equipment and for making in situ measurements of hydraulic conductivity were tested at Prudhoe Bay in spring of 1976.

6. Application of Simple Thermal Models

The same sort of crude model described above in connection with the Chukchi Sea (see also MacKay, 1972; Judge, 1973) was also applied to conditions representative of Prudhoe Bay. In this approach sensible heat is ignored, and it is assumed that salt is always rejected from ice-bearing permafrost, which is probably usually incorrect. The heat transport between the upper and lower ice-bearing permafrost boundaries is also ignored. This unnecessary restriction has been removed in a newer version of the model which has not yet been applied in any detail. Most of the input parameters were the same as used in connection with the Chukchi Sea. The sea bed profile was taken from OCSEAP maps and the sea bed temperature assumed constant at $-1.1^{o}C$. The upper boundary of the ice-bearing permafrost was assumed to be at $-1.8^{o}C$ and the lower at $0^{o}C$. The result is shown in Figure 8 and must be considered at best a crude preliminary guess. Nevertheless, it does indicate that ice-bearing permafrost may exist a large distance from shore.

7. Theoretical Developments

Our work on the development of a theoretical background for an understanding of subsea permafrost is largely supported by Sea Grant and NSF, but it is directed toward the goal of prediction which is of importance to OCSEAP.

We have been able to show that the transport of salt in the thawed layer at a region such as Prudhoe Bay is primarily by moving interstitial water and is efficient, so that the temperature at the lower boundary of the thawed layer is probably close to the freezing point of sea water. Heat transport, on the other hand, is primarily conductive. This situation, which is consistent with the data available so far, means that the model describing the development of the thawed layer is surprisingly simple. Further insight into these processes has been obtained by showing how a purely diffusive model of heat and salt transport is unstable to convection of the soil interstitial water. The abstract of a paper describing some of this work is included as Appendix III.

We have developed a technique for estimating shoreline retreat rate using temperature data from an offshore borehole. (The associated mathematics is an extension of that of Lachenbruch, 1957.) The best estimate at Prudhoe Bay awaits the results of an experiment to determine salinity in the soil before ocean transgression.

We have estimated the rate of development of the thawed layer out to the hole 3,370 m from shore at Prudhoe Bay and find the thawed layer thickness to be consistent with the available data. As noted earlier, a simple model of simultaneous thawing from the sea bed and from the bottom of the permafrost has been developed, together with a numerical technique for its solution. The model has not yet been applied in any detail.

Preparation of reports describing this work will receive high priority after completion of spring field work.

C. Tentative Remarks About Subsea Permafrost Conditions

Based on our results to date and those of other OCS investigators (RU 105, 204 and 271) and using data from other sources (Lewellen, 1973, 1976; Hunter and others, 1976; and industry) several broad and tentative statements about subsea permafrost can be made. These statements are preliminary as data are still completely lacking in most areas. The following list was prepared in collaboration with RU 105 and 271.

1. Subsea permafrost, defined as subsea material remaining below $0^{\circ}C$, probably exists over most of the Alaskan Beaufort Sea shelf, probably over part of the northern Chukchi Sea shelf, but is probably largely absent over most of the southern Chukchi Sea shelf except in near-shore areas.

2. A similar statement probably applies to ice-bearing permafrost.

3. Ice-bearing but ice-unbonded permafrost exists as well as ice-bonded permafrost. Liquid phase may be present in both cases; this would complicate the construction of tunnels.

4. The upper boundary of ice-bonded permafrost may be very irregular, or undefined. In places the bonded permafrost is probably perforated where the ocean has transgressed over large lakes which had depths greater than 2 m.

5. The bonded permafrost may contain layers of unbonded material. It probably also is discontinuous some distance from shore.

6. When a well-defined upper boundary of ice-bonded permafrost exists, its temperature is probably often close to $-1.8^{\circ}C$. In near shore areas it is usually colder, and near large rivers it may approach $0^{\circ}C$. Temperature and salinity at the phase boundary are related by the requirement of phase

equilibrium.

VIII. CONCLUSIONS

1. Existing data suggest that permafrost may be largely absent in the southern Chukchi Sea except in near-shore areas.

2. Ice-bearing subsea permafrost soil is mechanically bonded by the ice in some situations but not in others.

3. Permafrost temperatures on land at Prudhoe Bay suggest a lower mean temperature over the past year or so than the recent average.

4. Seasonal variations and mean annual sea bed temperature at Prudhoe Bay have been studied. Mean temperature shows a fairly smooth (but non-linear) increase with water depth up to about 3 m, and a slight decrease for greater depths. Extremely cold temperatures may be found in very shallow water. At Prudhoe Bay there seems to be a change in the flushing regime under the sea ice for depths between 2 and 3 m. At greater depths normal sea water salinity is maintained and the sea bed temperature remains at about $-1.7^{o}C$ during months of ice cover. Higher temperatures may be found before breakup.

5. Probing measurements have identified a seasonally active permafrost layer under the sea bed in near shore areas.

6. Application of a crude thermal model suggests that ice bearing permafrost may be found well out on the Beaufort Sea shelf.

7. Theoretical developments (including a better understanding of heat and salt transport processes), together with accumulating data, make it feasible to use more sophisticated models.

8. Some tentative remarks about the possible general and distribution of subsea permafrost in the Beaufort Sea have been made (Section V., VI.

and VII., C).

IX. NEEDS FOR FURTHER STUDY

The obvious need of the subsea permafrost assessment program is for more data, considering the 2,000 or more km of coast in the Beaufort and Chukchi Seas alone. At present only two drill lines, 350 km apart, exist in the Beaufort Sea, together with one in the Chukchi Sea at Barrow, yet many different geologic settings, oceanographic conditions, and shoreline processes are present.

Attempts to begin to fill some of these gaps are to be made under existing proposals. Some of this work is as follows:

1. Investigation of the effects of a large river on subsea permafrost conditions in the Alaskan Beaufort Sea.
2. Investigation of salinity profiles in fine-grained sediments.
3. Continued use of seismic methods and attempts at a better understanding of interpretation problems.
4. More detailed drilling, probing, sampling, and temperature measurements at Prudhoe Bay and elsewhere in the Beaufort Sea.
5. Extension of probing studies into the Chukchi Sea.
6. Study of related onshore conditions in the Chukchi Sea.
7. Study of heat and salt transport mechanisims in subsea permafrost.

Until the field work is completed, it is uncertain how much of this list can be successfully accomplished in the next few months.

Some problems not addressed by current proposals are:

1. Study of subsea permafrost conditions in an area of very rapid shoreline retreat (10 m a^{-1} or greater).

2. Application of seismic data to problems of large scale permafrost distribution.

3. Freezing of structures and piling into sea bed, and modification of salinity and temperature regimes.

4. Wider geographic coverage by field studies, as indicated by 1977 field work.

5. Application of models derived from field data, and laboratory and theoretical studies of heat and salt transport mechanisms.

6. Investigation of permafrost in other areas, such as Norton Sound.

In addition to these specific problems, a major effort will also be required to synthesize all the results.

X. SUMMARY OF FOURTH QUARTER OPERATIONS

A. Field and Laboratory Activities and Travel

No field work was performed this quarter. Laboratory work has consisted of design, construction and calibration of equipment for our spring field program.

Dr. Osterkamp's sabbatical leave at CRREL has greatly aided coordination with subsea permafrost investigators there. He attended the January 1977 meeting of the Permafrost Panel of the National Academy of Sciences at Hanover, New Hampshire, where he and others presented an overview of subsea permafrost research. Prior to the meeting Dr. Harrison visited USGS, Menlo Park, to discuss physical processes in subsea permafrost with Dr. Lachenbruch and Chukchi Sea permafrost conditions with Dr. Hopkins. After the panel meeting, a discussion was held at CRREL to coordinate activities of RU 105, 204 and 253. We both attended the Barrow synthesis meeting. We had productive meetings there and subsequently in Fairbanks with Dr. Hopkins.

B. Research Administration

No changes in data submission schedules are anticipated, although as noted earlier, preparation of reports describing studies of physical processes and their application to the development of models needs high priority after spring field work.

C. Funds Expended

About $35,000.

D. Problems

A troublesome problem is a lack of complete coverage of Chukchi Sea coastal areas by the coastal charts. The resulting lack of near-shore bathymetry complicates the prediction of subsea permafrost in these important areas.

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TABLE I

Temperatures (^{o}C) and Measurement Dates for Hole -226, Located Onshore

Depth (m)	5-29-75	7-26-75	11-11-75	3-3-76	5-7-76
0.40		- 0.310	-13.271	-22.570	- 9.919
0.90					-12.662
1.40	-12.118	- 4.461	- 6.505	-19.789	-14.468
1.90					-15.131
2.40		- 7.587	- 5.492	-14.930	-15.203
2.90					-14.947
3.40	-13.465	- 9.446	- 6.538	-13.692	-14.647
4.40			- 7.536	-12.355	-13.907
5.40	-13.041	-11.100	- 8.293	-11.399	-13.132
6.40			- 8.870	-10.733	-12.473
6.90					-12.124
7.40	-12.111	-11.456	- 9.344	-10.261	-11.830
7.90					-11.575
8.40		-11.422	- 9.681	- 9.992	-11.338
8.90					-11.135
9.36	-11.301	-11.314	- 9.925	- 9.855	-10.977

TABLE II

Summary of nearshore temperature data. Some missing entries in the table are due to incomplete data reduction.

Distance from shore (m)	Ice thickness (m)	Depth (m) below sea ice or water surface (m) – to sea bed	– to temp. sensor	Temperature (^oC)
		July 26-28, 1975		
On beach, 1.5 m from water	–	–	0.51 from surface	-0.3
1.5	0		0.82	-2.3
190	0		1.25	0
			2.11	-3.8
481	0		1.85	+1.0
			2.35	-1.0
About 1220 (Off end of dock)	0		$\approx$ 2	+2.0
		November 11, 1975		
23	0.6	0.76	0.66	-1.8
	0.6		1.84	-2.4
99	0.6	1.08	0.55	-1.6
	0.6		2.21	-3.0
	0.6		3.05	-3.8
162	0.6	1.20	0.75	-1.6
	0.6		1.92	-2.4
	0.6		2.78	-3.5

(Continued)

(Table II continued)

302	0.6	0.89	0.70	-1.5
	0.6		2.05	-2.6
	0.6		2.88	-3.9
1600		2.14	0.75	-1.4
			2.00	-1.5
			3.00	-1.2
		March 3-4, 1976		
23		0.76	0.62	-14.5
			1.38	-12.6
			1.66	-11.7
99		1.08	0.48	-13.9
			0.98	-12.4
			1.48	-10.3
			1.98	-8.5
162		1.20	0.83	-15.2
			1.33	-12.9
			1.68	-11.2
302		0.89	0.39	-14.8
			0.89	-13.1
			1.39	-11.3
			1.89	-9.7
			2.39	-6.6
513		1.78	1.78	-2.6

(Continued)

(Table II continued)

		May 4-7, 1976		
23	0.76	0.76	0.76	-11.3
61	0.92	0.92	0.92	-11.7
162	0.93	1.20	0.93	-9.0
202	1.30	1.30	1.30	-9.7
262	0.94	0.94	0.94	-10.3
352	1.22	1.22	1.22	-8.9
412	1.33	1.33	1.33	-7.6
442	1.50	1.50	1.50	-5.2
481		1.74	1.74	-3.6
601	1.77	1.77	1.77	-4.3
653	1.85	1.95	1.95	-3.7
742	≈ 1.80	1.93	1.93	-3.1
About 1220	2.00	2.14	2.14	-2.5
Near PB-3	≈ 2.0	4.7	4.7	-1.7
Between PB-3 and Reindeer Island	1.90	6.6	6.6	-1.7
Offshore from PB-2	1.95	16.1	16.1	-1.7
Near PB-1	1.94	2.6	2.6	-3.1

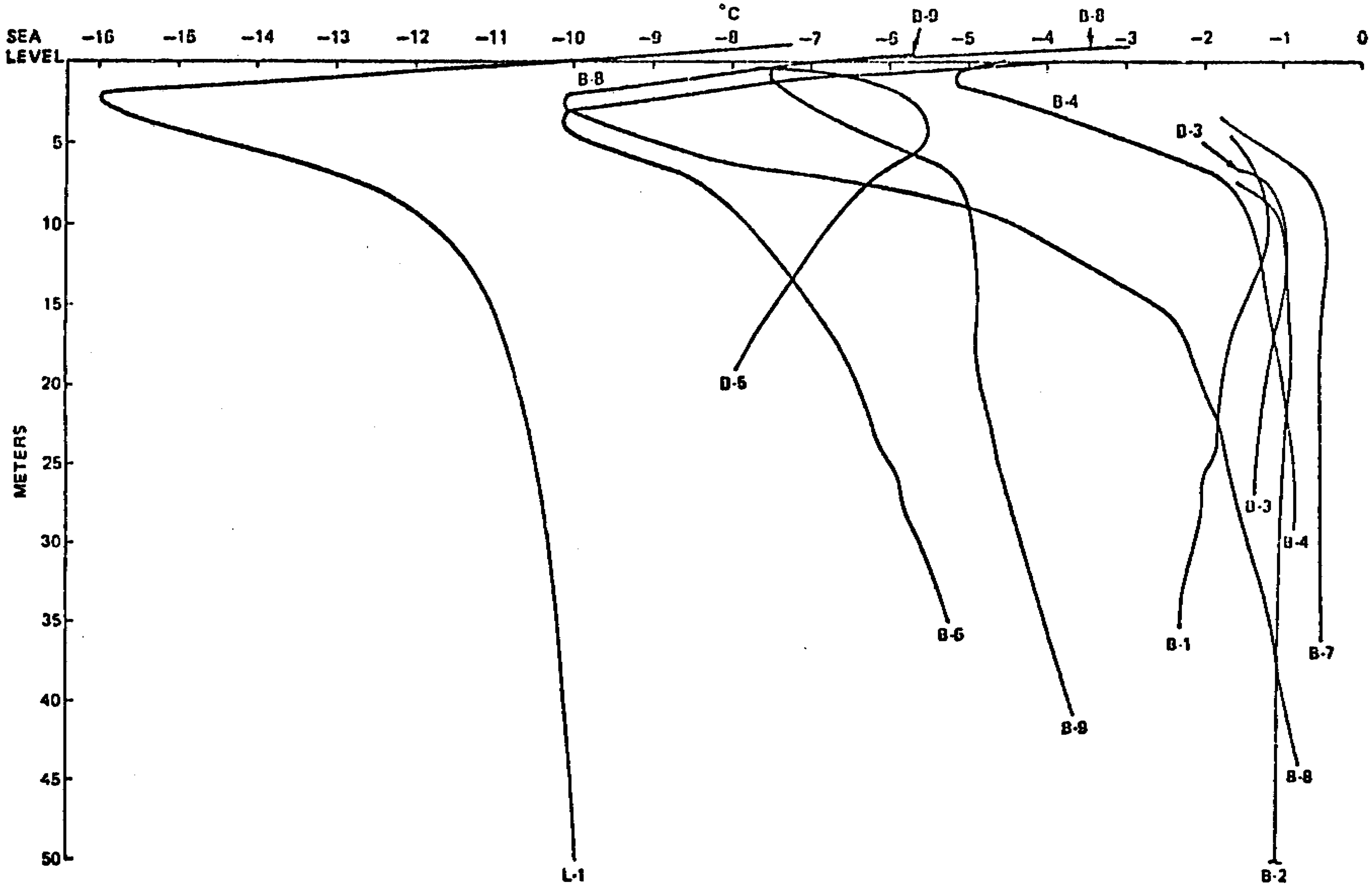


Figure 1. Soil temperature profiles for ten selected boreholes near Barrow (Lewellen, 1976).

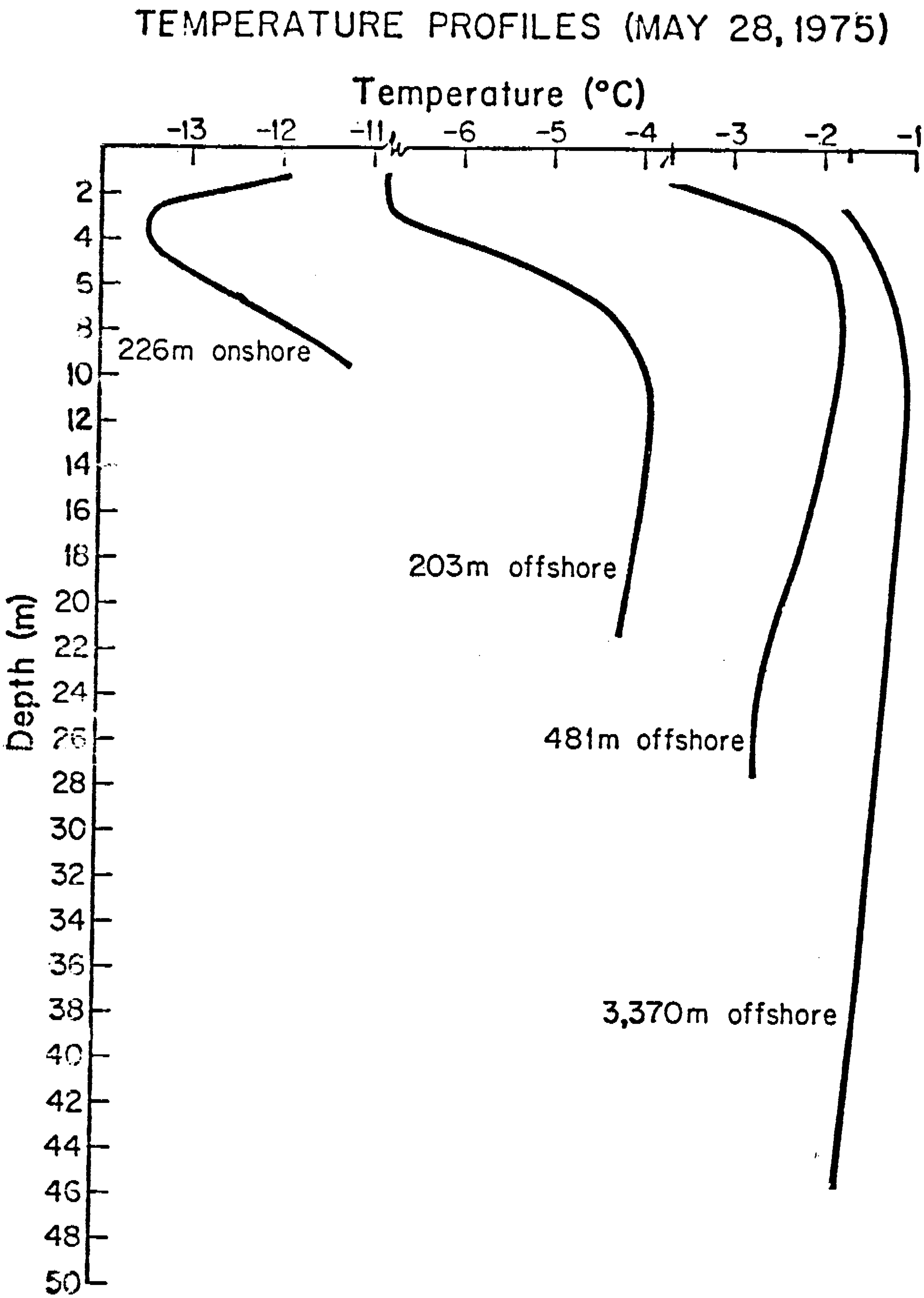


Figure 2. Soil temperature profiles from Prudhoe Bay (Osterkamp and Harrison, 1976 A).

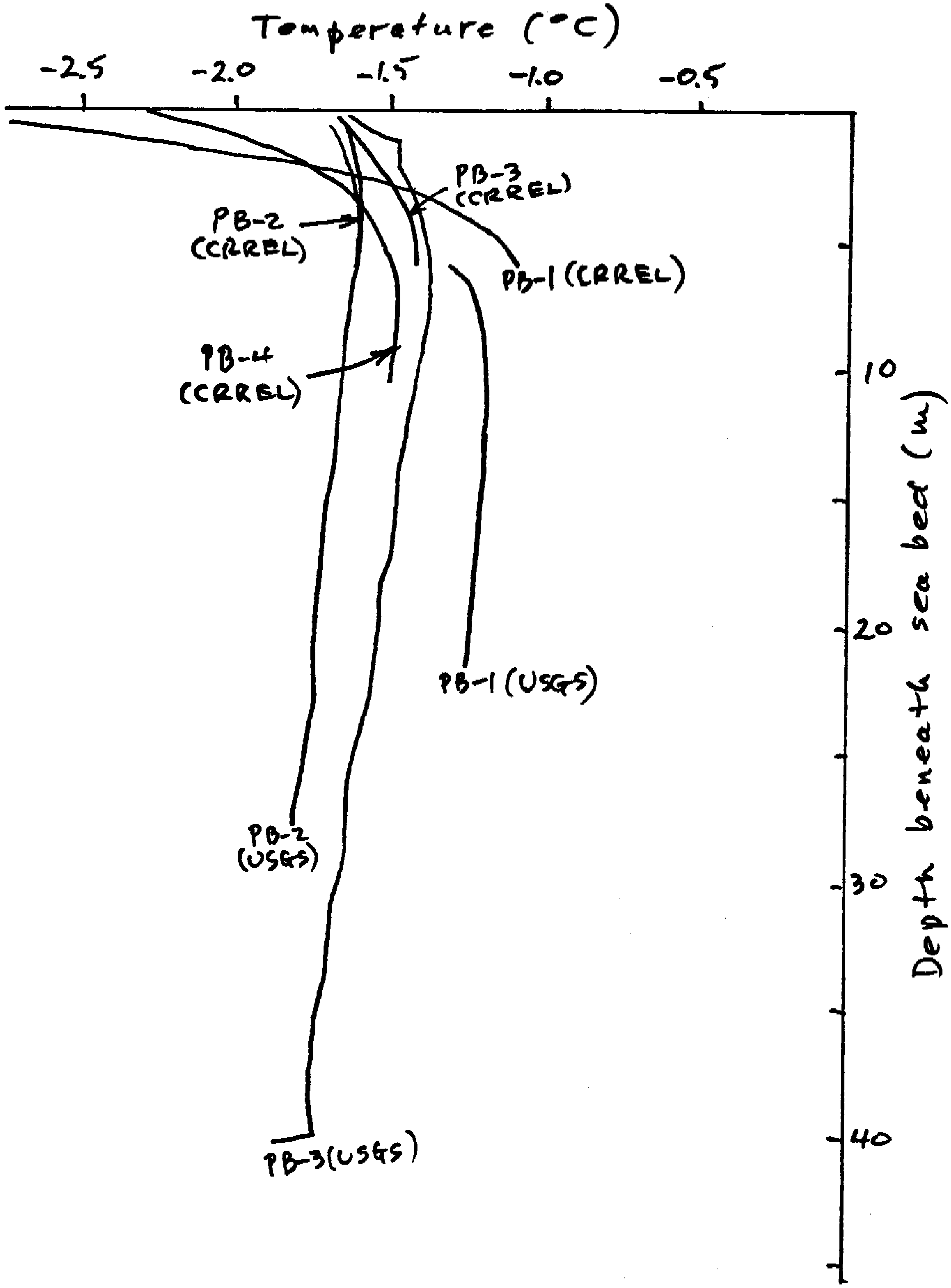


Figure 3. Soil temperature profiles from Prudhoe Bay (USGS-CRREL).

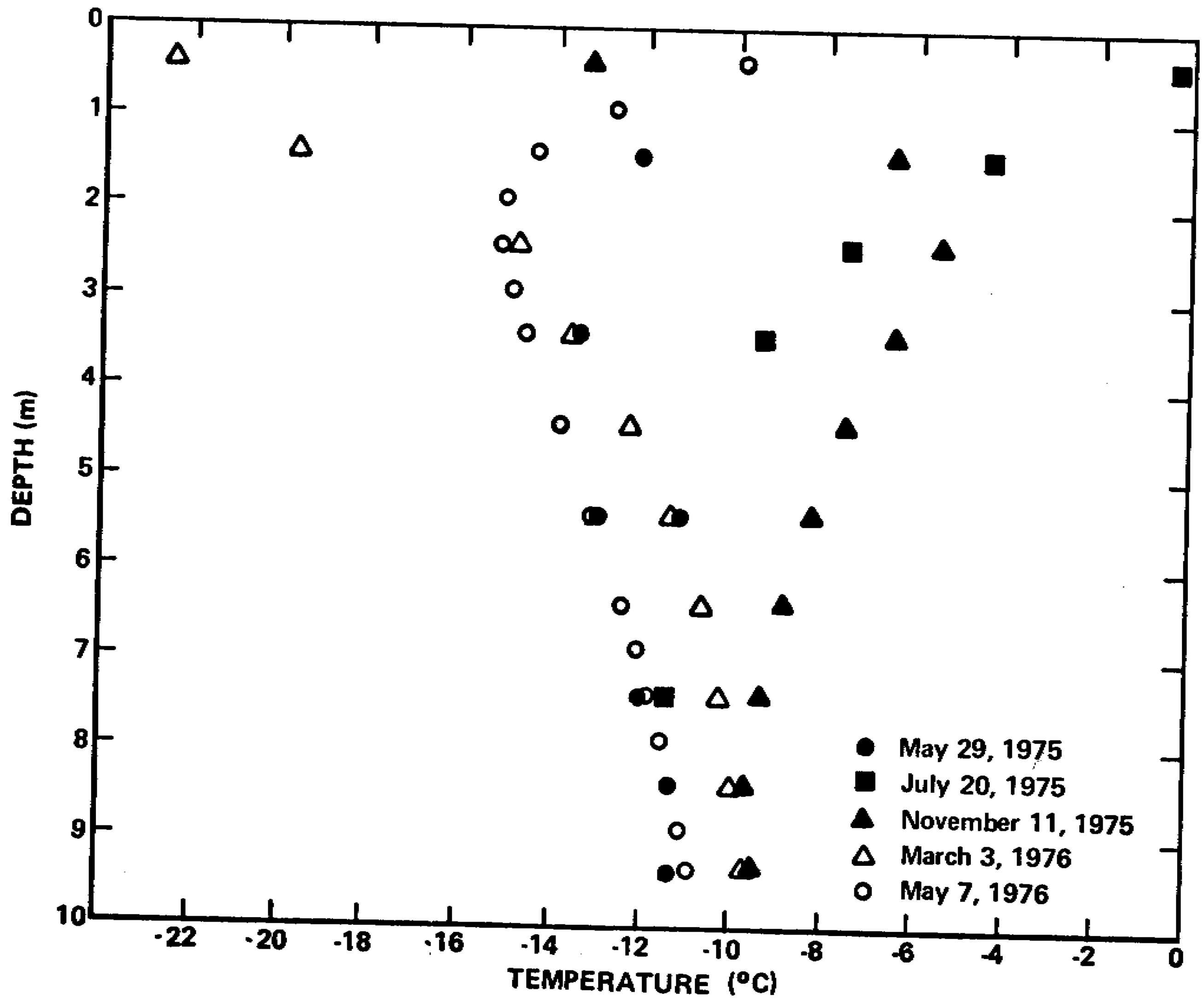


Figure 4. Temperatures in hole -226, on land 226 m from shore at Prudhoe Bay.

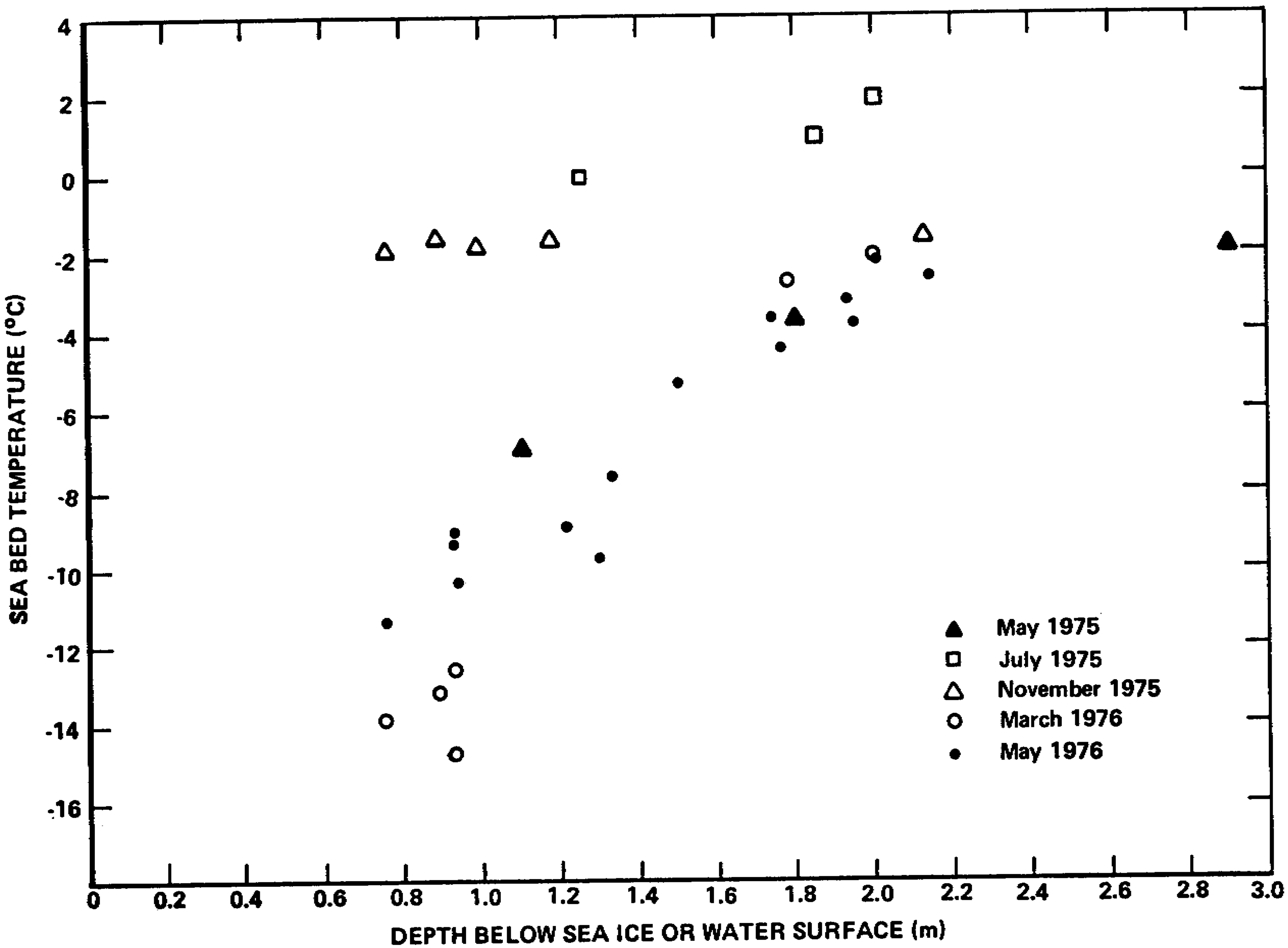


Figure 5. Seasonal temperature variations at the sea bed at Prudhoe Bay.

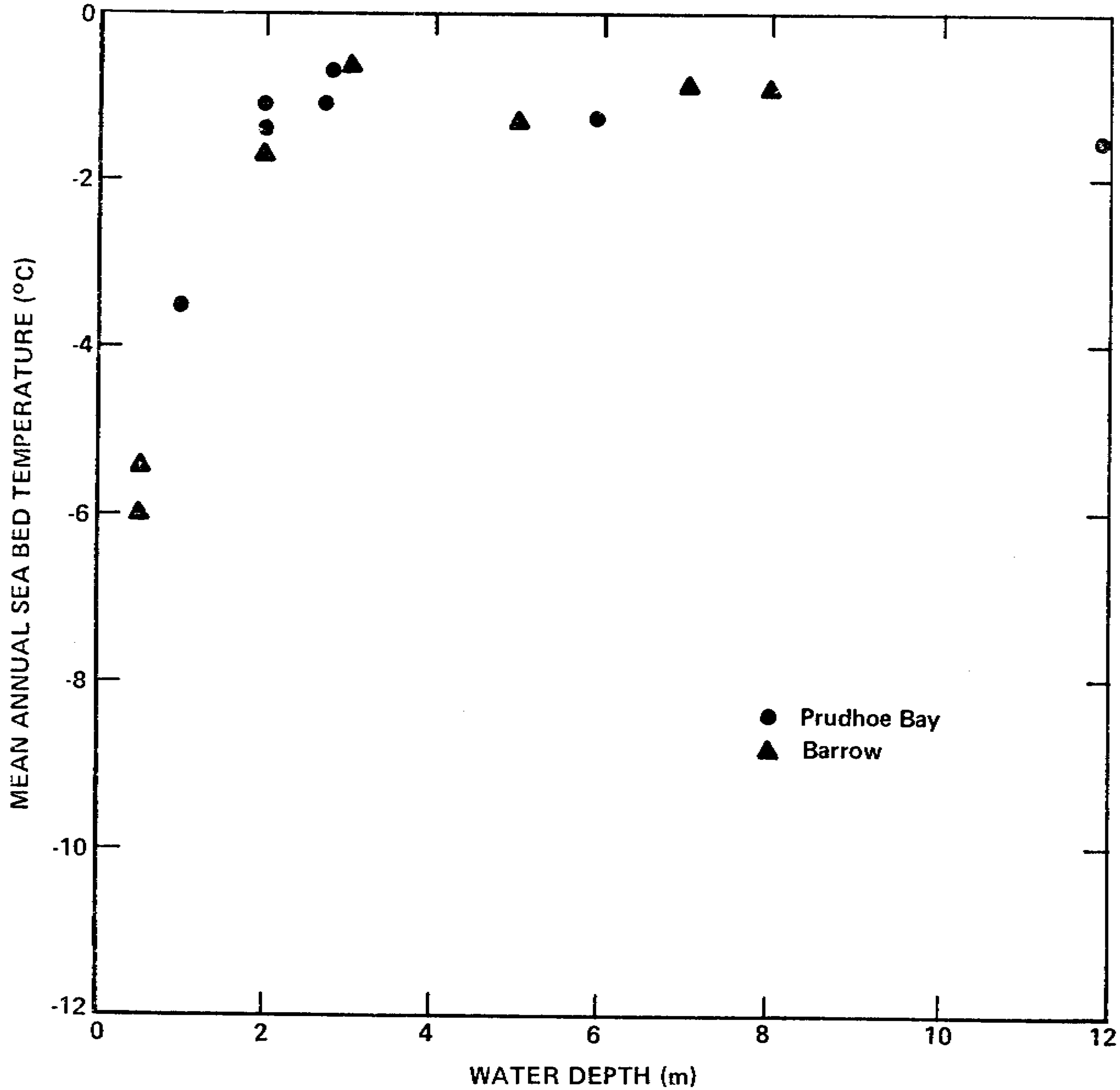


Figure 6. Dependence of mean annual sea bed temperature on bathymetry.

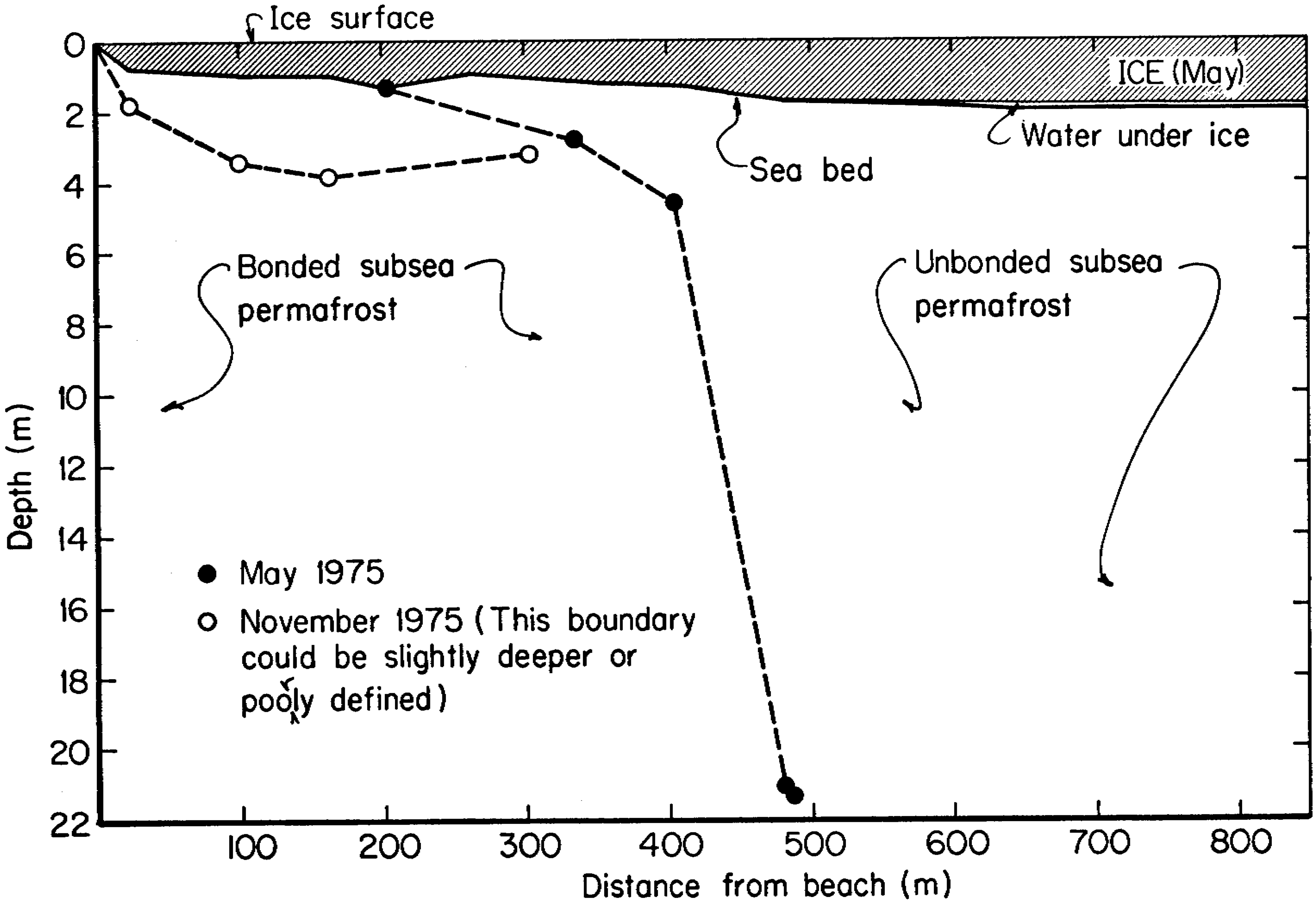


Figure 7. Data showing an active subsea permafrost layer near shore at Prudhoe Bay, at the site described by Osterkamp and Harrison (1976 A).

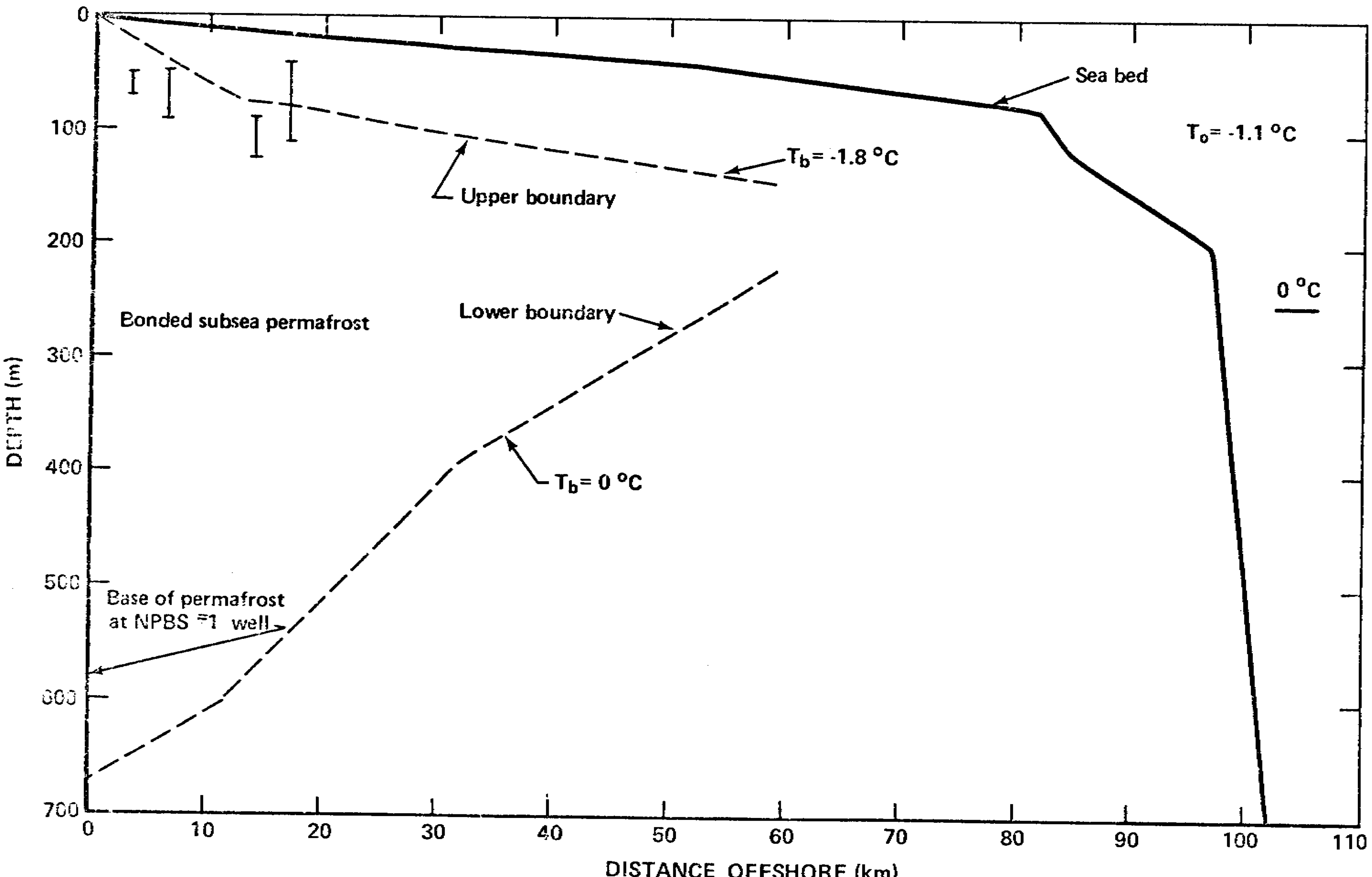
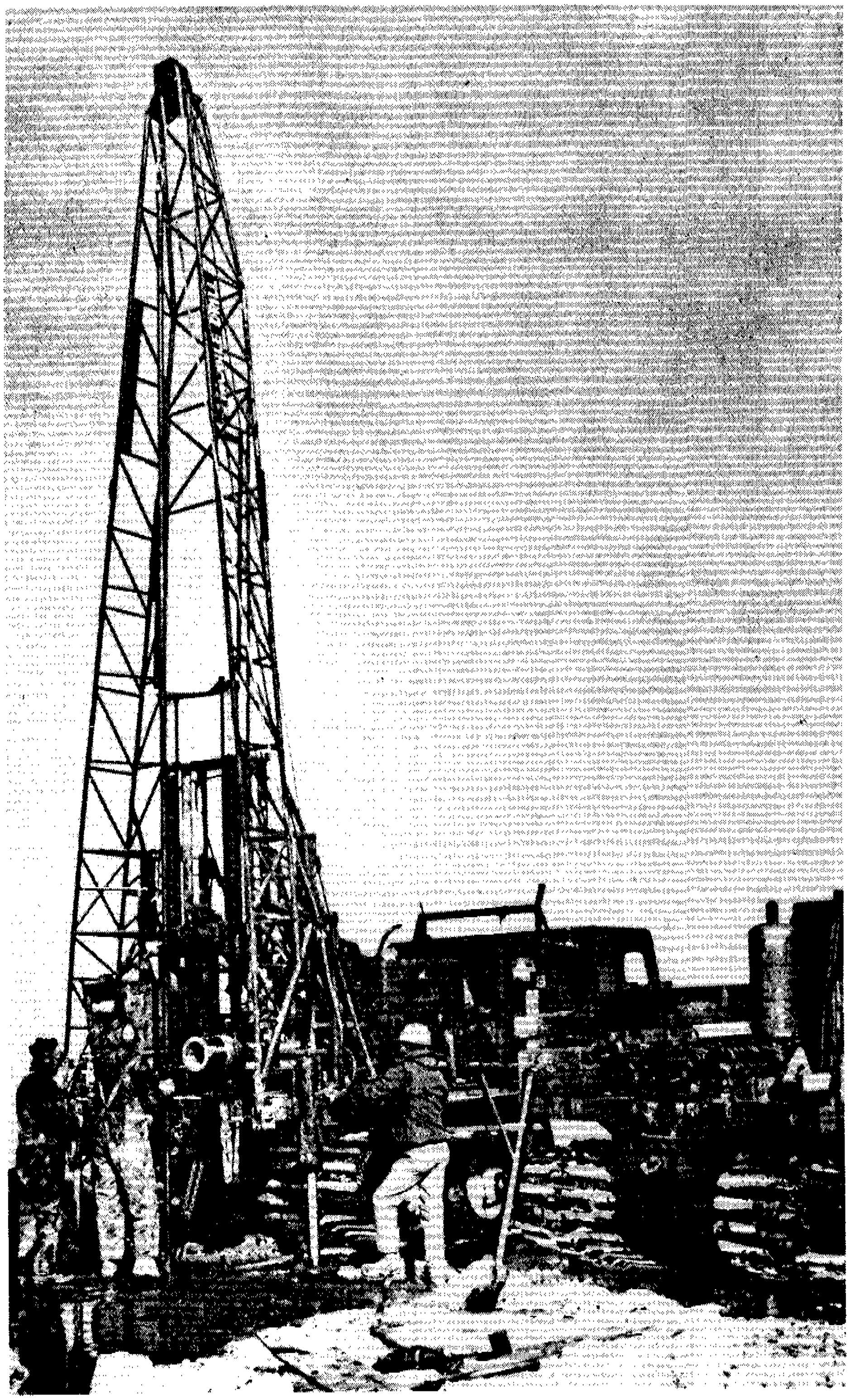


Figure 8. Application of a crude thermal model to prediction of bonded-unbonded subsea permafrost conditions off Prudhoe Bay. Although the details should not be taken seriously, the model does show that ice-bearing permafrost may extend well out on the Beaufort Sea shelf. Information from drilling and seismic work within 17 km of shore is shown by the range bars on the upper boundary. The position of the $0^{o}C$ isotherm at the edge of the shelf is from the OCSEAP reports of Aagaard (RU 151).

by T. E. Osterkamp and W. D. Harrison

APPENDIX I

Subsea Permafrost



Alaska State Highway Department crew operating on ice off Prudhoe Bay.

Its Implications for Offshore Resource Development

Large oil and gas deposits are thought to exist on Alaska's continental shelf. Their rational development requires a thorough understanding of the subsea soils, particularly along Alaska's arctic coast where subsea permafrost may present additional difficulties to the necessary drilling, trenching and use of these subsea soils as foundations for structures. Therefore, the variations in subsea soil types, their distribution, engineering properties and state of ice-bondedness must be known.

A general sea level curve, as shown in Figure 1 (Müller-Beck, 1966), indicates that the continental shelf along the northern coast of Alaska was exposed to cold air temperatures for long periods of time. For example, at Prudhoe Bay, the 15 m depth contour is about 20 km offshore and, according to Figure 1, could have been exposed to cold air temperatures for

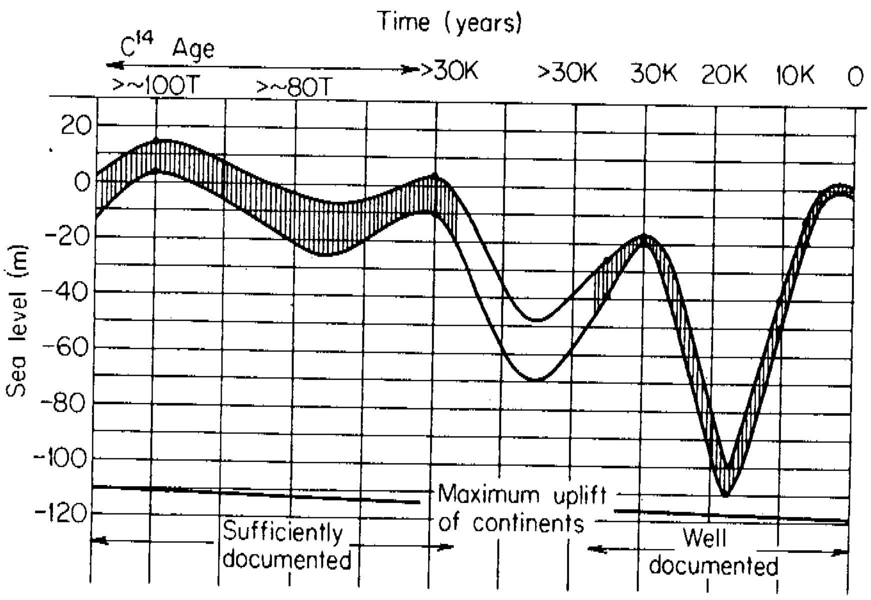


FIGURE 1. Generalized sea level curve for the past 10^5 years (after Muller-Beck, 1966).

40,000-50,000 years. This is sufficient time for a permafrost thickness of $\approx 6 \times 10^2$ m to form (Mackay, 1972). Subsequent increases in sea level have resulted in a state of ocean transgression on land until 3,000-4,000 years ago. The sea level has been nearly static since then, but coastal erosion, by thermal and mechanical processes, still continues along the flat northern coast of Alaska. The average rate of erosion is 1-2 m a^{-1} with maximum rates over 30 m a^{-1} at Cape Simpson and Point Drew (Alexander et al., 1975; Leffingwell, 1919).

The effect of this fairly fast coastal erosion is that the permafrost is subjected to a new set of thermal and chemical (salty sea water) boundary conditions more rapidly than it can respond to them. As a result, a state of disequilibrium exists after an ocean transgression and relict subsea permafrost may persist for thousands of years at a location such as Prudhoe Bay, given the conditions there

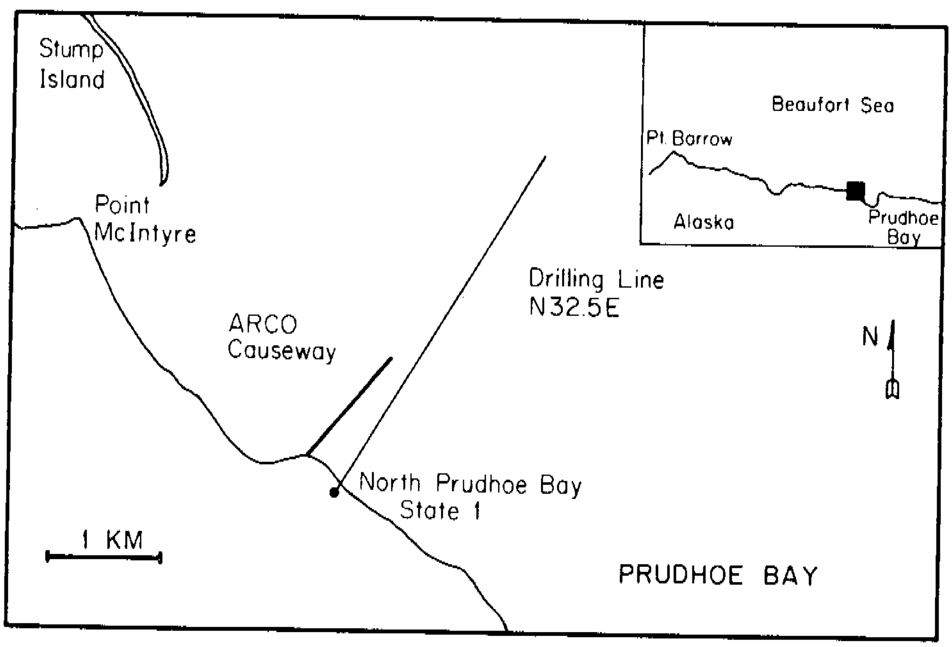


FIGURE 2. Map showing the location of the drilling line on the northwest corner of Prudhoe Bay.

(i.e., initial thickness 600-700 m, ice content of about 40%, bottom melt rate of 0.02 m a^{-1} and mean annual sea bed temperature near -1°C). Thus, it is probable that substantial areas of subsea permafrost exist on Alaska's continental shelf, particularly near shore, in the southern Beaufort Sea.

The authors (1976) conducted a drilling and sampling program during May 1975, at a site near the northwest corner of Prudhoe Bay (Figure 2) which showed that subsea permafrost exists there to at least 3.4 km offshore. Their conclusions, pertinent to this discussion, are as follows:

(1) Along the line of our drilled holes at Prudhoe Bay, ice-bonded permafrost exists almost up to the sea bed within 200 m off shore. At 481 m offshore, there is an unbonded layer 19 m thick beneath the sea bed. At 3,370 m, the unbonded layer is probably between 46 and 71 m thick. This unbonded layer exists in the presence of negative sea bed temperatures.

(2) A sharp, well-defined interface was found between the unbonded layer and the underlying ice-bonded subsea permafrost at all positions within 481 m from land.

(3) The subsea soils are composed of sandy gravel mixed with some silt and overlain by a thin layer of silty sand. This layer increases in thickness from a few meters nearshore to about 14 m at 3,370 m offshore.

(4) The mean annual temperature at the sea bed increases from -3.4°C at 203 m offshore (where ice freezes to the sea bed) to roughly -1.1°C at 481 m offshore and to -0.7°C at 3,370 m offshore.

(5) Where ice freezes to the sea bed, the mean annual sea bed temperature is several degrees lower (see (4) above) and the thickness of the unbonded layer is only a few meters. A few hundred meters farther offshore (481 m from the beach), where the ice does not freeze to the sea bed,

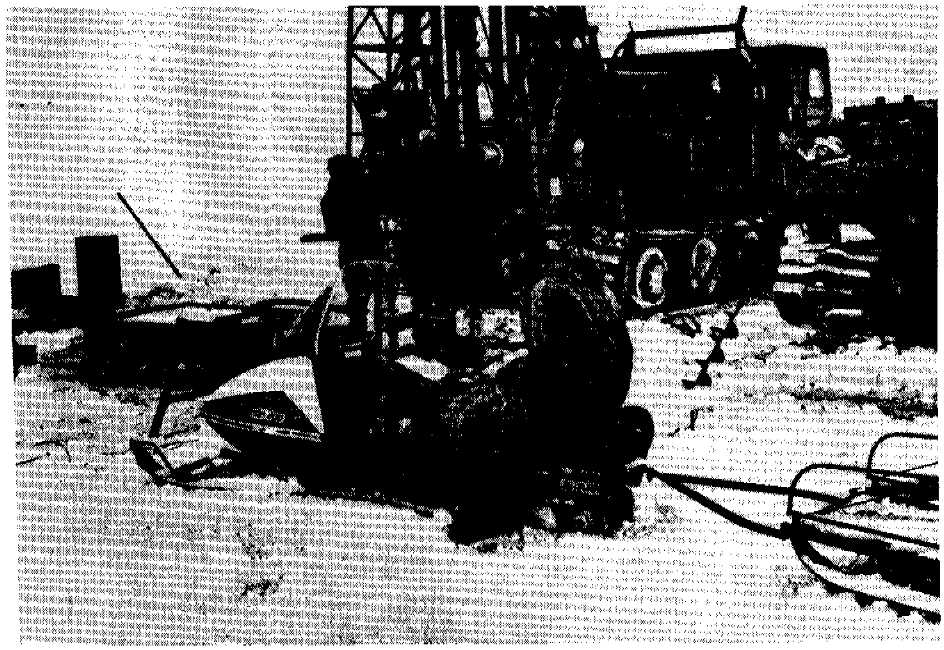
the thickness of the unbonded layer increases rapidly to about 19 m.

(6) The permeability of the subterranean permafrost is zero.

(7) Preliminary experiments indicate that the saturated hydraulic conductivity of the unbonded subsea permafrost is about 10^{-6} to 10^{-7} m s^{-1}.

(8) Salt concentrations where ice freezes to the sea bed range up to 3-4 times that of normal sea water. Where there is 0.1 to 0.2 m of water under the ice cover, the salt concentration is about twice that of normal sea water. Normal sea water exists under the ice cover 3,370 m offshore where there is about 1 m of water under the ice cover.

(9) A few small ice lenses were found in a hole 195 m offshore. No massive ice was found in any of the offshore holes.



Author Harrison checking instrumentation at drill site.

Further details of the drilling and sampling techniques, soil analysis and other results are given by Osterkamp and Harrison (1976).

The results of our drilling and sampling program, (1), (2), and (4) above, show that the ice in the permafrost melts after an ocean transgression even when the mean annual sea bed temperature is negative. This melting process produces an unbonded layer of soil at the sea bed which thickens seaward as shown in Figure 3. Note that the zero position was taken at the ice surface which was about 2 m lower than the land surface. We believe that this unbonded layer is a result of salt transport, by a mechanism other than diffusion, into the sea bed (Harrison and Osterkamp, 1976).

Except for massive ice bodies, the ice volume on land in a vertical permafrost profile decreases from the permafrost table to near saturation values at ≈ 10 m depth (Sellman and Brown, 1973; Mackay and Black, 1973). Figure 3 shows that this ice in the top 10 m of subterranean permafrost must be absent

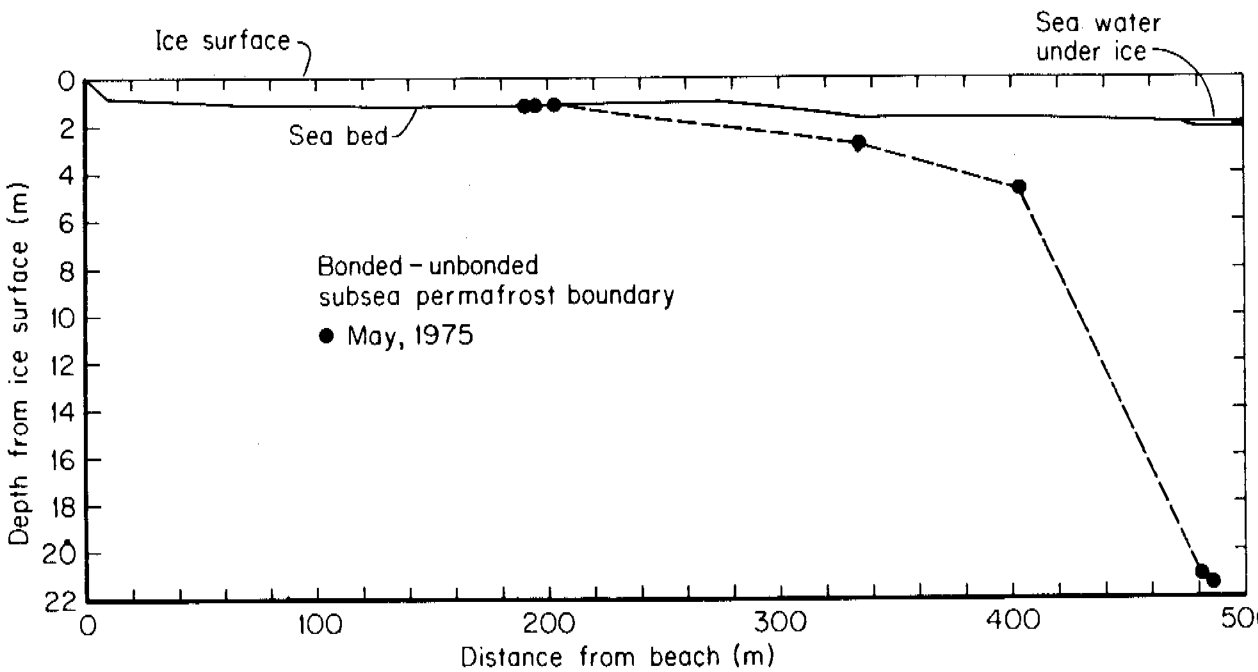
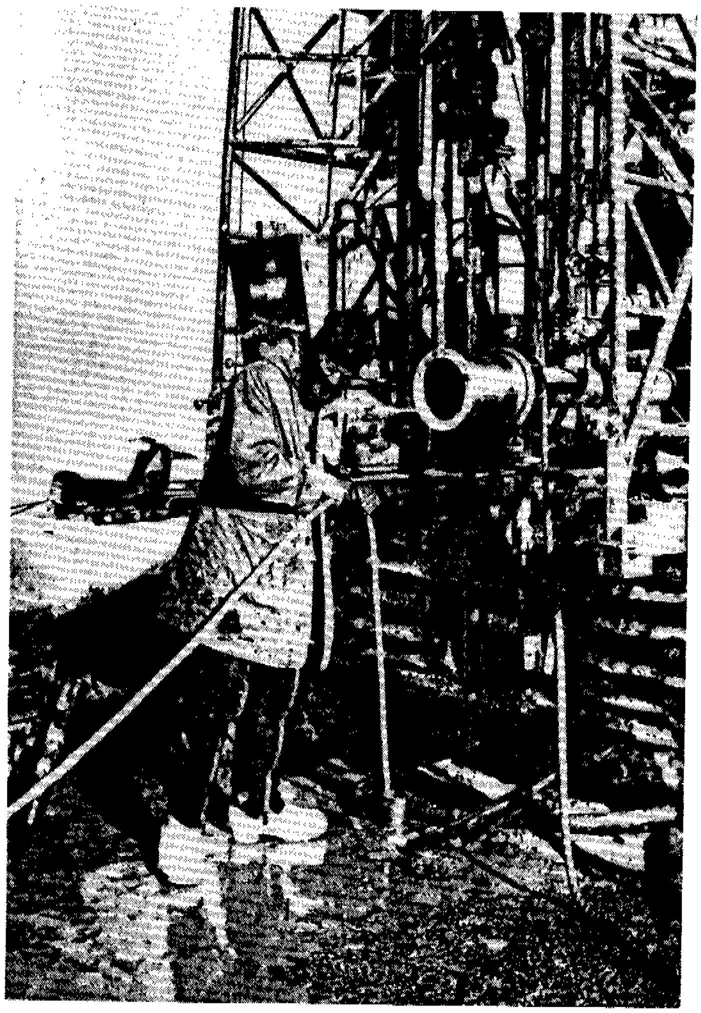


FIGURE 3. Profile of the nearshore subsea permafrost regime. Subsea soils to the right and above the dashed line are unbonded and soils to the left and below it are ice-bonded.

Author Osterkamp returning to read one of the drill holes.



Harrison lowering temperature probe (thermistor string) down drill hole.

at water depths > 2 m after an ocean transgression since the subsea soils are unbonded there to a depth > 23 m, measured relative to the land surface. In addition, massive ice bodies < 23 m in thickness must be absent at water depths > 2 m for the same reason. Therefore, the serious problems for foundations and pipelines on land created by the thawing of ice may be expected to be absent at water depths > 2 m.

The presence of such a thick unbonded layer indicates that it should be possible to use standard construction techniques for foundations and pipelines in this layer. Also, the sandy gravel is an excellent foundation material. A somewhat different situation will prevail if a foundation or hot pipe penetrates the ice-bonded subsea permafrost. In addition, the presence of a well-defined, moving boundary between the bonded and unbonded subsea permafrost may create problems for structural features that transect this boundary (e.g., pipelines, tunnels).

Figure 4 shows the thermal response of the subterranean permafrost to an ocean transgression. It is obvious that, where it penetrates the bonded subsea permafrost, a well producing hot oil will encounter the same thermal problems it does on land but to a greater degree, since the subsea permafrost is much warmer than subterranean permafrost. This problem may have a positive aspect in that well-bore freeze-back may be slowed by the warm permafrost temperature and salt water infiltration along the well bore.

The presence of these relatively warm sea bed temperatures just offshore, the unbonded nature of the sea bed and consideration of salt rejection processes during the freezing of sea water suggest that it may be difficult to freeze ice islands, gravel islands, causeways and similar structures into the sea bed where water depths exceed a few meters. This would substantially reduce the shearing forces that these structures could withstand.

An observation made during the drilling of a hole 195 m offshore was that the open hole filled with a highly concentrated brine which contained a small amount of ice slush at a temperature of -9.5°C. This hole was at a site where 1.1 m of ice was frozen to the bottom and where the subsea permafrost was bonded from the sea bed downward. The engineering significance of this observation is that a hole or trench made in the bonded subsea permafrost may be expected to fill

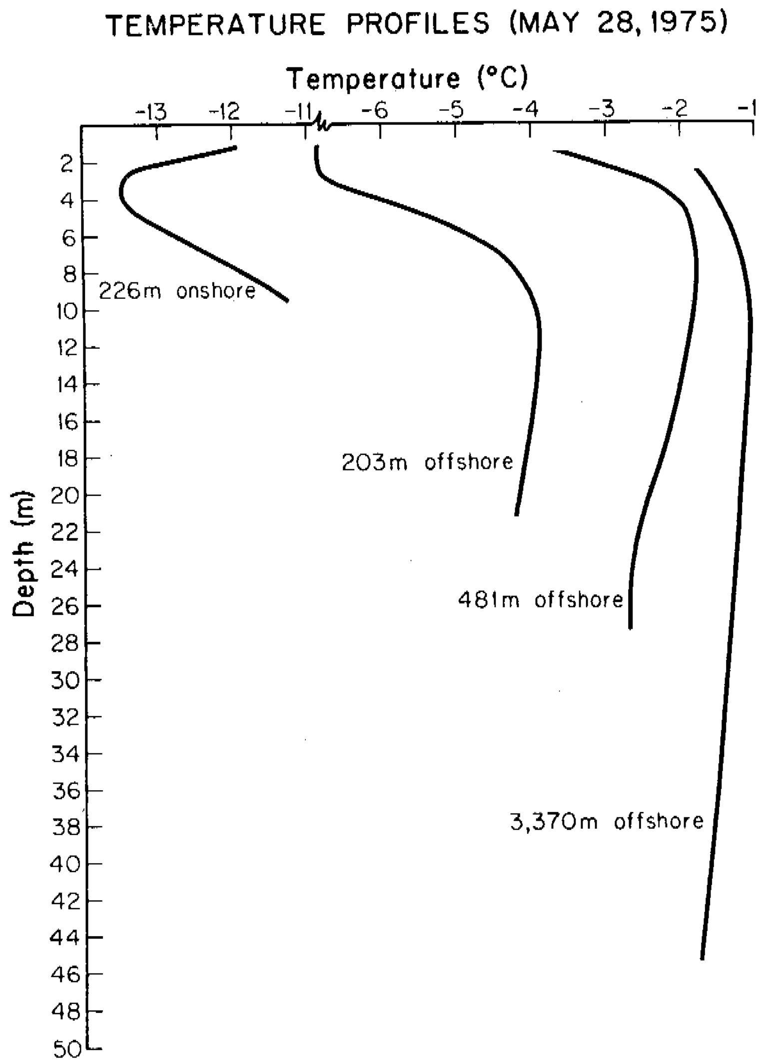


FIGURE 4. Temperature vs. depth profiles for several distances from the shore.

rapidly with very concentrated brine.

It should be kept in mind that the above results and conclusions are based on one line of drilled holes. Extrapolation to other sites must be done with caution. The effects of varying soil types, geological formations, sedimentation rates and coastal erosion rates, rivers and estuaries, inundated lakes, offshore islands, bathymetry, ice conditions and other parameters must be taken into consideration.

ACKNOWLEDGEMENTS

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Drs. Tom Osterkamp and Will Harrison are both Associate Professors of Physics with the Geophysical Institute, University of Alaska, Fairbanks.

APPENDIX II

QUARTERLY REPORT

October 31, 1976 - December 31, 1976

(i) Delineation of most probable areas for subsea permafrost in the Chukchi Sea from existing data

(ii) Subsea permafrost: probing, thermal regime and data analysis

T. E. Osterkamp

and

W. D. Hariison

Refer to published Quarterly Reports for the above period for Research Unit 253-55

APPENDIX III

DIFFUSION OF HEAT AND SALT AND THE ONSET OF CONVECTION IN SUBSEA PERMAFROST

W. D. Harrison and T. E. Osterkamp

Geophysical Institute
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Abstract

Some heat and mass transport processes in subsea permafrost are discussed. An exact solution is given for a coupled model in which both heat and salt are transported by diffusion. The model describes the development of a thawed layer beneath the sea bed after an ocean transgression over deeply frozen ground, and is a generalization of the well known Stefan problem. This purely diffusive model should break down with the onset of convection in the thawed layer after it has reached a critical thickness. The theory is compared with data from Prudhoe Bay, Alaska, where the present shoreline retreat rate is roughly 1 m a^{-1}. Although it is possible that a diffusive regime may exist within about 0.5 km of shore, farther offshore interstitial water motion is important, leading to efficient salt transport and relatively rapid development of the thawed layer.

Annual Report

Contract #03-5-022-55
Research Unit #271
Reporting Period: Annual Report Period Ending April 1, 1977
Number of Pages: 44

BEAUFORT SEACOAST PERMAFROST STUDIES

J.C. Rogers and J.L. Morack
Geophysical Institute
University of Alaska
Fairbanks, Alaska 99701
(907)272-5522

April 1, 1977

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I. SUMMARY

The objective of this study is to develop an understanding of the nature and distribution of permafrost beneath the ocean and barrier islands along the Alaskan Beaufort Sea Coast. Several general statements can be made regarding the distribution of offshore permafrost on the Alaskan Shelf of the Beaufort Sea. Three principal points discussed at the Barrow Synthesis Meeting in January, 1977, can be listed as bounds on the distribution.

On the basis of bathymetry and sea level history:

(1) Shallow, inshore areas where ice rests directly on the sea bottom are underlain at depths of a few meters by ice-bonded equilibrium permafrost. Ice-rich permafrost must be anticipated where ever the water is less than 2 m deep.

(2) Ice-bonded permafrost was once present beneath all parts of the continental shelf exposed during the last low sea level interval, and consequently relict ice-bonded permafrost may persist beneath any part of the shelf inshore from the 90 m isobath. Observed depths to relict permafrost off the Canadian coast range from 10 m to 250 m.

(3) Ice-bonded permafrost is probably absent from parts of the Beaufort Sea shelf seaward from the 90 m isobath, although subsea temperatures are probably below 0°C.

In addition to these general guidelines, some specific conclusions resulting from the current studies can be listed along with their possible implication to offshore oil and gas development:

a. From (2) above, we conclude that in some offshore areas, it should be possible to bury hot oil pipelines beneath the ocean at distances from shore where the depth of ice-bonded and ice-rich permafrost precludes thermal destruction by the pipeline. Such burial could provide protection from ice gouging.

In near shore areas where permafrost can be ice-rich and within a few meters of the ocean bottom, it may be necessary to construct surface causeways for hot oil pipelines to bridge the shallow permafrost zone.

b. The barrier islands are not uniformly underlain by ice-bonded permafrost. Areas with no ice bonding have been observed. In these cases, it should be possible for hot oil gathering lines to cross the island areas with no adverse effects from ice-bonded materials.

c. Also from (2) above, we conclude that cold gas lines can be buried in the offshore regions where a non-frozen layer exists but that the problem of freeze-back must be dealt with. The presence of salt brine complicates this problem beyond the onshore freezing problem.

d. Former thaw lakes which contribute to the variability of the upper permafrost surface can be found in subsea permafrost of land origin. It may be possible to utilize these areas for offshore structures and avoid ice-bonded materials if desired.

II. INTRODUCTION

A. General Nature and Scope

The known oil reserves along the Beaufort Sea coast coupled with a national need to develop these resources have focused attention on the distribution and character of permafrost in that area. Of particular concern to this project is the comparatively unknown areas offshore and along the barrier islands. Recently priorities have been established for attacking the problem area and a high priority was established for mapping the distribution of offshore permafrost.

This study of coastal offshore permafrost which utilizes seismic refraction techniques to probe the ocean bottom along the Alaskan Beaufort Sea coast was initiated in April of 1975. It will provide information relevant to task D-8 in NOAA's proposal to BLM.

B. Specific Objectives and Relevance to Problems of Petroleum Development

The most important parameter to be determined in this study is the distribution of offshore permafrost. Also, the depth to the top of the bonded permafrost beneath the ocean floor is to be determined. Using the equipment purchased by the program, data are being gathered which are of immediate practical value in determining the distribution and nature of offshore permafrost. An objective is compilation of the above parameters for use by other principal investigators and appropriate agencies and industries.

The distribution study has focused primarily on the Prudhoe Bay area with secondary emphasis at Point Barrow. The truncation of permafrost beneath the ocean is of interest, particularly the shape of the frozen-nonfrozen boundary. Thus, the second major objective is the determination of the shape of the boundary. One important facet of this objective is determining the nature and extent of permafrost beneath the barrier islands. These results will provide valuable information for refinement and testing of thermal models as well as for determining operational methods for offshore oil and gas development.

The third major objective is to provide information to support reconnaissance drilling programs including those of the University of Alaska, CRREL, and the USGS. Drilling provides information on bottom conditions only near the drill hole. It is possible, using the seismic technique, to extend such site specific information to areas remote from the drill site, by correlating seismic data at the drill site and at the remote locations. Also, seismic information can be used to suggest areas for future drilling investigations.

Specific and detailed relevance to problems of offshore petroleum development have been addressed in the synthesis document developed by the Earth Science Study Group at Barrow in January, 1977. The reader is referred to the section on permafrost-induced problems from that report.

III. CURRENT STATE OF KNOWLEDGE

Permafrost, which commonly occurs in high latitudes and altitudes on the earth, also exists beneath the sea floor along the Arctic Coast. At this time, although relatively little is known about offshore permafrost properties including its distribution and the dynamics of its formation and destruction, definite progress is being made. Several of the problem areas needing investigation have recently been discussed in "Priorities for Basic Research on Permafrost" and also in a position paper for the National Science Foundation titled: "Problems and Priorities in Offshore Permafrost."

The existence of offshore permafrost which has long been suspected as the result of ocean transgression upon land permafrost in northern latitudes is now a demonstrated fact. Lachenbruch (1957, 1968) discusses relict permafrost which can take thousands of years to dissipate.

More recently, permafrost has been reported beneath the Canadian Beaufort Sea (Hunter, 1974; Hunter et al., 1976) and beneath the water of Prudhoe Bay, Alaska (Osterkamp and Harrison, 1976). Some of the physical processes involved in the degradation of relict permafrost are beginning to be understood and it is clear that in addition to temperature, the porosity of the sediments and the salinity of the interstitial liquids are important. Current data are available in the annual reports of research units 253, 255, 256, by Harrison and Osterkamp. Some details of the processes involved are also found in Harrison and Osterkamp (1976). The results reported in this report are in agreement with the drilling results obtained by the Joint USACRREL/USGS drilling program (R.U.105) as reported by Sellman _et al_. (1976). Also, the results are in agreement with those of Osterkamp and Harrison. From their records and the seismic records presented in the following sections, it is clear that offshore permafrost which is ice-bonded exists in Prudhoe Bay and on some offshore islands. The distribution of this permafrost and the depth of its upper surface are currently known along several transects. Aerial distribution and depth information remain to be determined although it is possible to make some general statements regarding offshore permafrost. (See the summary section of this report.)

IV. STUDY AREA

Two principal areas investigated are shown in Figures 1 and 4. The first is the western end of the Beaufort Sea coast while the second area is closer to the eastern end of the Beaufort Sea coast. During both years of summer work (1975 and 1976), ice conditions were not favorable to marine work during the available field season. Therefore, the data are somewhat limited in geographical extent.

V. SOURCES AND METHODS

Shallow seismic refraction techniques have been documented by Dobrin (1975) and their application to the detection of sub-sea permafrost has also been described (Hunter, 1974; Hunter and Hobson, 1974). The seismic refraction data taken in and near Prudhoe Bay were collected using three 40 cubic inch air guns as an acoustic source and the refracted signal was detected along a 480 m hydrophone line towed behind the USGS vessel "Karluk." The air guns were fired simultaneously, although the firing circuit was designed with the capability of delaying the firing of any two air guns. The 24 channels of hydrophone output were recorded in analog form by a chart recorder and on magnetic tape. These data were gathered at several points along the ship transects, later scaled and reduced to time-distance plots.

Refraction data taken on offshore islands near Prudhoe Bay consisted of six channels taken on a digital enhancement hammer seismograph. The data are read from the seismograph and also reduced to time-distance plots.

Finally, the inverse slopes of the time-distance plots are used to determine seismic velocities in the sub-bottom material, depths to the layers, and the velocities are then used to determine whether the bottom materials are frozen. Permafrost velocities are typically between 2500 m/s and 3000 m/s while similar materials in the nonfrozen state typically have velocities ranging from 1600 m/s to 2000 m/s (Rogers et al., 1975). Significant velocity contrasts such as these, which are typical of coarse sandy materials, allow easy classification of materials into the frozen or unfrozen state.

Several lines of arcer data gathered by the USGS (Reimnitz et al., 1972) were generously provided by Erk Reimnitz of the U.S. Geological Survey, Menlo Park, California. These continuous reflection records were taken with a 500 Joule multi-tip electrode speaker fired at 1/2 second intervals. The reflected signal is received, filtered, and displayed on a 1/4 second scan. Of particular interest on these records was a large number (several thousand) of point reflectors observed to the 250 m depth limit of the system.

VI. RESULTS AND VIII. DISCUSSION

Several kinds of data have been gathered in the study of offshore permafrost including marine seismic refraction and reflection as well as seismic studies on some barrier islands. These data coupled with the results of geophysical investigations by others provide a better understanding of the character and distribution of offshore permafrost than has previously existed.

In this section we distinguish between permafrost as given by the thermal definition: material whose temperature has remained below 0°C for two or more years in succession (Lachenbruch, 1968) and ice-bonded permafrost: material whose physical characteristics are dominated by the freezing and bonding action of interstitial fluid. It also appears useful to introduce the distinction between ice bearing permafrost (material below 0°C with ice and fluid in the interstices) and ice-bonded permafrost. Since the seismic methods used depend primarily on the bonding effects for velocity enhancement, it is possible and indeed seems to be the case, that one can find small amounts of ice during drilling but observe no seismic velocity enhancement. Examples of this are discussed later in this section which includes work at Point Barrow and Prudhoe Bay.

Offshore Island Studies

Seismic refraction studies were conducted during the summer of 1976 on two offshore islands along the Beaufort Sea coast near Prudhoe Bay. The experimental techniques and equipment used on Cross Island and Reindeer Island were similar to those used on the Barrow spit (Rogers et al., 1975). Areas underlain by both frozen and unfrozen material were located on the islands.

In related work conducted in 1974 on Tapkaluk Island and on the Barrow spit using an explosive source, several sites with non-ice-bonded materials were identified. In the discussion that follows, the Barrow work is presented and the results of hand auger drilling are tied in with the refraction work. Also, the penetration depth of the enhancement-hammer seismograph lines is compared with the lines using an explosive source to establish an estimate of the minimum possible depth to hypothetical frozen layers in the case where no frozen layers were observed.

Point Barrow Area

Figure 1, an area map of the Point Barrow vicinity, shows the location of seismic refraction work on the Barrow spit, on the Tapkaluk Islands, and in Elson Lagoon. The line identified by A-A' locates a series of drill holes reported by Lewellen (1973).

The Area "A" of Figure 1 is shown in more detail in Figure 2 where several seismic refraction lines are indicated. With the exception of line I, all lines identified by letters were obtained using an explosive seismic source while those identified by numbers (and line I) were made with a hammer enhancement seismograph. The tundra/pea gravel boundary shown dashed was observed to be the boundary between frozen and nonfrozen subsurface material. Seismic lines to the west of the boundary produced only high velocities (~3000 ms^{-1}) while those to the east of the boundary produced only low velocities (~2000 ms^{-1}). Line I and 5-6 which transect the boundary showed a sharp transition from high to low velocities in the distance of a few meters.

A hand auger was used in several cases to verify that the high velocity materials were ice bonded. Similar drilling in the case of low velocity refractors failed to produce ice-bonded material to depths of 2 m, the depth limit of the auger.

Using the refraction data, it is possible to estimate the maximum possible depth for detection of frozen materials. The maximum penetration depth is calculated to be 0.22 times the length of the refraction line. Thus, if a frozen layer did exist below the 212 m line J, it would be below a depth of 212 x .22 = 47.4 m, since no high velocity layer was observed. The longest line shown in the figure, H, did not produce high velocities. It is estimated that if

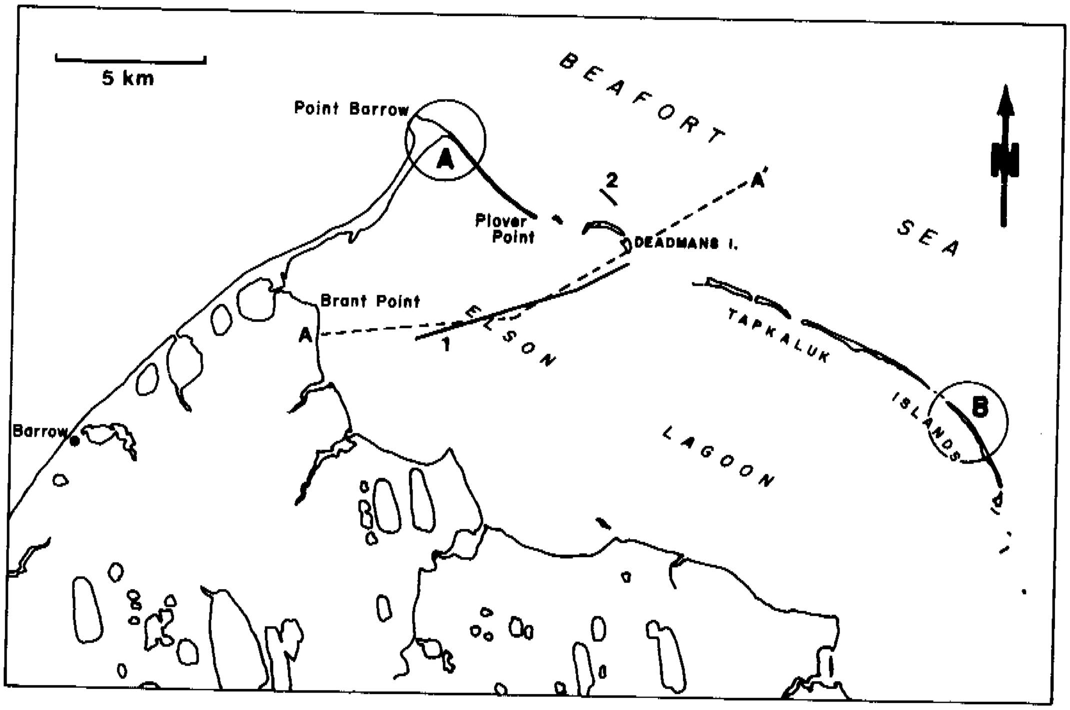


Figure 1 . Area map of Point Barrow, Alaska showing locations of seismic refraction work on land (A), on islands (B), marine refraction work (1) and (2) and a line with drilling information (A-A'). The depth of water in the Lagoon is generally less than three meters. From Point Barrow to the southern end of Tapkaluk Island there are several interconnected smaller barren islands. Their relief is seldom more than a meter and they consist primarily of sandy pea gravel.

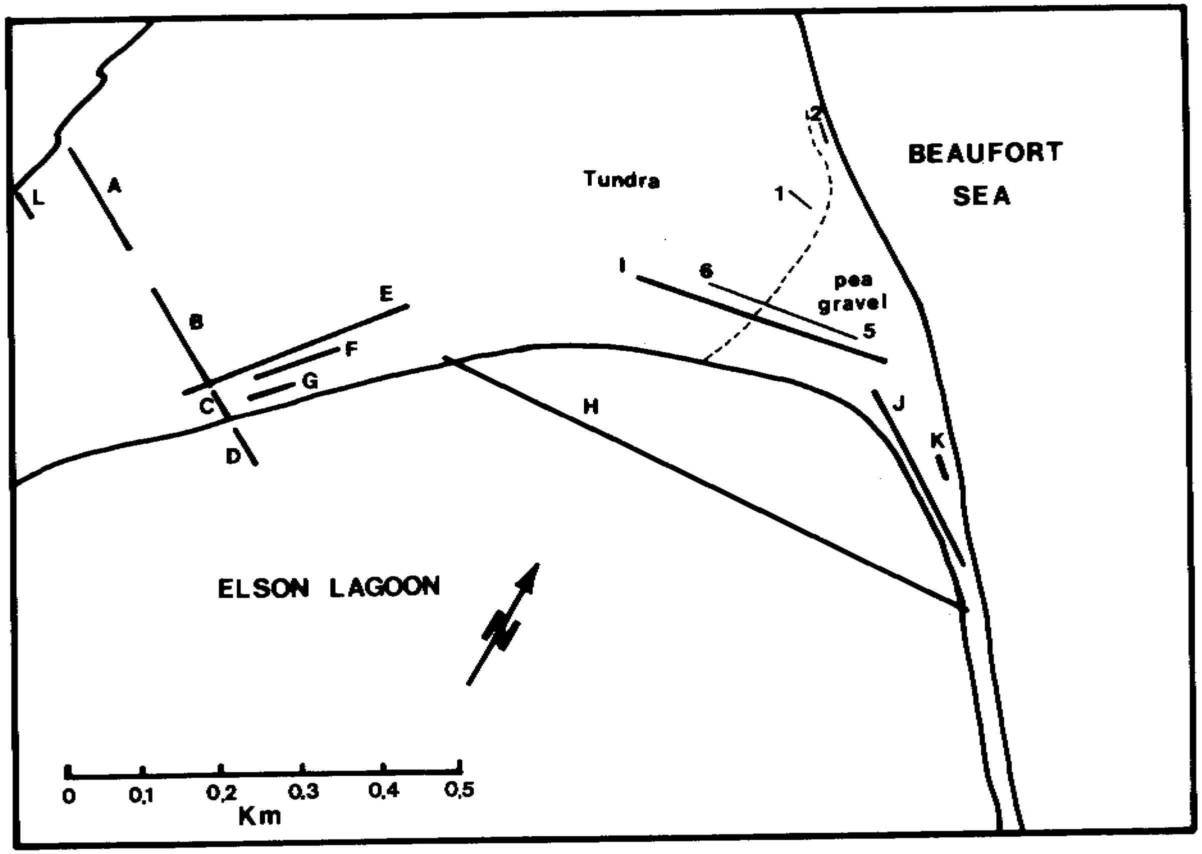


Figure 2. Area A from Figure 1 showing several refraction lines run using an explosive source (A through H plus J and K) and lines run using a hammer seismograph (1, 2, I and 5-6). The tundra/pea gravel boundary shown dashed was observed to be the boundary between frozen subsurface material and non-frozen subsurface material. Seismic lines to the west of the dashed line consistantly indicated frozen material while lines to the east indicated non-frozen material. Maximum penetration depth of the refraction signals and hence minimum depth to hypothetical frozen material is a function of line length. Minimum depth for hypothetical frozen layer from line J is estimated to be 47 meters, while for line H it is estimated to be 160 meters.

a frozen layer did exist beneath the line, its depth would be at 160 m or greater beneath the lagoon.

Usually the line length used with the hammer seismograph was either 30 m or 60 m, which would produce a maximum penetration depth of 6.6 m or 13.2 m respectively. However, in all cases where ice-bonded material was found, it was at depths of less than 3 m and the average of all depths observed was 2 m. Thus, even the short lines run with the hammer seismograph are seen to be adequate for observation of near surface ice-bonded layers.

Since the depth of the normal active layer on land is a meter or less, and since no frozen layer with surface depths in excess of 3 m was observed on the Barrow spit or on Tapkaluk Island, it is concluded that if a frozen layer does exist in the areas where no high velocities were observed, it is probably considerably deeper than the penetration depth of the hammer seismograph equipment. It is believed that such a layer, at depths considerably in excess of 6 or 12 m would be associated with relict ice-bonded materials and not formed beneath the island as the result of heat extraction from the surface of the island. Later in this report, seismic work on the islands near Prudhoe Bay is discussed and in most cases no frozen layer was observed using the hammer seismograph. However, in instances where an ice-bonded layer is seen, it is within two meters of the surface of the island.

Line A-A' of Figure 1 was examined by Lewellen (1973) and temperatures ranging to -1.4°C were measured at depths of about 5 m. A marine seismic refraction line using an air gun source was run through the center of Elson Lagoon as shown by line 1 in Figure 1. No high velocities were observed. It is estimated that the penetration of the seismic signals was at least 20 m and perhaps 30 m or more. Thus, although the material temperature is considerably below 0°C, it is not ice bonded. These conclusions are in agreement with lines H and D of Figure 2.

Area B of Figure 1 is the site of refraction measurements using an explosive source and line length of 202 m. No high velocity layers were observed. The maximum penetration depth of the signal is estimated to be 44 m, a figure considerably in excess of what one would estimate for the thickness of the active layer. Temperature measured by Lewellen was -2.5°C at depths of 35 m. The presence of salt in the pore water is obviously the reason that the materials are not ice bonded. Presently the fraction of the pore water that is frozen is not known, but it is believed that even though the material is not ice bonded, it is ice bearing. This conclusion is in agreement with observations by the driller.

Cross Island

Figure 3 showing Cross Island, indicates the site of refraction studies during July of 1976. Eight lines were run on the island with a hammer enhancement seismograph. The longest was 58 m and the shortest was 28 m in length. Approximate locations with respect to the shore line are shown on the figure. The orientations, which were established with a compass, are approximate. A summary of the maximum velocities observed is presented in Table I along with an estimate of the depth of ice-bonded material where high velocities were observed.

In general, the lines near the grassy area produced high velocities indicative of ice-bonded materials while those farther away (lines 5 through 8) produced lower velocities. Only line 6 with a velocity of 2357 ms^{-1} produced a velocity that might be attributed to ice-bearing sandy gravels that are not ice bonded. Thus these materials may be partially frozen. Similar to the islands and spits near Barrow, vegetation is associated with ice-bonded materials and nonvegetated areas considerably removed are found not to be ice bonded. For the

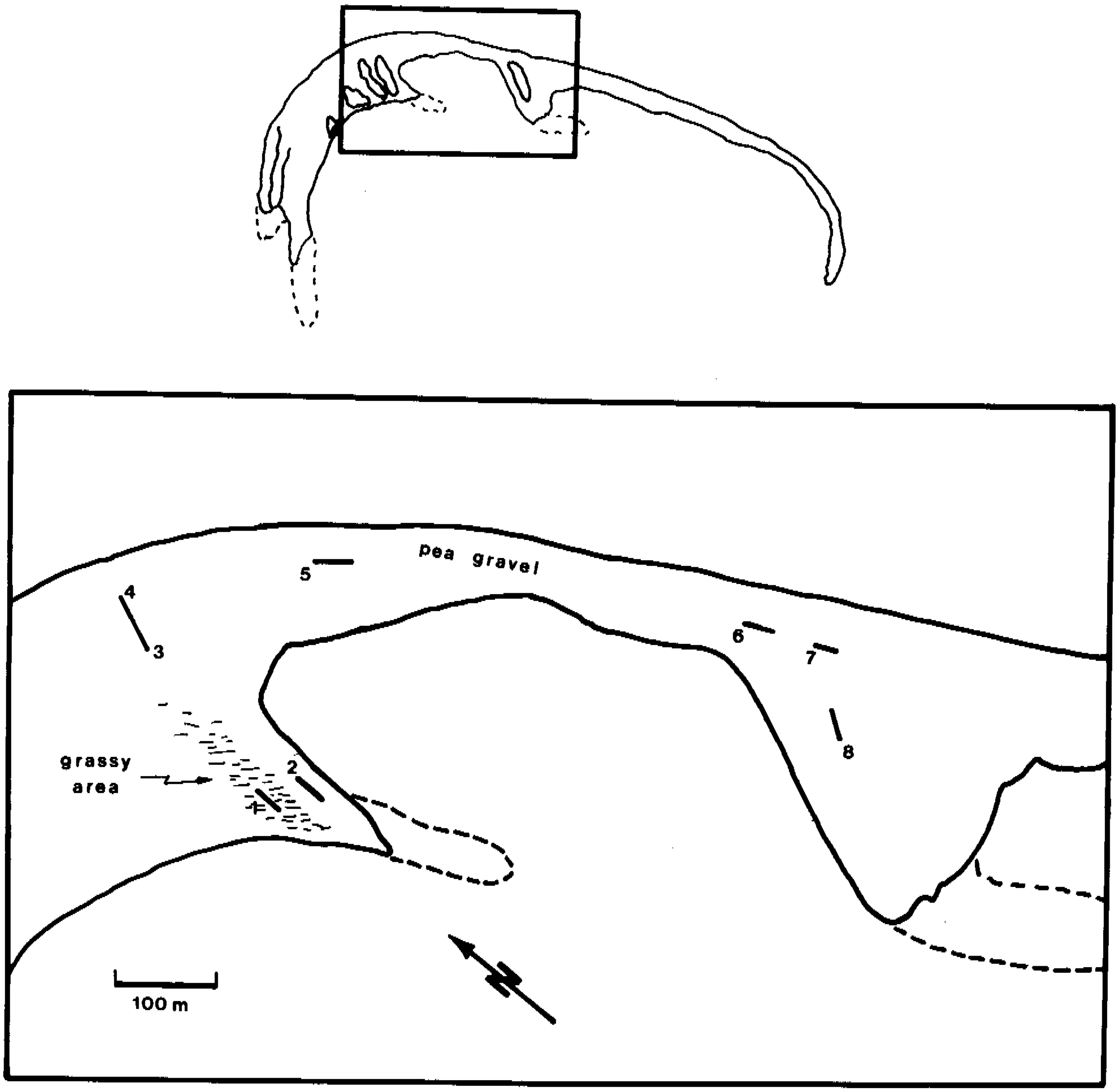


Figure 3. Location of Cross Island refraction work. All lines were run with a hammer enhancement seismograph. Lines 1 through 4 displayed high velocities ($3000\ ms^{-1}$) while velocities measured for lines 5 through 8 were $2500\ ms^{-1}$ or less.

TABLE I

Results of Cross Island Refraction Studies

Line	Maximum Velocity ms^{-1}	Depth to Maximum Velocity Layer
1	3103	1.3
2	3191	2.0
3	3333	2.0
4	3659	1.9
5	2121	1.3
6	2357	0.9
7	2142	1.2
8	1979	1.1

reasons discussed in an earlier section, it is believed that the areas where no ice bonded layer was seen are probably not bonded to depths considerably in excess of the 6 to 12 m penetration depth of the hammer seismograph.

Barnes and Reimnitz (1974) discussed the rate of movement of the northeast shore of Cross Island. Their measurements indicate an average retreat of 6 to 7 m per year. Under such a movement pattern, the portions of the island near lines 3 and 4 will be "older" than portions near lines 1 and 2. Assuming a constant width (which is not true since this portion of island appears to be growing narrower over the last 25 years) we can estimate an age for the materials near lines 3 and 4. Given the island width of approximately 350 m, we estimate an age of about 50 to 58 years. The remains of a cabin estimated to be 30 years old are located approximately 130 m from the present advancing shore line. Using the present retreat rate for the shorelines, the material surrounding the cabin will be about 22 years older when it is on the edge of the island. The total time (52 years) for the cabin to move across the island is a minimum age estimate since the cabin was probably not constructed on the extreme southeast shore of the island. Thus, the growth period for the ice bonded layers after their construction is in excess of 50 years on the wide portion of the island. The narrow portion of the island between lines 5 and 6 may have a maximum age of 20 years or less. This area is not underlain by an ice-bonded layer.

Reindeer Island

Seismic refraction and reflection measurements were conducted with a hammer seismograph on Reindeer Island within about 5 m of the Humble Well casing (Reimnitz and Barnes, 1974). Humble reported a 20 m thick permafrost layer near this casing. Three refraction lines were run with a total length of 70 m and no ice-bonded layers were observed. The highest velocity observed was 1901 ms^{-1} which was observed at a depth of 12 m beneath the surface of the island. These observations appear to conflict with previously reported permafrost conditions which indicated permafrost from the surface of the island to a depth of 20 m. Using the penetration factor of 0.22, we estimate a penetration depth of just over 15 m for the 70 m line.

In addition to the refraction lines on Reindeer Island, a reflection measurement was attempted in an effort to detect the lower boundary of the 20 m thick permafrost layer reported earlier. Moveout corrections were calculated for a 20 m reflection depth and reflection data were taken over a 40 m line, but no reflectors were identified. We conclude that either there is no boundary between an ice-bonded layer and non-ice bonded materials, or, if there is a boundary, it is sufficiently diffuse so as to provide poor reflection.

Refraction Studies, Prudhoe Bay

Several air gun refraction lines made in Purdhoe Bay are shown in Figure 4 and identified with letter A-A', B-B', etc. The line A-A' is adjacent to the drill

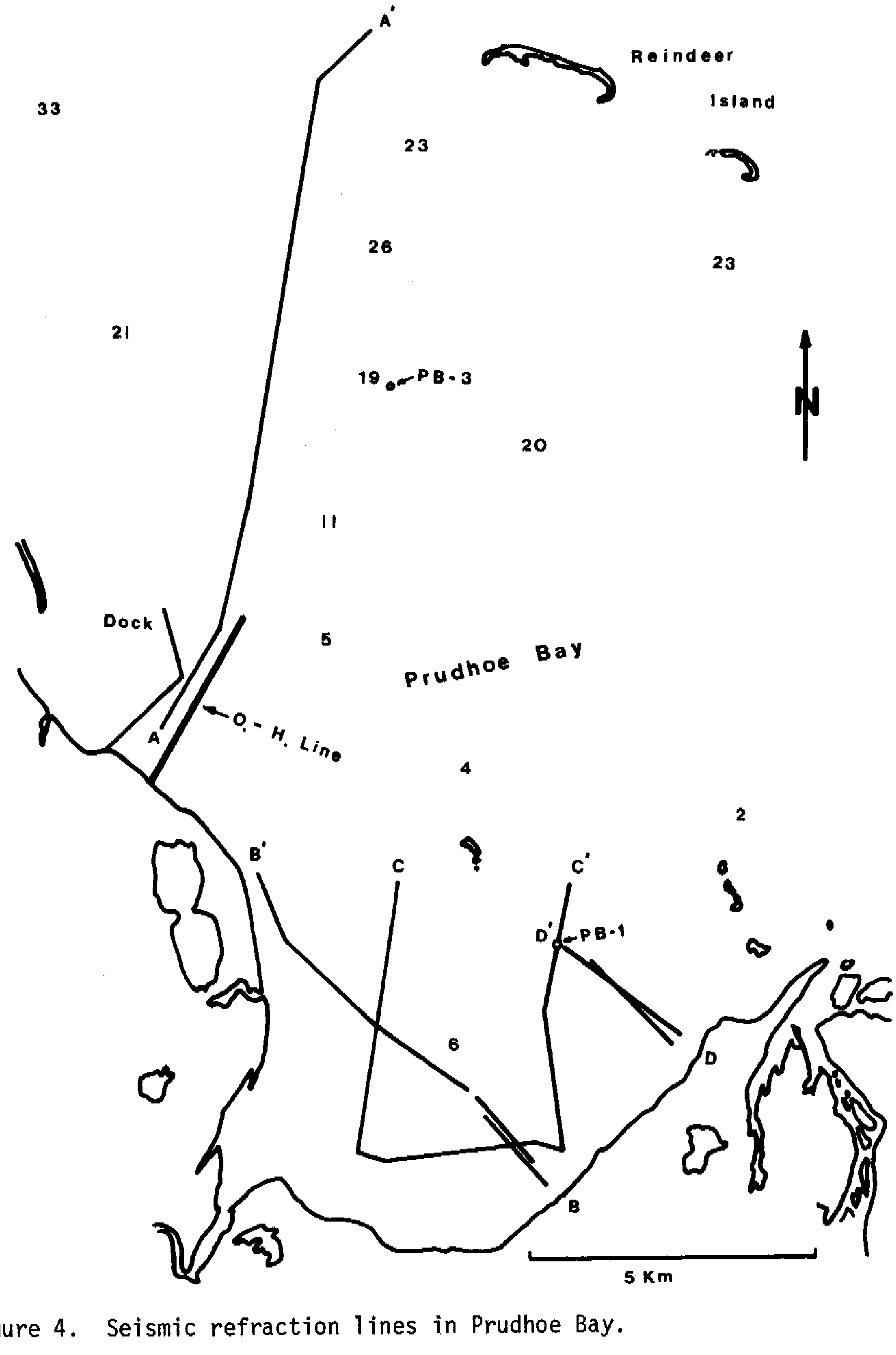


Figure 4. Seismic refraction lines in Prudhoe Bay.

line of Osterkamp and Harrison (1976) which has subsequently been extended by USACRREL/USGS (Sellmann et al., 1976) with drill holes PB-3 and PB-2.

Line A-A'

Figure 5 is a section through line A-A' starting at the northeast shore of Prudhoe Bay and extending 14 km to a point west of Reindeer Island. The shoal seen in the figure is a bottom feature which extends from the island. Drill holes have been indicated on the figure as vertical lines extending downward from the sea surface. Also, a combination of seismic refraction and reflection lines have been plotted. In the first 3.3 km of the line (the extent of the Osterkamp-Harrison drill line), there is good correlation between the refraction points, the drilling points, and reflection information scaled from the refraction data.

A variety of evidence about the upper boundary of the bonded permafrost has been suggested on the figure by connecting the air gun refraction and reflection points with the drilling information of Osterkamp and Harrison. Their probing data indicated a hard boundary as did the refraction data although the latter indicated a rough surface with local slopes up to 11 or 12° in some places. The reflection data was not of the continuous profile type but was obtained from air gun shots spaced approximately 0.3 km apart. Each shot did not provide good reflection data so the horizontal spacing of the reflection points is generally greater than 0.3 km. This behavior suggests an irregular ill-defined and in places diffuse surface. It is possible that local material type variation coupled with salinity variations and relict ice contribute to such a boundary.

Line C-C'

During the summer of 1976, refraction lines were run in Prudhoe Bay to the southernmost edge of the ice. Line C-C', a 13 km long U-shaped vessel track, is shown in Figure 4. Although the air gun system was more powerful than that used for line A-A' by a factor of three, no high velocity refractors were observed nor

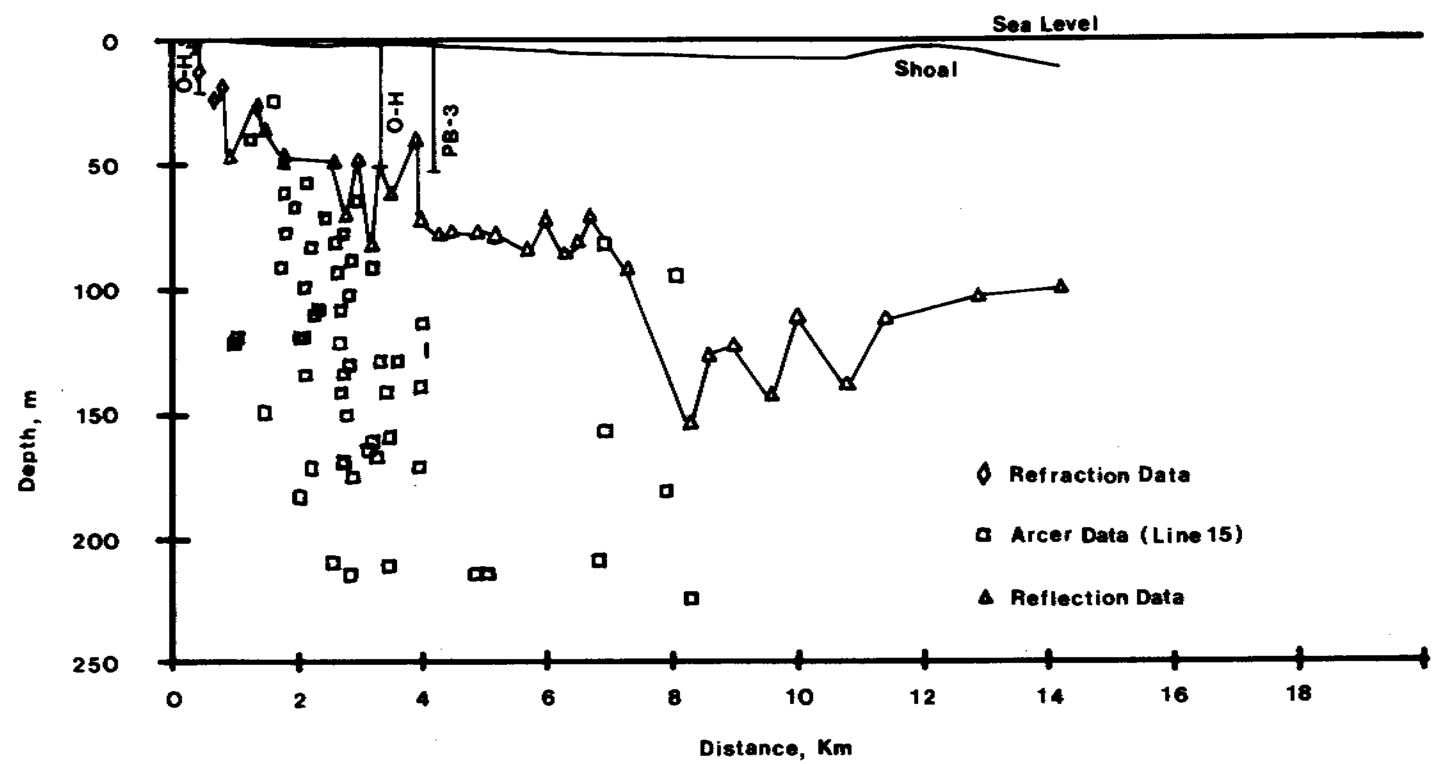


Figure 5. Vertical section through line A-A' of Figure 4

were reflection events seen on the refraction records. Particular care was exercised in examining the nearshore records from the southeast corner of the line but no ice-bonded material was observed.

Lines B-B' and D-D'

These two lines displayed high velocity refractors near shore. Figure 6 shows the lines and indicates by cross hatching the areas where ice-bonded materials were observed. The section through B-B' shown in the figure indicates the depth to the observed high velocity refractors along the line. On the easterly end of line C-C', the depth to the refractor observed was 13 to 14 m. No other refractors or reflectors were seen along these lines.

Data taken by the USGS in drill hole PB-1 indicate a very steep temperature gradient which suggests that Prudhoe Bay may be an old thaw lake. Dave Hopkins (personal communication) of the USGS has speculated that the shoals along the northern edge of Prudhoe Bay and the small islands may be used to estimate the former boundary of "Lake Prudhoe." His suggestion is shown in Figure 6 along with the 1.8 m (6 feet) depth contour. It appears that the bottom relief, the temperature data, sedimentation rates and the seismic data combine rather nicely to support the idea of Prudhoe Bay being a former thaw lake. The former lake is rather large compared to nearby lakes on land today, but it can be speculated that other such features (possibly smaller) exist along the Beaufort Sea coast. Since they may be associated with depressions or actual "windows" in the permafrost surface, it is possible that they may prove a useful feature in offshore construction activities.

Some drilling information is available along line B-B'. C.R. Knowles (personal communication) has reported on a channel and dock survey conducted for ARCO in 1969. The work involved drilling five holes on a line that roughly corresponds to line B-B'. Maximum depth of the holes was about 8 m and their

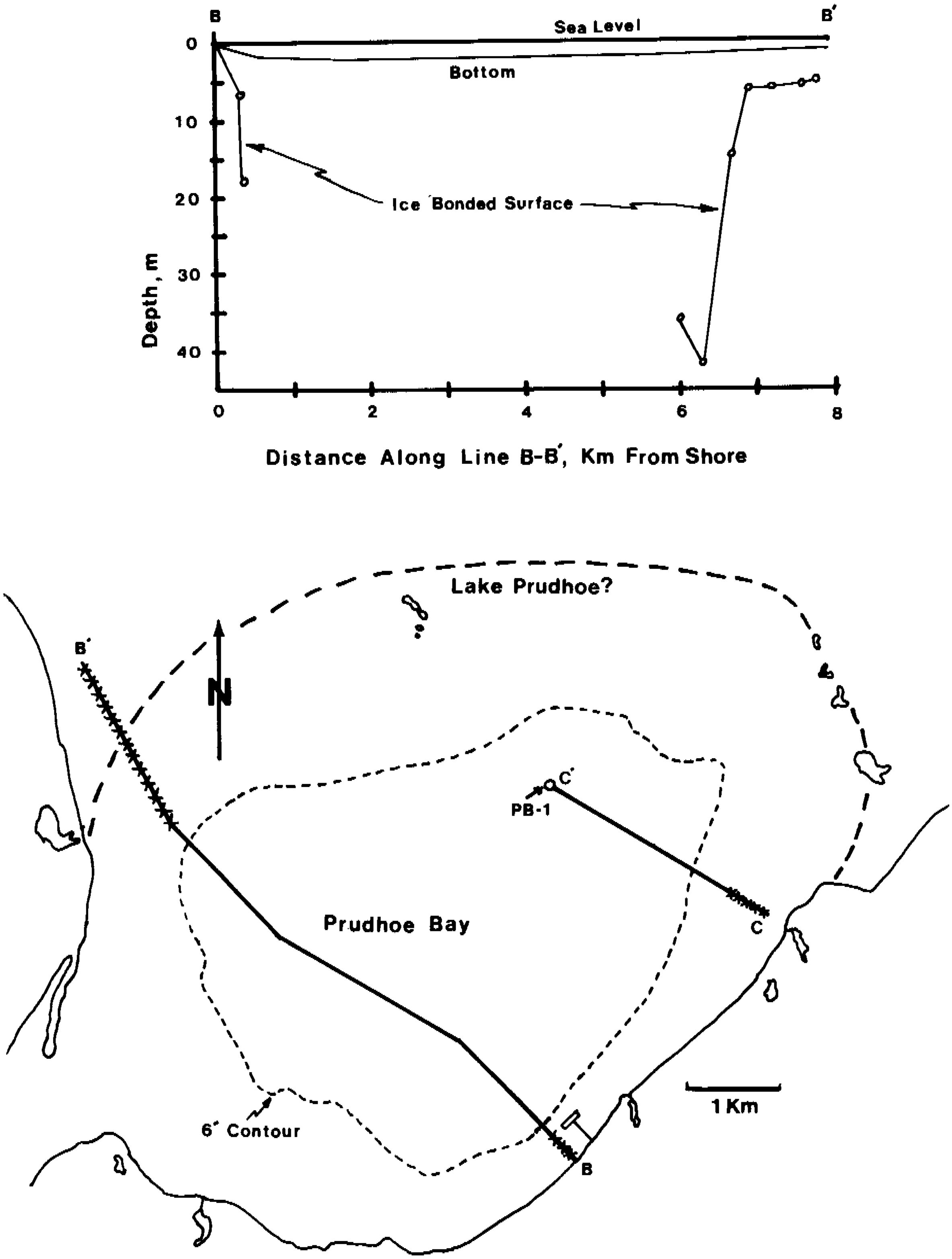


Figure 6 Refraction lines in the south end of Prudhoe Bay.

spacing was approximately 1.5 km. In each of the five holes, permafrost (described in the drill logs as frozen sandy gravel) was reported to be 5 to 6 meters beneath the ocean surface. These results are not in strict agreement with our seismic data, as shown in the top of Figure 6. Since it has been shown that the seismic apparatus used in Prudhoe Bay is capable of detecting ice-bonded material to depths of at least 40 meters, we conclude that, although the drill logs show frozen material, in fact the material is ice bearing and not ice bonded. This interpretation is in agreement with our observations on Tapkaluk Island and Reindeer Island.

Sparker Reflection Data

During the summer of 1971, the United State Department of the Interior Geological Survey (Reimnitz _et al._, 1972; Barnes _et al._, 1973) carried on a high-resolution seismic survey of the inner shelf of the Beaufort Sea using a low-power arcer system.

In the area covered from the Colville River to the Sagavanirktok River, the records show a large number of "point" reflectors which appear as hyperbolas. A typical record is shown in Figure 7. We analyzed forty-two kilometers of these records which contain hyperbolas ("hypes") in or near Prudhoe Bay. In all cases, depth estimates were made assuming a 2000 ms^{-1} velocity in the subbottom materials. This velocity was an average value obtained from the refraction records.

Figure 8 shows the locations of the lines analyzed which were selected to coincide with our seismic reflection and refraction data. The distance of each point reflector from the receiving hydrophone versus the distance along the line for each line is shown in Figure 5 and in Figures 9 through 14.

Because the hydrophones gather signals from a cone-shaped volume, the depths of the reflectors may be less than the distance displayed on the record (Figure 7).

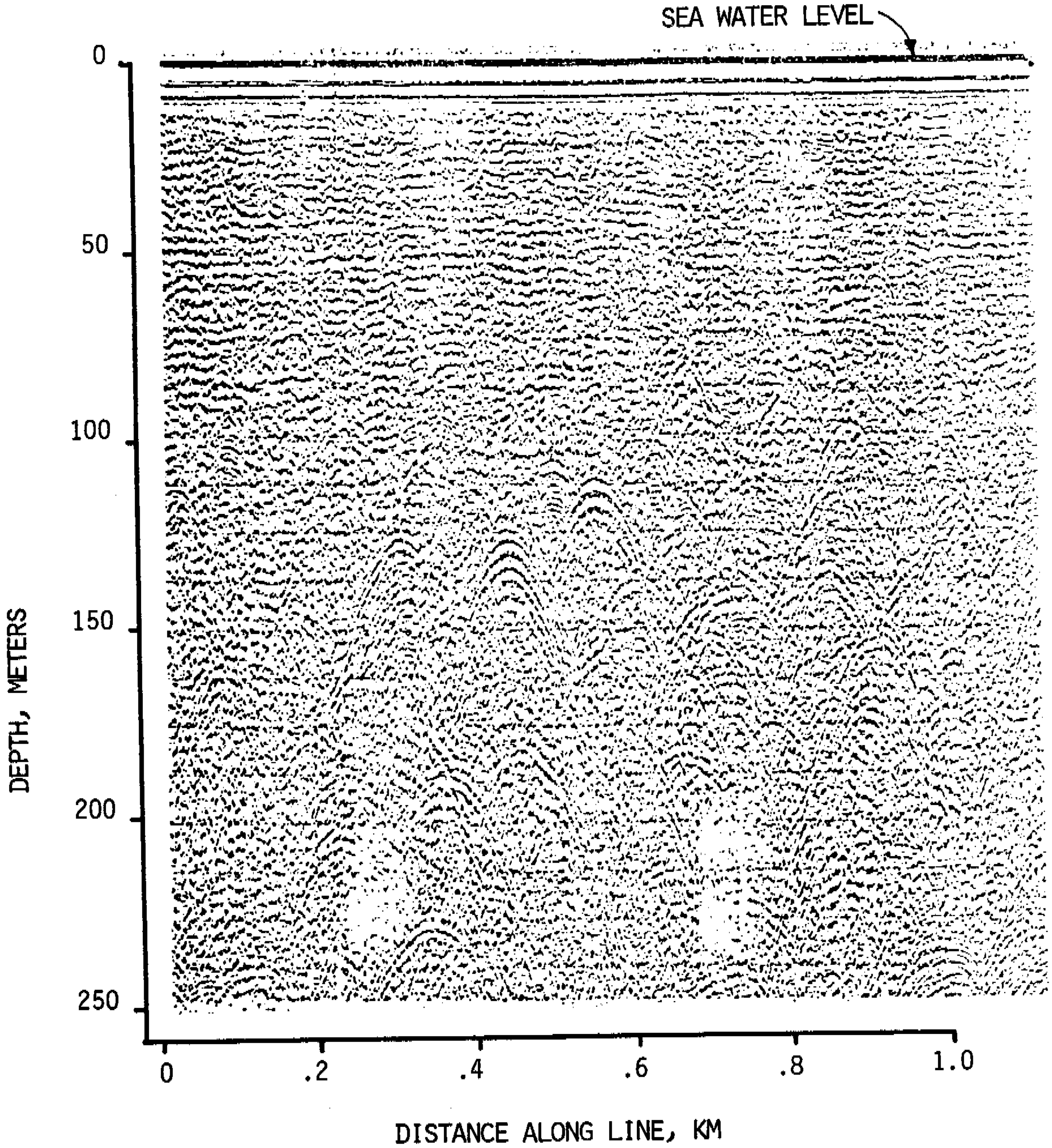


Figure 7. Typical arcer data showing the hyperbolas in the record caused by "point" reflectors.

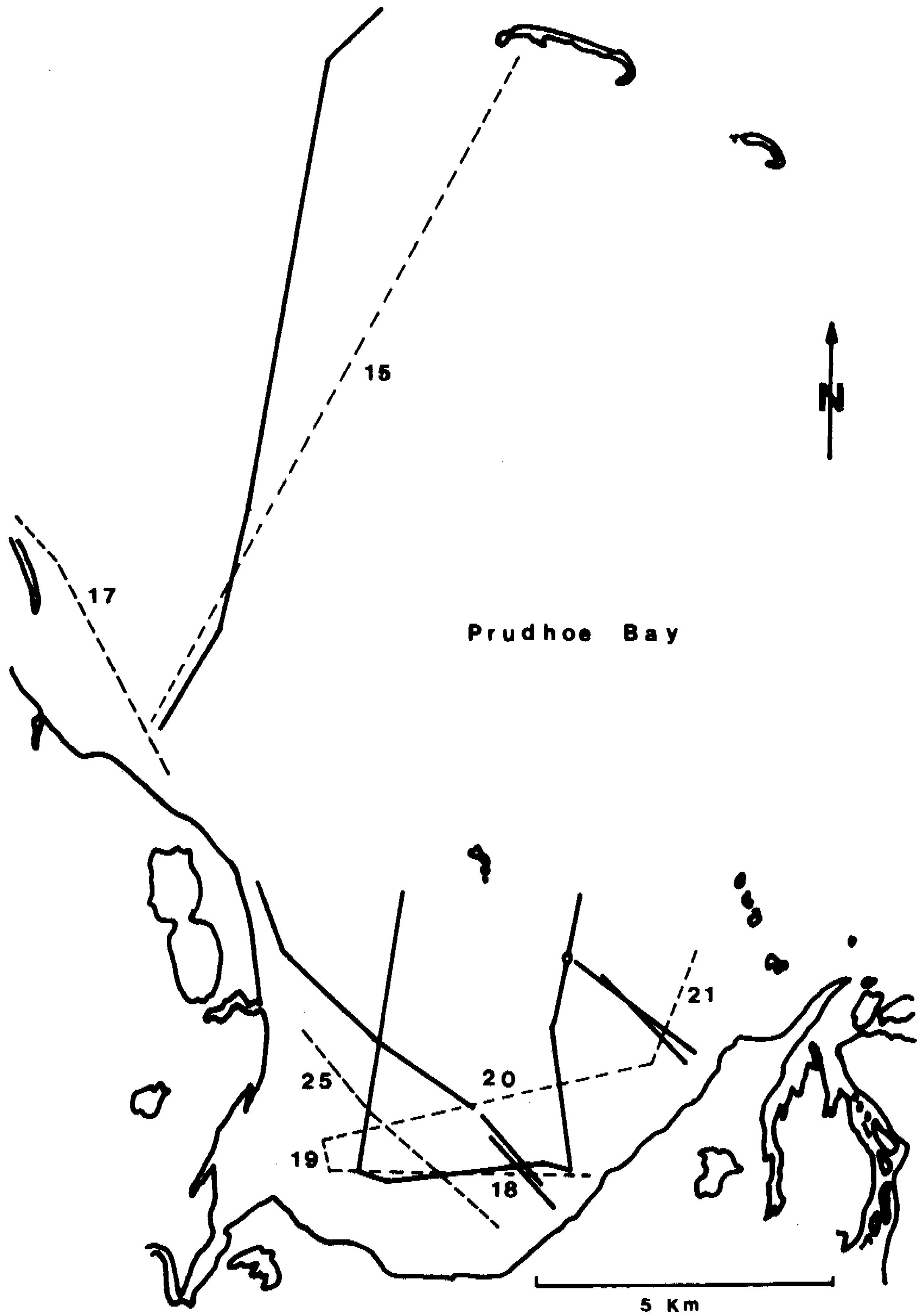


Figure 8. Refraction lines (solid) and arcer lines (dashed) in Prudhoe Bay.

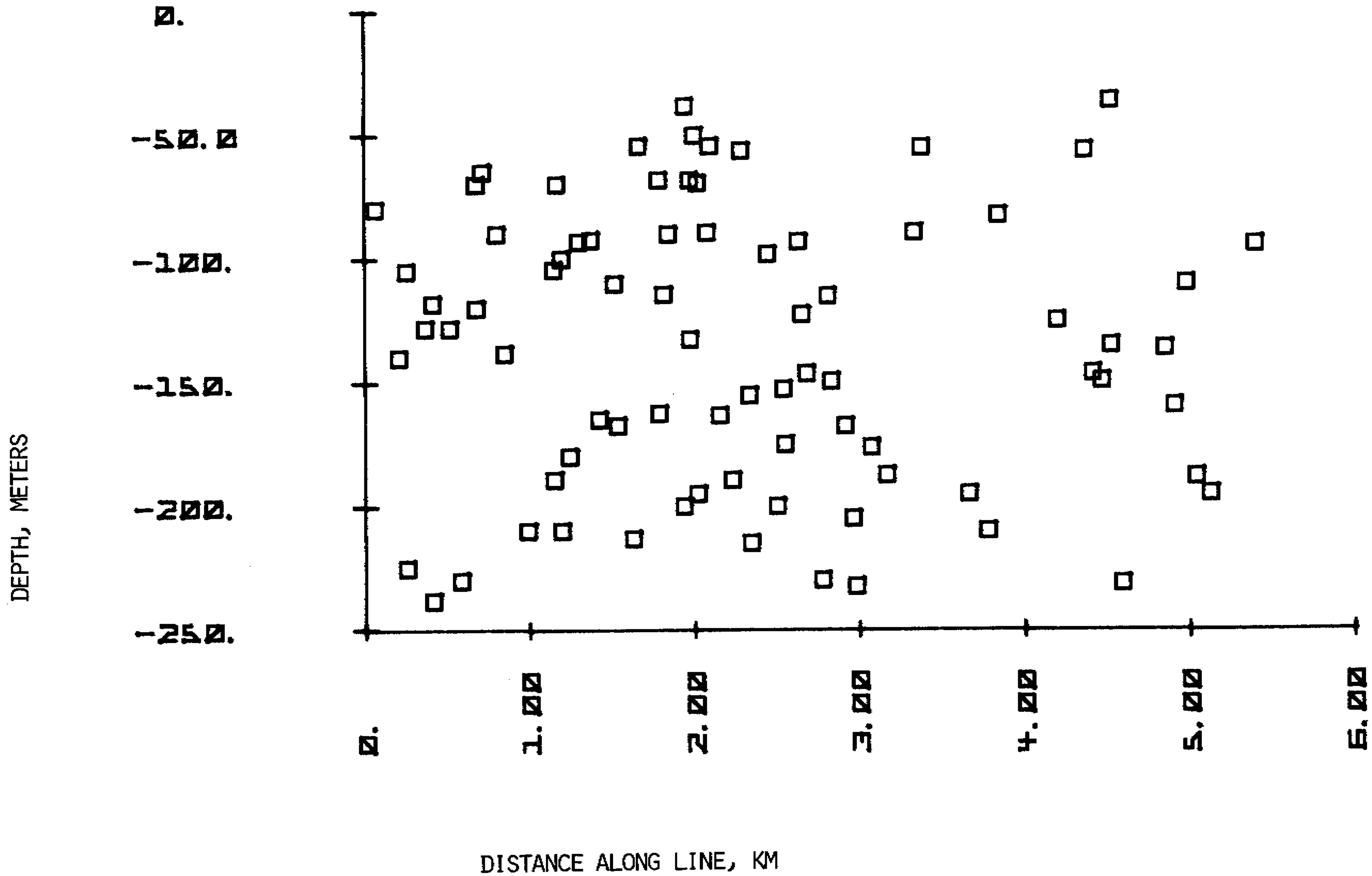
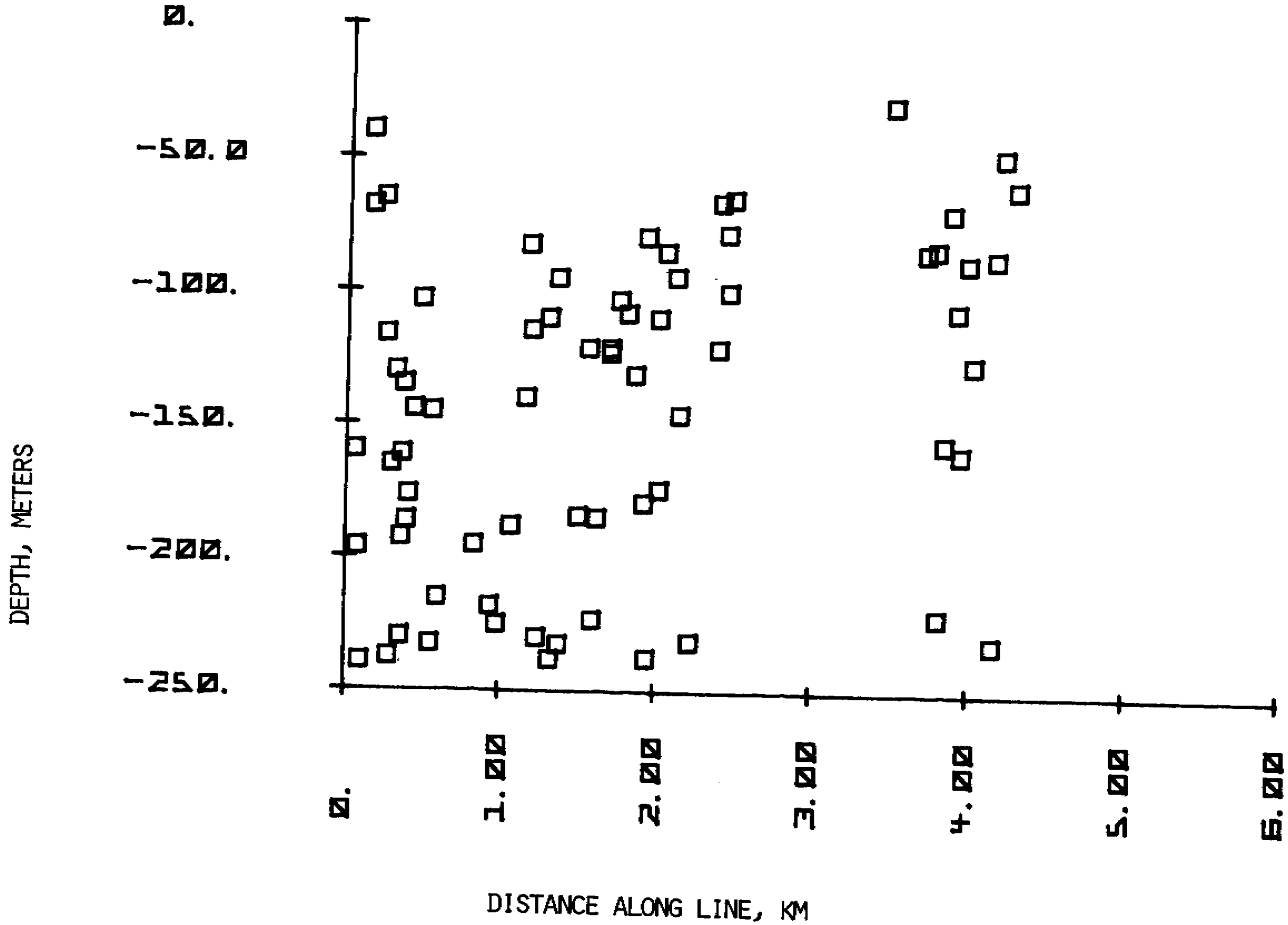
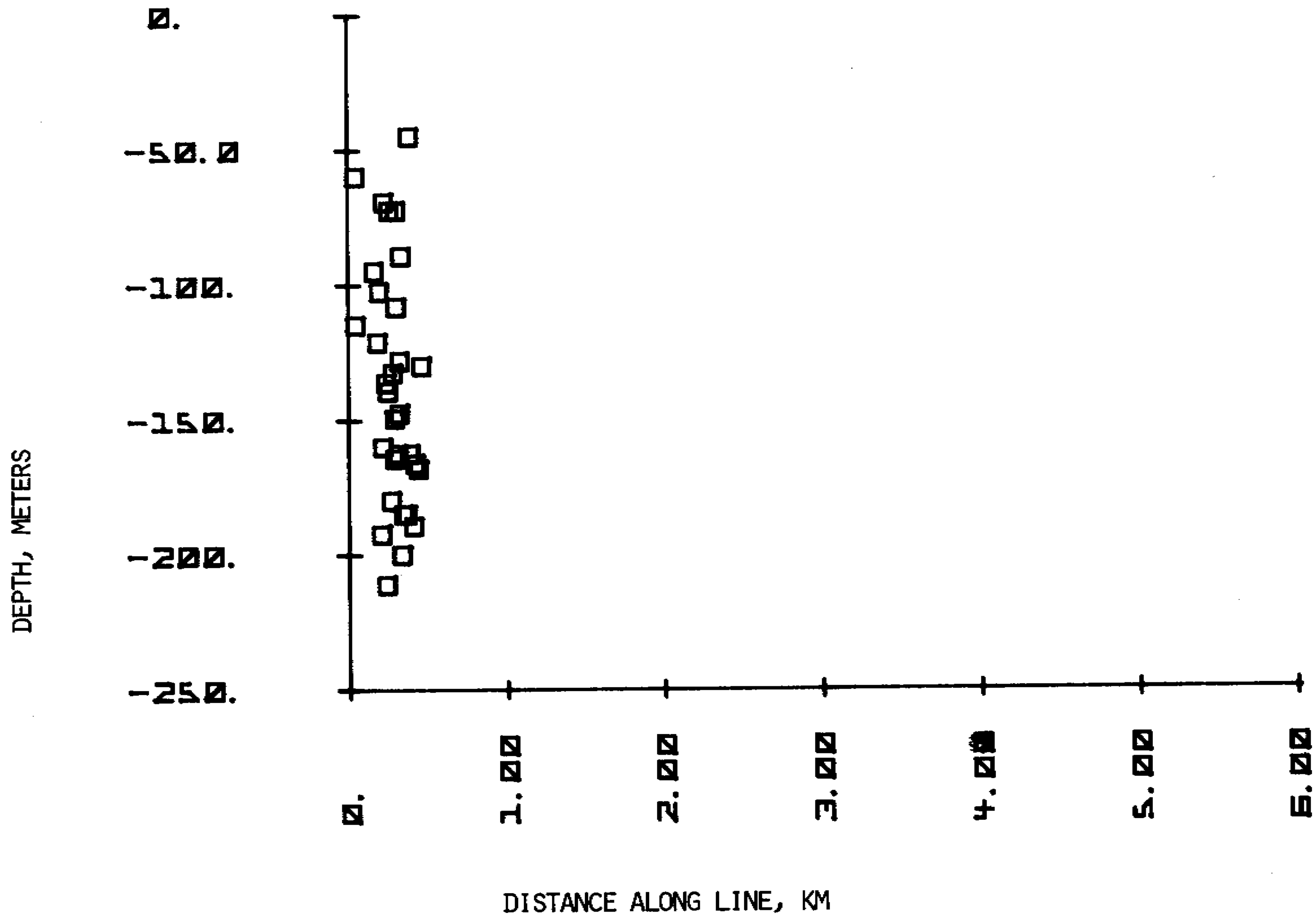


Figure 9. SPARKER REFLECTION LINE 17



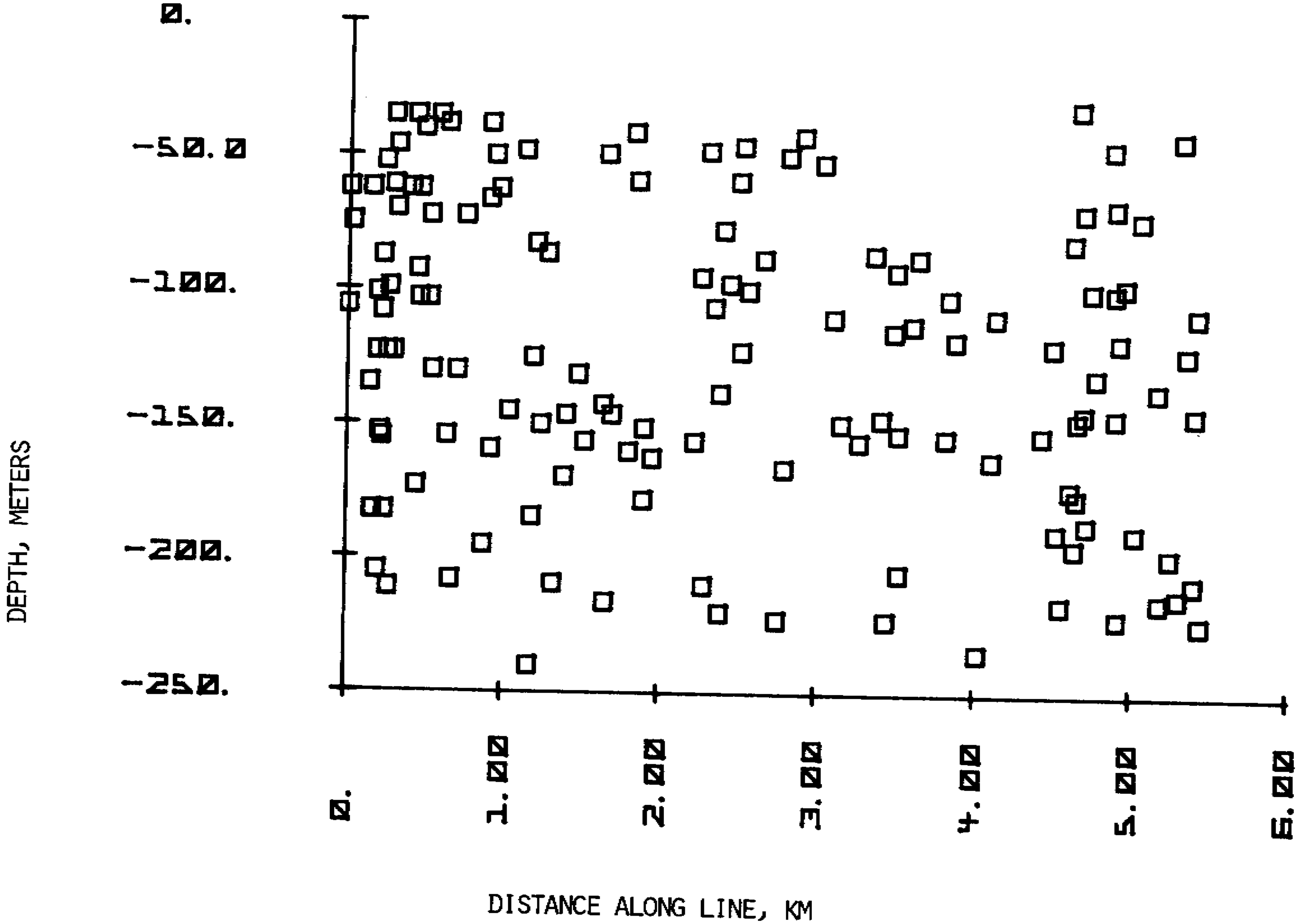
SPARKER REFLECTION LINE 18

Figure 10.



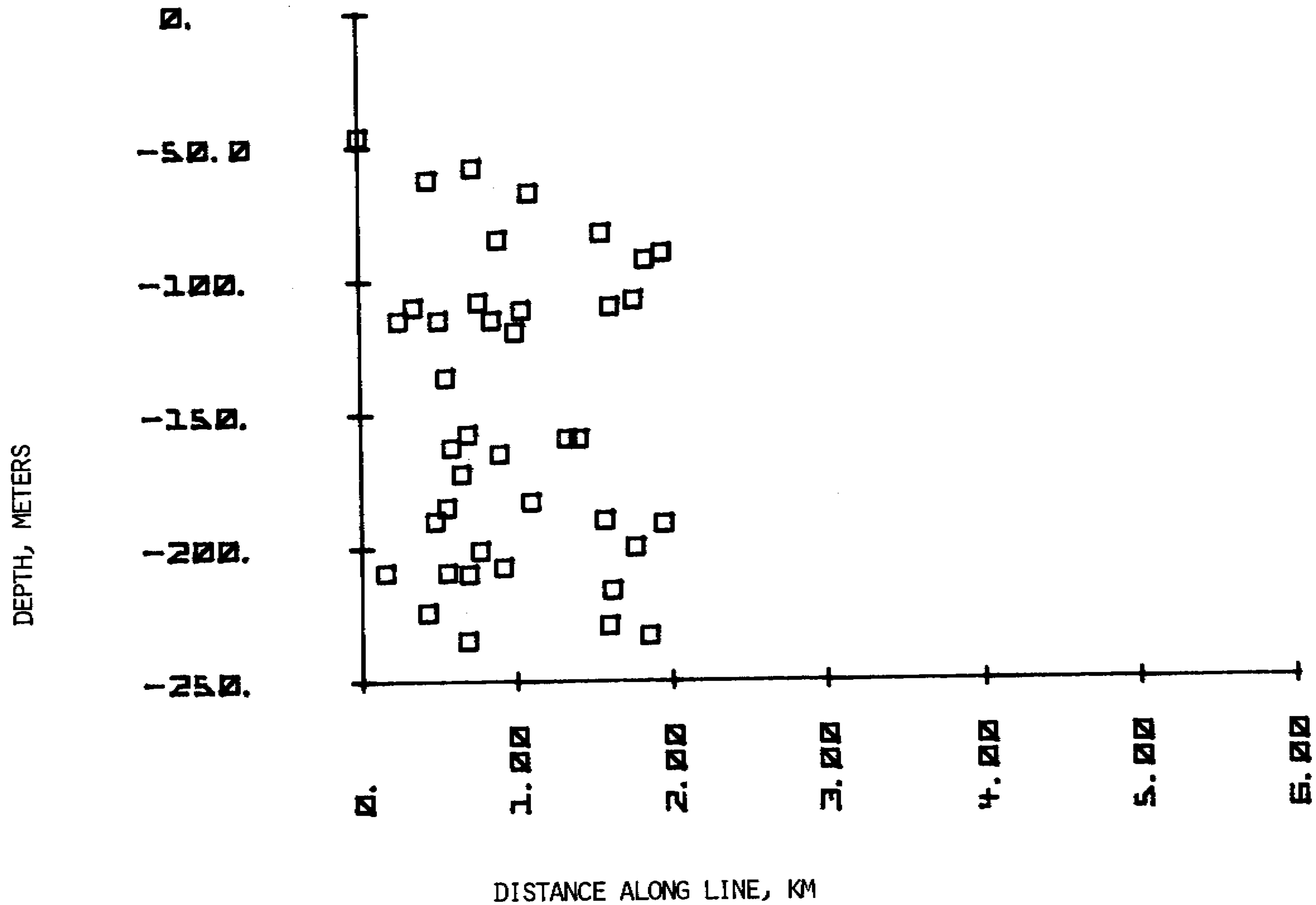
SPARKER REFLECTION LINE 19

Figure 11



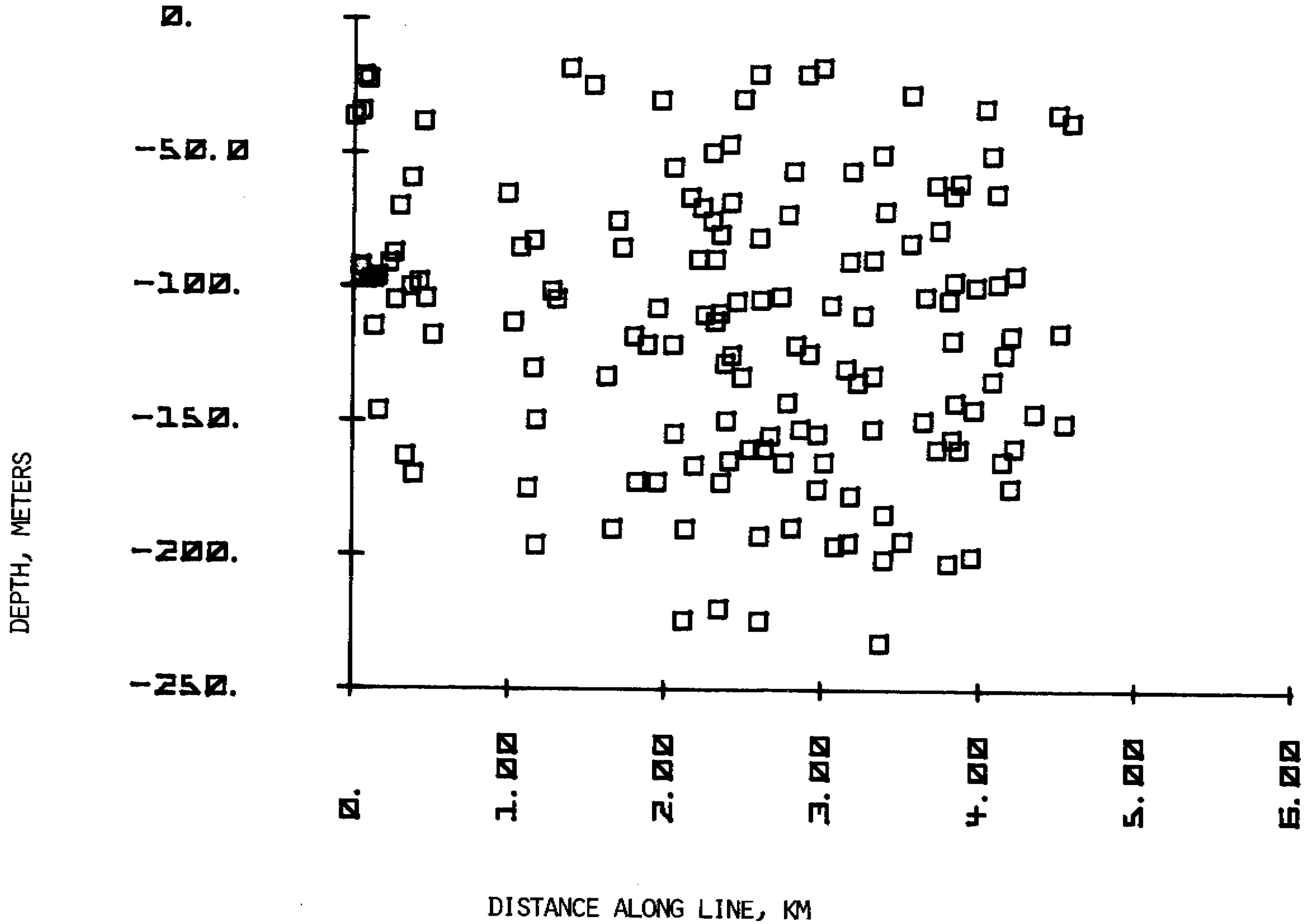
SPARKER REFLECTION LINE 20

Figure 12



SPARKER REFLECTION LINE 21

Figure 13



SPARKER REFLECTION LINE 25

Figure 14

The listening configuration is shown in Figure 15. The angle of the cone was determined to be ~90° as shown in Figure 15 by measuring the deepest and shallowest depth and the width of individual hyperbolas.

In order to estimate the distribution of the reflectors as a function of depth, the number of reflectors in each 24 foot interval from 0 ft to 250 ft was counted and normalized by the total line length. These totals are plotted in Figure 16. The number of reflectors is seen to increase with depth down to 125 m and then decrease with depth. If the density of reflectors were uniform, the number of reflectors seen would increase linearly with depth (shown by the sloping line in Figure 16). This behavior is the result of the larger volume sampled by the hydrophone with increasing distance.

Two possible explanations were considered in order to account for the decrease in the number of reflectors with depth. One possible explanation is a uniform density of reflectors to a certain depth, below which there are no reflectors. If this were the case, in order to fit the data, the maximum depth of the reflectors would be between 150 m and 175 m. A more reasonable explanation is to assume that the density of the reflectors decreases with depth. Figure 17 shows the effect of dividing the number of reflectors by the listening volume in each depth interval. The results show an increase in the density from the surface to about 50 m and then a linear decrease in the density. Since the reflectors are easily seen in the data to depths of 250 m, one must conclude from Figure 17 that the reflectors do not exist in very great numbers below 250 m. The average reflector density at all depths is 6.1×10^{2} per km^3. This figure can be used to estimate an average distance of 120 m between reflectors.

The actual size of the "point" reflectors can be estimated by considering the frequency spectrum of the arcer source and the band pass of the recorder. The band pass of the system was 430 to 905 Hz which corresponds to wavelengths

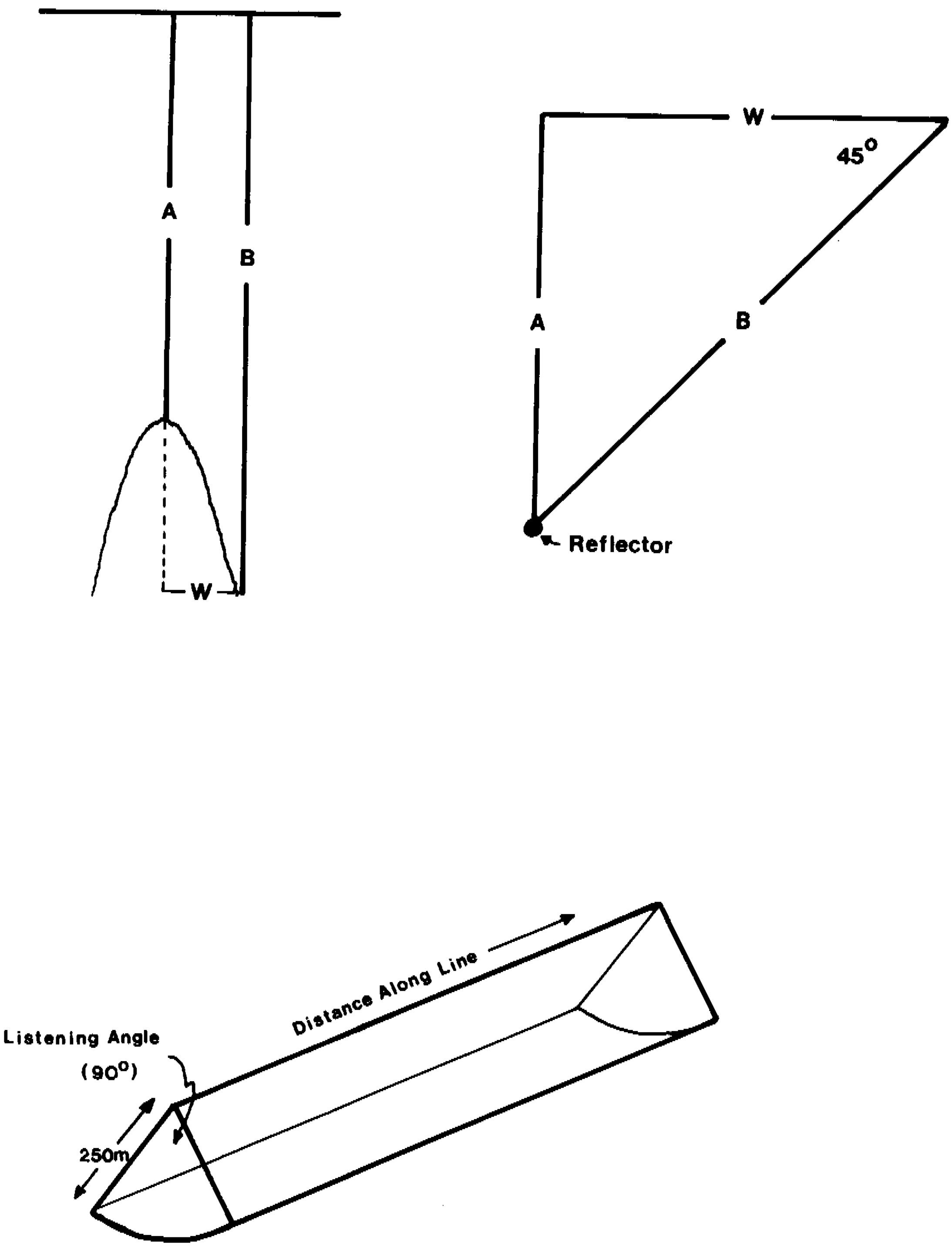


Figure 15. Observation geometry for point reflectors.

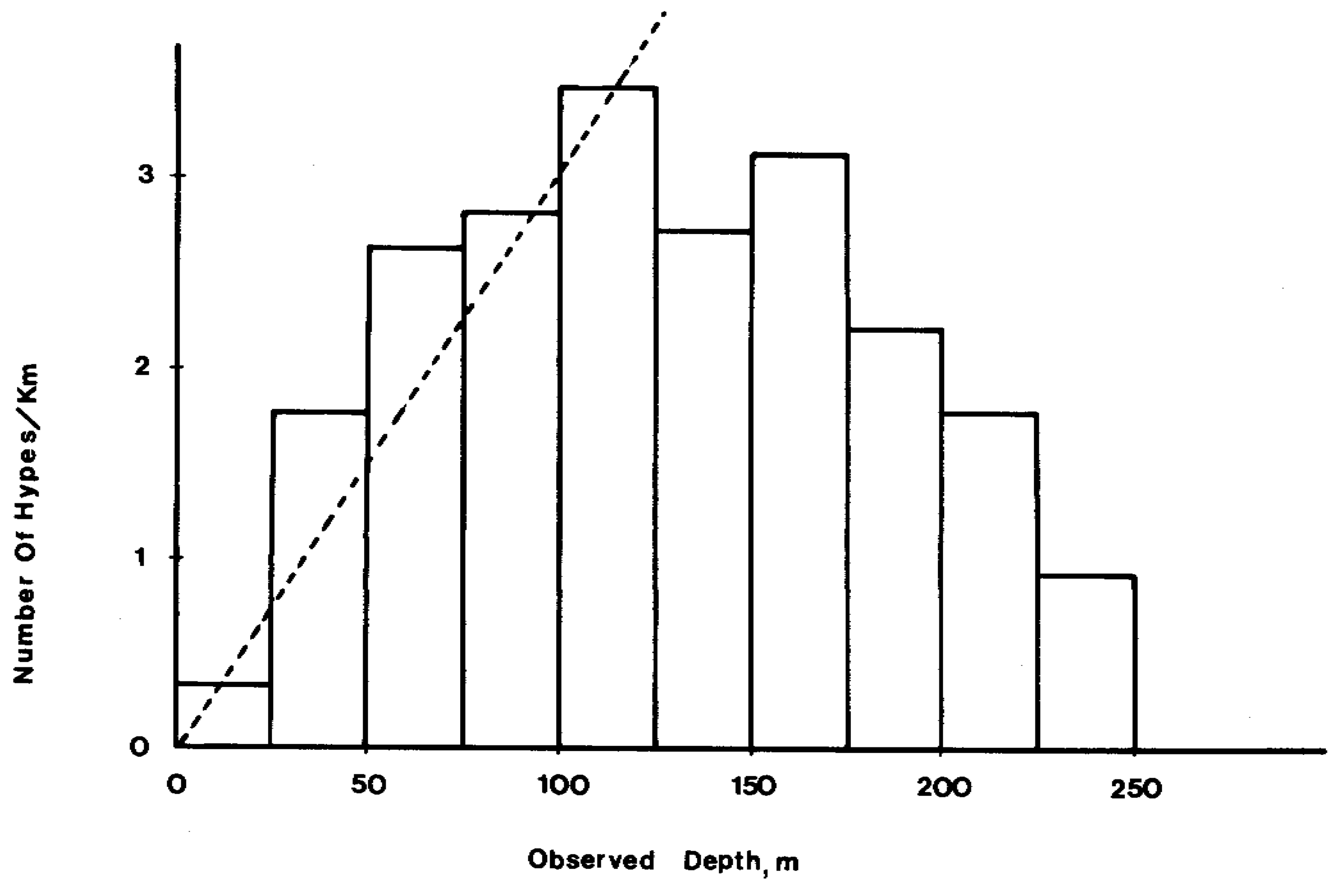
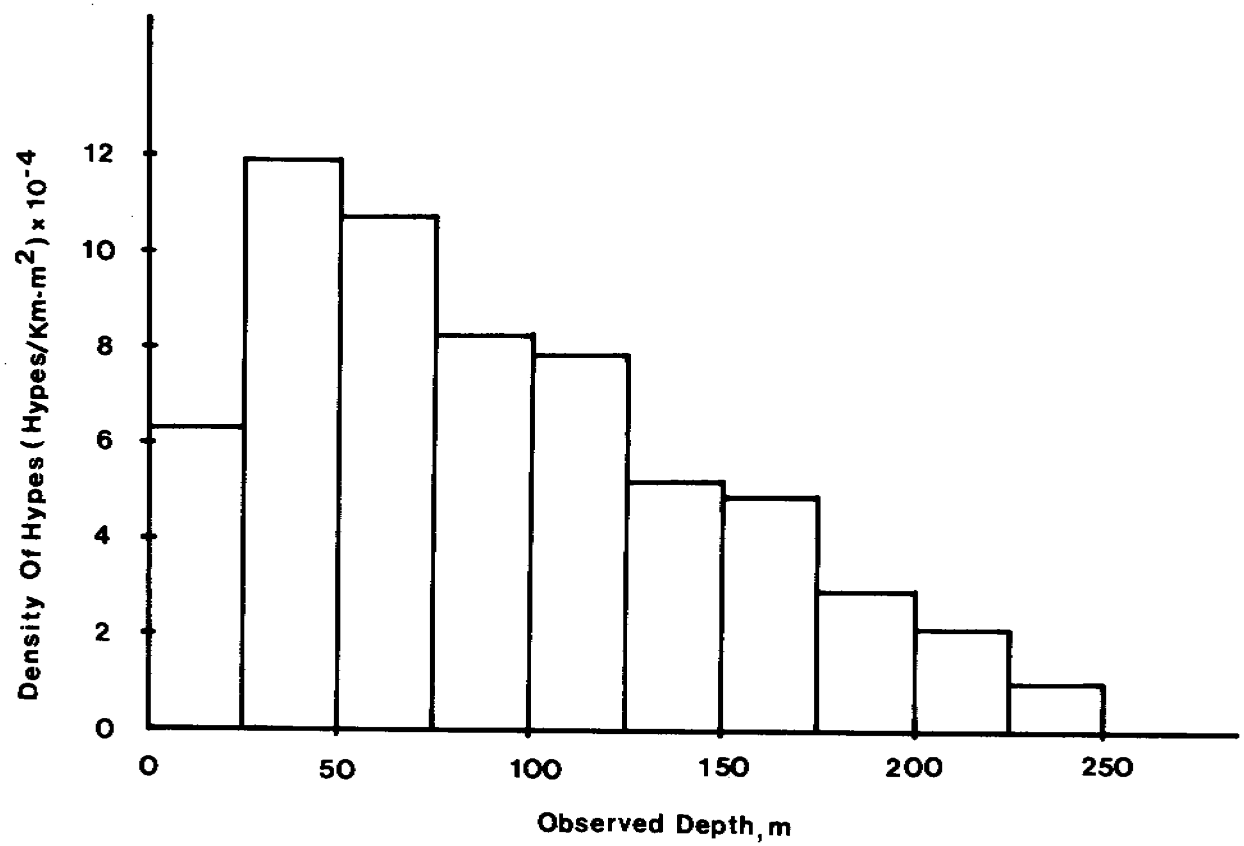


Figure 16



Density Of Hypes (Hypes/Km·m²) x 10⁻⁴
0
2
4
6
8
10
12
0
50
100
150
200
250
Observed Depth, m

Figure 17

from 2.2 to 4.7 m if the velocity of sound in the medium is assumed to be 2×10^3 m/sec. Objects with dimensions less than one wavelength would be poor reflectors and would most likely not be observed. On the other hand, objects which are 10 times larger than a wavelength, say 20 to 40 meters, would cause the hyperbolas to be flattened on the top, a feature not observed in the arcer data. Furthermore, objects of this size would be about equal in size to the wavelengths produced by the air gun sources (50 to 100 Hz), and thus should be seen in the air gun data. Neither situation is observed in the data, that is, the hyperbolas are not flattened nor are there point reflections seen in the refraction data.

In summary, the reflectors seen in the arcer data can be characterized as probably being between 2 and 20 m in dimension, principally located at depths from about 25 m down to 250 m with a maximum concentration near 50 meters and a density which decreases with depth below 50 m.

Initially it was thought that the "point" reflectors might give an indication of ice-bonded material. Presently, it is not known what the reflectors are although several possibilities have been suggested and a few of those discounted. The possibility that the reflectors are large erratics has been discounted on geological considerations (Reimnitz, 1972). Likewise, the possibility that they are an artifact caused by ice floating in the water near the vessel has been discounted.

Our early analysis indicated that the presence of the "point" reflectors might be controlled by the ice-bonded permafrost interface. Figure 5 shows a plot of the reflection and refraction data along Line A-A'. Plotted on the same graph are the arcer data from Line 15 of Figure 8. The point reflectors lie below the ice-bonded permafrost interface in almost all cases and the upper extent of the reflectors dips at about the same rate as the ice-bonded permafrost interface. Arcer Line 17 which is parallel to the coast line has a supporting behavior with hyperbolas observed only beneath the refraction interface. In no cases do the arcer data show a continuous boundary for the ice-bonded material. This strongly indicates that the actual surface of the ice-bonded layer is very rough and diffuse. The precise nature of the boundary is not yet known and should be investigated in more detail.

A number of arcer and refraction lines (see Figure 8) were also analyzed in Prudhoe Bay. Whereas the refraction lines indicated ice-bonded material only around the shoreline of the bay, the arcer lines showed "point" reflectors throughout the bay. If the bay is actually an old thaw lake as discussed earlier, then it seems unlikely that the "point" reflectors are massive ice inclusions.

Two other possibilities that have not been investigated in detail are that the reflectors are large brine inclusions or gas hydrates.

In summary, there seems to be no correlation between the "point" reflectors and an ice-bonded permafrost boundary. Although the possibility that the reflectors are massive ice inclusions has not been ruled out, it seems unlikely. Perhaps most important is the fact that the arcer data does not show a discrete boundary for the ice-bonded permafrost. This implies that the surface is rough and diffuse.

VIII. CONCLUSIONS

At this time in the project, it is possible to test several conclusions about offshore permafrost. Some of the conclusions are site specific, while others have more general implications. The nature and implications of the conclusions are discussed below.

A. The upper surface of the ice-bonded permafrost dips downward away from shore to depths of about 100 m at distances of approximately 15 to 20 km away from shore. This conclusion strictly applies only to Line A-A' of Figure 4, but in areas with similar shoreline history, similar soil properties and similar ice content in subsurface soils, it might be expected that Line A-A' is representative of the upper surface of the ice-bonded permafrost.

One major implication of such a surface is that bottom founded structures and buried pipelines will probably not be affected by offshore permafrost if they are sufficiently far from shore. Perhaps near the shore, it will be necessary to design hot oil pipelines supported by artificial causeways to bridge the shallow permafrost zone, but at greater distances from shore it may be possible to bury them. In all cases, the irregular and thermally fragile upper surface of the bonded permafrost warrants care in determining operational methods offshore.

B. Seismic reconnaissance on three barrier islands indicates that they are not completely underlain by bonded permafrost, but that some may be completely free of ice-bonded permafrost. Certainly this conclusion is dependent upon the history of the island; whether it is a fragment of a former shoreline or whether it is a constructional feature. Also, the width of an island, its migration rate and soil types are important.

From the standpoint of offshore petroleum development, the islands may be useful platforms for drilling purposes. Therefore the condition of the permafrost beneath them is important. Also, oil produced seaward of the islands will probably be brought to shore by buried pipelines which will perhaps cross under the islands. Again, whether or not the islands contain bonded permafrost will be an important consideration.

The fact that all offshore islands are not underlain by bonded permafrost provides an important distinction from the standpoint of their history and

and formation. A complete understanding of island growth and movement must include an understanding of their different permafrost characteristics.

C. Prudhoe Bay appears to be an old thaw lake and therefore presents a large dip or possibly a window in the surrounding bonded permafrost surface. This is site specific information, but it seems unlikely that there are not other old thaw lakes offshore along the Beaufort Sea coast. Knowledge of such sites could provide permafrost free locations for bottom founded structures or, if such locations are not desirable for a particular application, old thaw lakes could be avoided. Whatever their use, knowledge of their existence can be expected to affect offshore construction activities.

D. Several island sites have been studied where seismic velocity data and drilling data seemed not to agree. That is, drilling evidence indicated frozen material, but refraction velocities were not high. Our conclusion is that ice-bearing materials should be distinguished from ice-bonded materials. Brine inclusions depress the freezing point of a material and tend to spread the freezing point from a discrete temperature to a range of temperatures corresponding to various stages of freezing. Thus a material may have ice inclusions but may not be ice bonded and hence present a relatively low velocity compared to the totally bonded material. The distinctions between ice bearing and ice bonded is important from the standpoint of material properties. For example, an ice-bonded material may have a high resistance to shear stress, but the same material when not ice bonded may have little shear resistance.

E. The cause of the reflectors seen on sparker reflection records is not known at this time. Statistically they are most numerous at depths of 50 to 100 m. Several possible sources have been postulated.

F. High resolution continuous reflection data have consistently not shown an upper permafrost surface, although a surface has been observed by refraction techniques and drilling information indicates such a surface. If the averaging nature of the refraction technique and the discrete nature of the drilling technique are considered, one must conclude that the upper surface of the permafrost is diffuse and not smooth over distances on the order of meters.

IX. NEEDS FOR FURTHER STUDY

In order to fully understand offshore permafrost characteristics and their importance to offshore oil and gas development, additional work is required in several areas.

Aerial Distribution

As continued efforts are expended on the drill line from the new ARCO dock to and beyond Reindeer Island, it is desirable to continue seismic investigations in close support of that effort. Of particular interest are the variations in the permafrost surface in the lateral direction. Thus additional lines parallel to the existing seismic line to Reindeer Island and at right angles are needed. Also, the shape of the upper permafrost surface surrounding "Lake Prudhoe" will aid in determining the feasibility of exploiting such a feature in offshore development. In addition to this close support work, wide area coverage should be obtained. The most likely technique is probably the use of commercial geophysical data in a manner similar to Hunter (1976).

Island Studies

Further land seismic investigations on the offshore islands will facilitate an understanding of these important offshore features and can ensure their proper role in offshore exploration and development. Seismic studies on the islands, coupled with adjacent marine seismic investigations can produce information on island history and can indicate whether or not island permafrost is instrumental in island migration.

Hyperbolic Reflectors

The hyperbolic reflectors seen on arcer records are known to be widely distributed along the Alaskan Beaufort Sea coast. In order to learn more about them, several studies should be performed. More precise three dimensional locations can help to determine possible origins. Also, it is desirable to obtain a better determination of size and size distribution. Perhaps a "point" reflector can be located near an existing drill hole or, should one be located by seismic techniques, it may be possible to drill into it to answer the question.

Nature of the Permafrost Surface

Although drilling efforts have located the upper surface of the permafrost at discrete points and refraction methods have at some locations indicated such a surface, the nature of the interface is not well known. In some instances, drilling has indicated a surface, but refraction and reflection techniques do not indicate a surface. Further examination of the seismic returns from the upper boundary as a function of frequency are required. Such studies could provide good evidence of the nature of the upper boundary and indicate the boundary conditions for small scale thermal models.

X. SUMMARY OF 4TH QUARTER ACTIVITIES

A. Laboratory Activities

1. Field work: None conducted
2. Scientific party: John L. Morack and James C. Rogers participated in laboratory analyses and report writing.

3. Methods: Sparker reflection data provided by the USGS in Menlo Park, California, were analyzed and compared with seismic reflection and refraction data.

4. Sample localities: Figure 8 of the April, 1977, annual report indicates the location of the sparker lines analyzed.

5. Data analyzed: Approximately 52 kilometers of arcer reflection data were scaled and analyzed.

B. Problems Encountered

With limited boat time available, difficulty with ice was encountered during field work in the third week in July. In order to overcome this difficulty, boat time has been scheduled during mid-August.

C. Estimate of Funds Expended

Approximately $95,000 has been spent to date.

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ANNUAL REPORT

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BENTHOS-SEDIMENTARY SUBSTRATE INTERACTIONS

Dr. Charles M. Hoskin

Institute of Marine Science

University of Alaska

March 31, 1977

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FIGURE LIST

I. SUMMARY OF OBJECTIVES

This study will determine what relationship, if any, exists between the grain size characteristics of Bering Sea bottom sediment and the distribution and abundance of macrobenthos living in and on the sedimentary substrate.

II. INTRODUCTION

General Nature and Scope of Study

Grain size parameters will be correlated with abundance and species composition of the macrobenthos.

Specific Objectives

Correlations will be sought between weight percent gravel, sand, silt, clay and mud, mean size, standard deviation (= sorting) and grain size modes and abundance and species composition of the macrobenthos.

Relevance to Problems of Petroleum Development

Disturbance of interactions between macrobenthos and sediment may cause changes in the distribution and abundance of the benthos. Because the benthos is a part of the food web which man harvests at various levels, changes in the benthos may affect the richness of the harvest.

III. CURRENT STATE OF KNOWLEDGE

There are no data yet available to accomplish the objectives of this work. Grain size analyses for 66 stations are available, and of the 27 stations for which macrobenthos are available, only 9 have corresponding sediment data.

IV. STUDY AREA

Southern Bering Sea, between 54°-61°N. Lat., 158°-174°W. Long.

V. SOURCES, METHODS, RATIONALE OF DATA COLLECTION

No new samples have been collected in this reporting year. Samples now available were collected by van Veen grab and provided to me by Dr. Howard Feder and his co-workers.

VI. RESULTS

There are 9 stations having matching sediment and macrobenthos data (Fig. 1), from which the variation in grain size modes can be seen. Tabulation of macrobenthos species abundance from these stations has been done. No species is common to all 9 stations, and the data available are too sparse to warrant comment except that macrobenthos seems to be as variable as grain size modes. When macrobenthos data for the remaining 57 stations becomes available, correlations between sediments and benthos can be made.

VII. DISCUSSION

None

VIII. CONCLUSIONS

None

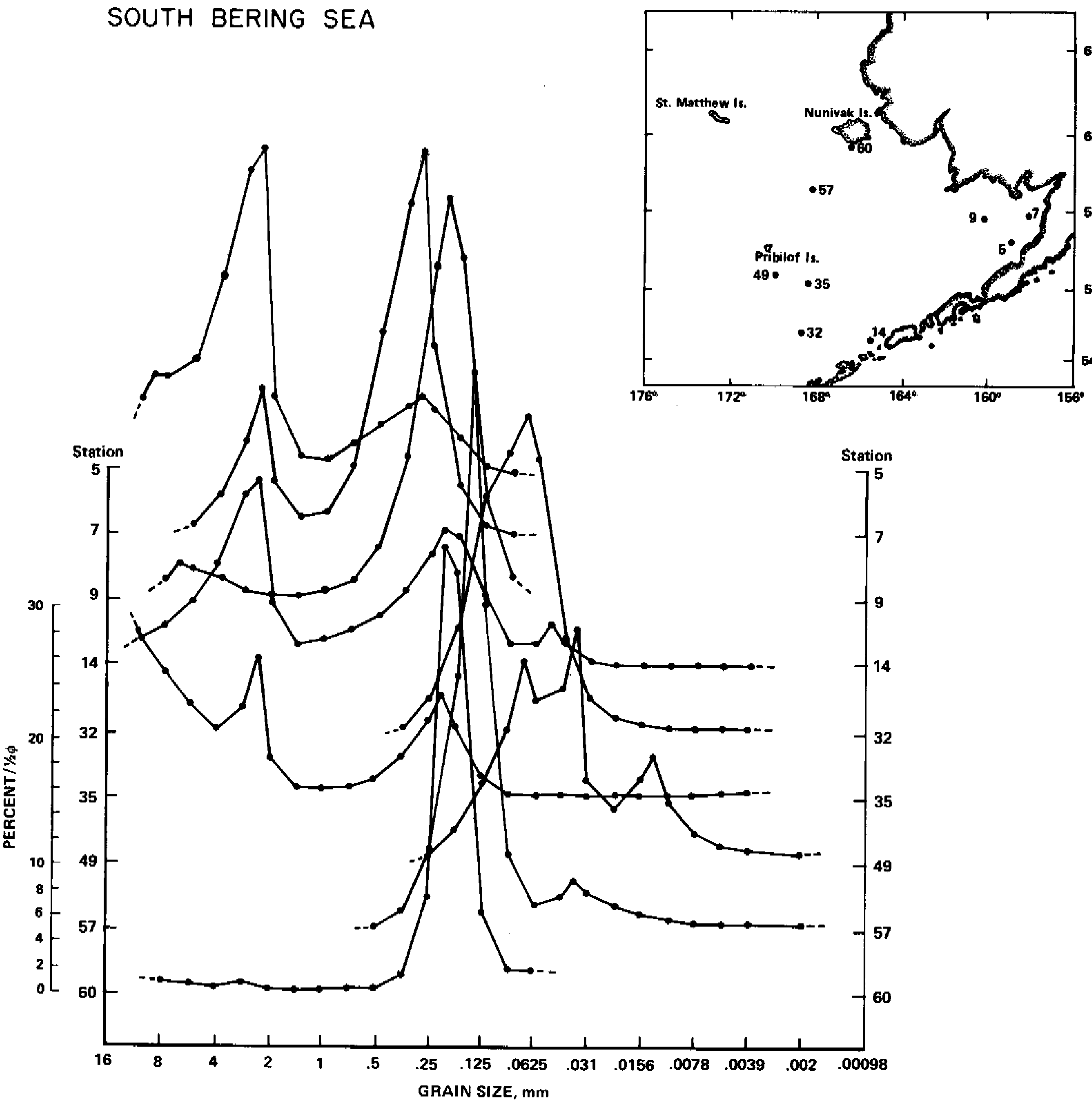

Figure 1. Size-frequency curves for 9 sediment samples from the southern Bering Sea having corresponding macrobenthos data. Large numbers at the ends of each curve are station numbers, and locations for these are shown in the inset. The y-axis zero intercept for each curve is located at the heavy bar following each station number.

IX. NEEDS FOR FURTHER STUDY

It seems likely that substrate characteristics in addition to grain size may be important influences for distribution and abundance of the macrobenthos. Bulk density, water content, shear strength, and degree of agglomeration (all interrelated) should be measured and evaluated with regard to the benthos data. This will require new samples. Mineral studies are in progress (see X).

Correlations will also be sought between grain size data and the results of the chemistry program of Dr. David Burrell for the Bering Sea samples.

X. SUMMARY OF FOURTH QUARTER OPERATIONS

Ship Activities

None

Laboratory Activities

Aliquots of the sand fraction (2.00 to 0.0625 mm) for each of the 66 sediment samples from the southern Bering Sea have been embedded in polyester resin and thin sections are being cut to aid mineral identification. This work will be part of the masters degree research of Ms. G. H. Kris Tommos in Geological Oceanography in the Institute of Marine Science, University of Alaska.

Samples have been made available for Norton Sound (32) and the Chukchi Sea (32) through Dr. David Burrell's chemistry program, and these will be analyzed for gravel, sand and mud contents.

Results

None

Problems Encountered

Unavailability of the macrobenthos data has slowed the progress of this study.

OCS COORDINATION OFFICE

University of Alaska

ENVIRONMENTAL DATA SUBMISSION SCHEDULE

DATE: March 31, 1977

CONTRACT NUMBER: 03-5-022-56   T/O NUMBER: 3   R.U. NUMBER: 291

PRINCIPAL INVESTIGATOR: Dr. C. M. Hoskin

Submission dates are estimated only and will be updated, if necessary, each quarter. Data batches refer to data as identified in the data management plan.

Cruise/Field Operation	Collection Dates		Estimated Submission Dates[1]		
	From	To	Batch 1		
Discoverer Leg I #808	5/15/75	5/30/75	Submitted		
Discoverer Leg II #808	6/2/75	6/19/75	Submitted		
Miller Freeman	8/16/75	10/20/75	Submitted		

All data for FY '76 have been submitted.

Note: [1] Data Management Plan has been approved by M. Pelto; we await approval by the Contract Officer.

ANNUAL PRINCIPAL INVESTIGATORS' REPORT
OCSEAP Research Unit #327

Shallow faulting, bottom instability, and movement of sediments in lower Cook Inlet and western Gulf of Alaska.

Principal Investigators: Monty A. Hampton
Arnold H. Bouma
U.S. Geological Survey, Menlo Park, California

I. Summary of objectives, conclusions and implications with respect to OCS oil and gas development.

Geological investigations in lower Cook Inlet and the western Gulf of Alaska (Kodiak Shelf) were conducted in 1976 aboard the R/V SEA SOUNDER during a period of 6 weeks. Seismic profiling and sampling of bottom sediments were the prime activities, but also limited side-scan sonar and bottom television observations were made.

The prime objectives were the identification of active faults and sediment instability as part of an assessment of environmental geologic hazards, and to obtain information about sediment types and their distribution.

Lower Cook Inlet revealed only a limited number of small surface faults and no slump phenomena were observed. The central part of the area, covering most of the nomination area, is covered by several different types and sizes of bedforms formed from sand-sized material primarily. Active motion of sand was observed that may impose certain difficulties when developing offshore structures. The distribution of the various types of bedforms, clay mineralogy studies and scanning electron microscopic analysis shed light on the movement of suspended material entering Kennedy Entrance and moving up in the inlet along the eastern shore, and becoming mixed with the outflowing water moving through the western half of lower Cook Inlet, the lack of deposition of fine particulate matter in the main body of the inlet, and areas of movement of bottom material.

The Kodiak Shelf, characterized physiographically by flat banks and transversely trending troughs, shows no deposition occurring on the banks, except in local depressions, and that the troughs act as sinks. Studies on volcanic ash from the 1912 Katmai eruption confirm these general lines. Stevenson Trough forms an exception as it contains mostly clean sand and even bedforms in its lower reaches. A relatively high-energy current regime and active sediment transport seem to occur.

The shelf break has a complicated nature and reveals that active seismicity influences the sediments in that area, causing large and small-sized submarine sliding.

Both the influence of seismicity, and the sweeping clean of the bank tops and concentrating finer materials in the troughs, pose certain difficulties in OCS oil and gas development. The relationship between physiography and sediment type shows the influence of the current regime and determines the distribution of benthic biota.

II. Introduction

A. General nature and scope of study: Assessment of the environmental geologic hazards, sediment types and sediment distribution of lower Cook Inlet and the Kodiak Shelf, western Gulf of Alaska.

B. Specific objectives: The identification of active surface faults, areas of sediment instability, the relationship of sediment types with regard to bottom morphology and circulation patterns, and types and movement of bedforms.

C. Relevance to problems of petroleum development: The above-mentioned objectives have direct relevance to problems of offshore petroleum development. Active faulting and sediment instability might endanger emplacement of offshore structures. The relationship between morphology and sediment characteristics will identify the presence of areas where erosion is more active than deposition and of areas that are sediment traps and consequently may act as sinks for nutrients as well as pollutants.

III. Current state of knowledge

Lower Cook Inlet: The results of the survey conducted during the summer of 1976 revealed that:

1) Very few surface faults were observed within the nomination area (see Appendix C in 1977 1st Quarter Report). Faults have been divided into three categories. One group contains the faults that are confined to Tertiary rocks. They offset the deformed rocks below a distinct angular unconformity without offsetting the unconformity itself. A second category contains the faults that offset Tertiary and Quaternary formations but do not show an offset on the sea floor. However, it has to be kept in mind that the local overburden of unconsolidated sand can destroy any surface expression which means that part of this category of faults can be active still. The third group of faults reveals an offset at the sea floor and is considered to be active.

None of the faults is of such a size that correlation between tracklines is possible, even when the 1976 survey by Petty-Ray Geophysical (contract from U.S. Geological Survey, Conservation Division, Anchorage) is added to our survey net.

2) In general the surface sediment distribution shows a direct inverse relationship of grain size to the width and depth of the lower Cook Inlet. Except for around the Barren Islands and Augustine, one encounters an overburden of gravelly sand where the water is shallower than 100 m (Bouma and Hampton, 1976; see also Tables 1 and 2). With a decrease of width and depth of lower Cook Inlet to the north, an increase of gravel occurs.

Several different types and sizes of bedforms were observed in lower Cook Inlet. Although our bottom television observations reveal very high rates of bottom movement of sand (up to 30 cm/sec) on crests of large sandwaves, no studies are known that deal with transport of these bedforms themselves. Identification of the different types of bedforms is presented by Bouma et al. (1977a,b). The latter is also inserted in the 1977 1st Quarter Report, Appendix D.

Results of grain-size analyses of some of the sand samples are listed in Appendix I, and preliminary interpretations of scanning electron microscope examinations, revealing the activity of grain movement, is presented in Appendix II. A plot of the most conspicuous bedforms - sand waves - is given in Figure 1. The data come from our 1976 summer work (Bouma and Hampton, 1976; Hampton and Bouma, 1976; Bouma et al., 1977 a,b) and from copies of side-scan sonar and high-resolution seismic records of the above-mentioned Petty-Ray Geophysical survey. These copies were not of such quality that smaller bedforms could be distinguished accurately.

3) Bathymetry was plotted by Petty-Ray Geophysical from their records. The result was presented on a 1:96,000 scale with 2 m contour intervals in water shallower than 100 m, and 5 m intervals for deeper water. We replotted this information on a 1:250,000 scale with 5 m contour intervals throughout. However, the original bathymetry has not been made public yet by the U.S. Geological Survey, Conservation Division and therefore cannot be included in this report.

4) Our seismic records, collected in 1976, were used to produce a thickness map of the upper unconsolidated sediments. The results were presented in Appendix B of the 1977 1st Quarter Report.

5) Clay mineralogy investigations by Jim Hein, U.S.G.S., clearly indicate the effects of water movement in lower Cook Inlet. Material from the eastern Gulf of Alaska enters Cook Inlet through Kennedy Entrance. The outflowing water, moving along the western side of lower Cook Inlet has a distinct clay mineral suite, different from the one entering Kennedy Entrance. Mixing of the northward flowing water mass with the southward moving one seems to occur north of Anchor Point. No data presently exists on the outflow through Shelikof Strait and the possibility of outflow through Stevenson Entrance. The present clay mineralogy data are given in Appendix III.

Kodiak Shelf: The results of the survey conducted during the summer of 1976 revealed that:

1) The shallow bedrock structure consists of a series of folds that apparently trend in a general northeast-southwest direction. However, they show enough deviation in trend and discontinuity that confident regional correlations of fold axes cannot be made at this time. Especially obvious are major anticlinal crests that occur near the shelf break (see 1976 6th Quarterly Report; Bouma and Hampton, 1976).

2) Surface and shallow subsurface faults occur over the Kodiak shelf but are most concentrated in a zone just off the southeast coast of the Kodiak islands and near the shelf break on Albatross Bank. Confident correlation between tracklines cannot yet be made (see 1976 6th Quarterly Report; Bouma and Hampton, 1976).

3) Unconformities occur at several places on the shelf. Most commonly the seismic profiling records show a relatively smooth unconformity surface separating folded and faulted bedrock below from nondeformed sediments above. Local thicknesses of up to 160 m of sediment have been measured above the unconformity, but over much of the area the unconsolidated sediments are missing and bedrock is exposed at the surface. An isopach map of the sediments above the unconformity is in preparation.

The seismic profiling records that extend beyond the shelf break, onto the continental slope, often show two or perhaps three unconformities.

4) Dart cores recovered from the areas where bedrock is exposed consist mostly of olive gray to gray siltstones and silty sandstones. Paleontologic age dating and petrologic studies of the bedrock samples are currently underway.

5) The textures of the surficial sediments of the Kodiak shelf show a relation to physiography. The broad, flat elevated banks are covered by sands that commonly contain coarser material up to boulder size but rarely contain significant quantities of silt and clay. The sediments of the troughs, on the other hand, typically are finer grained than those of the banks. Many sediments in Kiliuda, Chiniak, and Amatuli Troughs contain major portions of mud, whereas those in Stevenson Trough are mostly clean sands. Gravel and coarser material does occur locally in the troughs (See Tables 1 and 2, 1976, 6th Quarterly Report; Bouma and Hampton, 1976; and Appendix IV.)

6) Volcanic ash in surficial sediments also shows a relation to physiography and, combined with the textural data, has implications as to sediment dispersal on the Kodiak Shelf (Appendix IV). Ash contents are low to moderate on the flat, elevated portions of Albatross and Portlock Banks, suggesting that these are areas of winnowing of unconsolidated Pleistocene sediments. In local depressions on the banks, as well as in Kiliuda, Chiniak, and Amatuli Troughs, ash contents are high, suggesting that these areas are depositional sinks. Sediments in Stevenson Trough contain low to moderate amounts of ash and apparently is swept by relatively strong and consistent currents that do not affect other parts of the shelf. Apparently, insignificant quantities of modern terrigenous sediments are accumulating on the Kodiak Shelf, and the sedimentary environment is essentially one of reworking Pleistocene deposits.

7) At least two distinct populations of clay minerals are present on the Kodiak shelf (Appendix III). One probably is derived from the Copper River whereas the other seems to be derived from the sedimentary bedrock exposed on the Kodiak shelf.

8) Submarine slides have not been observed on the Kodiak shelf, but they are abundant on the adjacent upper continental slope (Appendix V). Large rotational slumps occur off southern and middle Albatross Bank and off Portlock Bank, but they are absent off middle Albatross Bank. Small, shallow debris slides occur locally in all areas.

The large rotational slumps are associated with slope steepening and are therefore ultimately related to tectonism. The debris slides are probably stratigraphically controlled. Large earthquakes may serve to trigger both the large and small slides.

IV. Study area

1) Lower Cook Inlet between Shelikof Strait at latitude 58°40'N and Cape Ninilchik at latitude 60°N, mainly encompassing OCS Lease Sale Area CI.

2) Kodiak Shelf between Amatuli Trough (59^{o}N) and the middle of southern Albatross Bank at latitude $56^{o}40'$N, mainly encompassing OCS Lease Sale Area No. 46.

V. Sources, methods and rationale of data collection

All results presented to date came from data collected during a 6-week cruise aboard the R/V SEA SOUNDER during June and July 1976. Some additional data for lower Cook Inlet came from copies of a 1976 Petty-Ray Geophysical survey made under contract to the U.S. Geological Survey, Conservation Division in Anchorage. Additional high-resolution seismic records were collected by R. von Huene aboard the S.P. LEE during his 1976 survey off Kodiak.

Seismic and sampling methods have been discussed in Bouma and Hampton, 1976 and Hampton and Bouma, 1976 (see also Appendix A of 1977 1st Quarter Report).

The rationale for collecting data with the instruments and equipment, described in the above-mentioned publications, is that such procedures are the only ones generally recognized to achieve the objectives of the proposed study.

VI, VII, VIII. Results of the past year, discussion and conclusions

It has to be kept in mind that the earlier-mentioned 1976 cruise aboard the R/V SEA SOUNDER was a reconnaissance. Consequently no specific details would be studied at that time due to lack of time and lack of previously published information. Our results present some general lines and a number of additional data are required to validate the present conclusions.

The high energy environment in lower Cook Inlet has a direct impact on the bottom. Where sufficient unconsolidated sand-sized material is available the bottom is characterized by different types and sizes of bedforms, such as sandwaves, sand ridges and dunes. Where such loose material is scarce or absent one finds sand ribbons, sand tails, boulder fields or smooth bottom. The nature of this smooth bottom, which also underlies all mentioned bedforms, is not known to date.

Although high velocities of sand moving on the crests of large sand waves were noted, we have the feeling that little or no net migration of the large sand bodies takes place. If this is true the bottom represents the last transgressional phase and the overall sediment distribution is a relict one. The high velocities of sand under tidal action may nevertheless form local hazards to offshore activities, such as pipelines.

The Kodiak shelf is tectonically active, and judging from the seismic profiling records, contains a number of active faults. Active deformation causes occasional changes in elevation of the sea floor, as occurred in 1964.

Unconsolidated sediments on the shelf appear to be nearly exclusively made up of Pleistocene glacial deposits. Significant sources of modern sediment are lacking. Thickness of unconsolidated sediments locally is as great as 160 m, but this covering is very thin or absent over broad areas of the shelf, exposing folded sedimentary bedrock at the sea floor.

Shelf circulation is reworking the unconsolidated Pleistocene sediments winnowing fines from the flat, elevated areas of the banks and depositing this material in local depressions on the banks and within the troughs. Stevenson Trough, however, is swept by currents that apparently do not affect other areas of the shelf, preventing the accumulation of fines.

The shelf apparently is devoid of major areas of slumping, but the upper continental slope shows several examples of slope instability.

IX. Needs for further study.

The results of the 1976 cruise in lower Cook Inlet clearly indicate the lack of understanding about the characteristics of the various types of bedforms: morphology, areal extent of any one bedform field containing one type of bedforms, boundary conditions between different types of bedform, sand movement, net movement of each type of bedform, nature of basal material, the local influence of bottom topography, and the effects of water movement on these bedforms under normal tidal action and under storm conditions.

A few additional samples are required for clay mineralogy and SEM studies, especially around Augustine Island and the northern terminus of Shelikof Strait. Both studies will aid in an understanding of the motion of particulate suspended matter and bedload movement within and outside of sandy areas, respectively.

The Kodiak Shelf area displays different aspects, the importance of which is already shown by the distribution of sediments and volcanic ash, and the relationship with the bottom morphology. Several additional samples will be required to check the present conclusions, to better determine the influence of Kiliuda, Chiniak and Amatuli Troughs and the depressions on Albatross and Portlock Banks as possible sediment sinks and areas in which nutrients concentrate, and to analyze the influence of Stevenson Trough on the shelf circulation patterns.

It is also necessary to study the geotechnical properties of the bank and trough sediments, as well as those above and below the shelf break to help delineate the influence of seismicity on the unconsolidated sediments.

It is our opinion that by going after the above-mentioned questions rather than to enlarge the 1976 coverage at this time, we are able to provide a better data base for circulation and biologic investigations.

X. Summary of 4th Quarter operations

No cruises or field projects were conducted. This period was utilized to measure grain size distributions, carry out microscopical analyses on volcanic ash, continue the SEM studies on grain morphology, and examine the copies of the Petty-Ray Geophysical records obtained from the U.S. Geological Survey, Conservation Division.

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Table 1. Position, lithology, color and other shipboard characteristics of samples collected on board the R/V SEA SOUNDER in lower Cook Inlet and Kodiak Shelf.

Sample No.	No. of attempts	Latitude	Longitude	Water Depth m/Core length, cm	Lithology, color and additional remarks
1 G	2	57°56.50'	150°13.55'	191	no recovery
* 1 V	1	57°56.54'	150°13.56'	192	Clean ms, dark with echinoid, and worm tubes
2 G	1	59°37.55'	151°18.87'	73	Slightly sl/c, dark, high amount of organic material sl/c=10 90
* 3 V	2	60°05.36'	152°34.13'	40	Slightly muddy sandy g with cobble sized material, grey. Barnacles encrusted to rock fragments. g/s/sl/c=60-30-5-5
* 4 V	1	60°05.45'	152°34.54'	40	Sandy g with some rock fragments, greyish brown. Numerous small pelecypods and sea fans. g/s/sl/c=94-3-2-1
5 V	1	60°04.70'	152°33.83'	47	Slightly muddy pebbly s, grey. g/s/sl/c=40-55-3-2
6 V	1	59°19.02'	153°41.45'	26	Clayey sl/fs, dark grey. s/sl/c=45-40-15
7 V	1	59°16.22'	153°32.12'	32	Sl/s, dark grey, some pumice. s: 90% vf, 10% f. s/sl/c=80-15-5
* 7 S	1	59°16.24'	153°32.12'	32	Sl/fs, some pumice. Abundant gastropod shells, molluscs and worm tubes.
* 8 S	1	59°10.69'	153°44.10'	36	Slightly sandy pebbly clayey sl, dark grey. Abundant fauna: molluscs and barnacles. g/s/sl/c=30-6-58-6. Abundant shell fragments.
* 9 V	1	59°41.60'	152°36.10'	35	Pebbly s, dark, some sessile organisms. g/s/sl/c=30-67-2-1
10 V	4	59°41.25'	152°34.90'	51	Sandy g, dark. g/s/sl/c=95-5-tr-tr
11 V	2	59°34.50'	152°35.90'	75	Sandy g, dark grey. g/s/sl/c=95-4-tr-tr
12 V	2	59°34.60'	152°36.10'	67	Sandy g, dark grey. g/s/sl/c=54-44-1-tr
13 V	1	59°25.75'	152°50.09'	63	Ms, dark grey. 60% ms, 30% fs, 10% vfs
* 14 V	1	59°30.0'	152°46.01'	65	Ms, dark grey. 2% cs, 93% ms, 5% fs
14 S	1	59°30.06'	152°46.06'	61	Ms, dark grey. 5% cs, 95% ms, 5% fs
* 15 S	1	59°31.08'	152°54.0'	45	Ms, dark grey. Some shell debris, 4% cs, 93% ms, 3% fs

Sample No.:
G=gravity core
V=van Veen grab sample
S=Soutar modification of van Veen grab
CD=Chain dredge
D=Dart core

No. of attempts:
number of lowerings with that sampling device before an acceptable sample is obtained. If no recovery: see under remark.

Water Depth m/Core length cm:
waterdepth in meters at the time of the station without tidal correction/length of core in cm as recorded on board ship.

Lithology, color and additional remarks:
g/s/sl/c=gravel/sand/silt/clay ratio in percentages from smearslides.
tr=trace, g=gravel, vcs=very coarse sand; cs=coarse sand; ms=medium sand; fs=fine sand; vfs= very fine sand; s=sand; sl=silt; c=cla

Biology
- * Biology noted in lower Cook Inlet
- ** Biology noted on Kodiak Shelf
- – see Table 2 on additional notes

Table 1. cont.

Sample No.	No. of attempts	Latitude	Longitude	Water Depth m/Core length cm	Lithology, color and additional remarks
16 S	1	59°23.2'	153°06.6'	48	Pebbly s, grey. Small pebbles. g/s/sl/c=10-88-1-tr
17 S	1	59°20.7'	152°53.5'	74	Clean s, vf to c, grey. s=100%
18 S	3	59°12.15'	152°44.8'	122	Clean s, dark grey. s=98% pebbles and c 1%, ms 90%, fs 9%
* 19 S	1	58°56.25'	152°23.36'	75	Very slightly silty s with shell fragments (35%) s/sl/c=97-2-1. ms 90%, fs 10%
20 D	2	58°53.45'	152°25.50'	82	No recovery
* 21 CD	1	58°53.15' to	152°22.28'	-	Chain dredge. Primarily rounded pebbles and boulders: samdstone, shale, basalt, plutonics. Varied biota: many sponges
		58°53.52 to	152°19.15'	-	
* 22 S	3	58°51.20'	152°24.90'	154	Sandy g. 50% clastics and 50% shell fragments, forams, etc. g/s/sl/c=55-40-4-1
* 23 S	2	58°55.7'	152°34.3'	170	60-65% clastic, rest biogenic. S, grey. ms prim. g/s/sl/c=1-97-1-1
* 24 S	1	58°58.49'	152°31.11'	147	Sl s, grey. 10% shell fragments. s/sl/c=97-2-1
24 G	1	58°58.90'	152°30.45'	147	Tr recovery
25 S	1	59°03.2'	152°31.2'	133	Pebbly s. g/s/sl/c=5-92-2-1
* 26 S	1	59°08.1'	152°22.1'	119	S. 100%. Range: c-f; ms=median. Some shell fragments
27 S	1	59°26.3'	152°20.7'	74	S, less than 1% g. Clean. Range vc-m; median=coarse
* 28 S	1	59°21.35'	152°25.9'	78	S 100%. Range: m-f; median=m. Some shells
* 29 S	2	59°14.98'	152°28.15'	89	S 100%. Range: m-f; median=m. Some shells. Large phlogopite flakes.
* 30 S	2	59°16.65'	152°21.70'	91	Shelly s: 15% shell fragments, 85% s. Range: c-f; median=m.
* 31 S	2	59°20.25'	152°19.10'	90	Shelly s: 15% shell fragments, 85% s. Range: m-f; median=m.
* 32 S	1	59°19.45'	152°06.13'	69	Sandy g, grey. Shell fragments (25%), coral, molluscs. g/s/sl/c=67-32-tr-tr
* 33 S	2	59°26.35'	152°12.49'	50	Pebbly s, much fauna on surface. 35% shell fragments. g/s/sl/c=15-85-tr-tr
* 34 S	3	59°36.55'	151°52.00'	28	Fs with few animals. 20% shells, shell fragments, forams. 80% s: ms/fs/vfs=10-80-10
* 35 S	1	59°37.35'	152°14.30'	50	Sandy g with clams and brittle stars. g/s/sl/c=73-27-tr-tr

Table I. cont.

Sample No.	No. of attempts	Latitude	Longitude	Water Depth m/Core length cm	Lithology, color and additional remarks
* 36 S	2	59°41.50'	152°13.0'	46	Pebbly s with shells (25%). S range: vc-f; median: ms g/s/sl/c= 33-74-2-1
* 37 S	1	59°46.30'	151°13.0'	56	Sandy g with shells (20%). ms/fs=85-15 g/s/sl/c=69-31-0-0
38 S	2	59°44.65'	151°59.05'	18	G (100%). Rocks up to 15 cm, well rounded, one rounded cobble: 20 X 12 X 8 cm
* 39 S	1	59°40.75'	151°57.15'	35	G with abundant fauna: urchins, crabs, clams, etc. Very little fs. Pebbles and cobble well rounded.
40					No sample station
41 S	1	59°36.25'	151°56.00'	30	Clean ms well sorted, sub-rounded to sub-angular 10% shells. ms/fs= 85-15
42 S	2	59°36.20'	151°45.60'	30	Silty s, ms well sorted, sub-rounded to sub-angular, shells 5%, g/s= 25-70
* 43 S	1	59°36.63'	151°22.07'	52	Silty s, well sorted, dark, some clams, s is vfs/fs/ms=75-20-5% s/sl/c=96.5-3-0.5
* 44 S	2	59°35.25'	152°22.90'	62	Clean s (98%) well sorted, some shell fragments, s is ms/fs/cs= 79-20-1 g/s/shells=1-98-1
* 45 S	1	59°34.80'	152°36.10'	-	Muddy s with pebbles abundant fauna.
* 46 S	2	59°44.40	152°32.05'	71	Sandy g, some shell fragments, g/s=75-24 1% shells, s is ms/fs/c= 85-14-1
* 47 S	2	59°55.49'	152°28.60'	25	Sandy g, shells (5%) s poorly sorted vcs/cs/ms/fs/vfs=2-25-50-18-5 g/s/shells=75-20-5
48 S	1	60°00.50'	151°22.46'	45	Sandy c, well sorted, sub-rounded to angular, 99% s fs/vfs/ms=90-7-3 s/sl=99-1
* 49 S	1	59°56.00'	152°03.90'	47	Shelly g, g well rounded, g/s/shells=80-15-5 s: cs/ms/fs=80-10-10
50 S	2	59°52.50'	151°54.50'	32	Sandy g, sub-angular to rounded, s: cs/ms/fs=30-55-15, g/s/shells= 70-15-10
**51 S	1	58°12.54'	151°55.74'	60	Cobbles and boulders with fauna, washed sample, no s.
52 G	2	58°24.54'	151°14.35'	107	NO SUITABLE RECOVERY-small sample g/s/c=25-75-.1
**52 S	1	58°24.42'	151°13.80'	86	Pebbly s with clams (no further analyses)
**53 S	2	58°12.56'	150°39.79'	175	Sandy g, with shell fragments. s: cs/ms/fs/vfs=5-10-70-10, g/s/shell= 40-15-45
**54 S	2	58°07.36'	150°30.26		Muddy s, also forams and shells=10%, glass shards, lithic fragments s, ms/fs/vfs=10-75-15, g/s/sl/c=.5-89-.5-.1%

Table 1. cont.

Sample No.	No. of attempts	Latitude	Longitude	Water Depth m	/Core length cm	Lithology, color and additional remarks
55 S	2	58°01.86'	150°21.64'	184		Muddy s, ash-glass shards, s/sl=99.5-.5% s is 95% fs, well rounded
55 G	1	58°01.86'	150°21.64'	183		Pebbles, not much else.
56 S	1	57°55.22'	150°12.77'	194		S, overlain by small amount of clay and possible ash, s 100% well-sorted.
**57 S	1	57°50.94'	150°03.74'	190		Muddy s, ash 97% s: cs/ms/fs/vfs=10-15-65-10%, lithics are rounded, shell fragments and forams
58 S	1	57°46.99'	149°55.40'	232		Silty s w/pebbles. ash; s=cs/ms/fs/vfs=15-15-60-10; g/s/sl-c=5-94-1
59 S	1	57°46.60'	149°29.66'	495		Pebbly s, high amount of shards, s 90% fs to vfs. Lithics are well-rounded; g/s/sl-c=3-97-tr
60 S	1	57°45.96'	149°37.41'	444		S 99%, glass shards, lithics are rounded, s=cs/ms/fs=1-9-90% g/s/sl-c=1-99-tr
-**61 S	1	57°35.61'	150°24.46'	112		Pebbly s w/g, forams, shells, ash. S very well sorted, g/s/shells=25-60-15
**62 S	1	57°39.05'	150°32.48'	102		Pebbly s, abundant brittle stars and clams, pebbles well rounded, s well sorted g/s/sl-c/shells=20-55-1-24
-**63 S	1	57°43.96'	150°39.25'	90		Pebbly s, abundant fauna, lithics well rounded, s mod. sorted, g/s/sl-c/shells=25-40-1-34
-**64 S	1	57°47.50'	150°45.00'	83		Sandy g, shell fragments. Lithics well-rounded, mod. sorted s, sub-angular to sub-rounded; g/s/sl-c/shells=40-20-1-39%
-**65 S	2	57°51.50'	150°51.50'	77		Sandy g, with ash, s 85% fs-vfs, lithics well rounded; g/s/sl-c/shells=35-20-1-44
**66 S	1	57°55.10'	150°59.30'	-		Shelly s, much shell debris, glass shards, s 90% fs/vfs; g/s/sl-c/shells=5-15-1-79
-**67 S	3	57°59.70'	151°06.40'	82		Pebbly s, glass shards, s: cs/ms/fs/vfs=1-5-55-40, lithics rounded; g/s/sl-c/shells=10-30-1-59
-**68 S	2	57°28.10'	151°28.70'	154		S 97%- abundant glass shards, well sorted, s/sl/c=97-2-1
**69 S	2	57°23.25'	151°10.95'	80		S 90%, about 95% ash, fs/vfs=75-25, lithics rounded; s/sl/c=90-9-1
-**70 S	1	57°24.08'	150°52.25'	96		Clean s, 99%, lithic fragments rounded, s:cs/ms/fs/vfs=<1%-12-80-8
-**71 S	1	57°20.01'	150°59.08'	95		Clean s, 99%, lithics round-subrounded, few shards, s-ms/fs/vfs=15-75-10. Clay-silt=1%
-**72 S	1	57°24.20'	151°05.10'	92		S 99%, lithics mostly sub-rounded, abundant shards, ms/fs/vfs=1-97-2, 1% clay-silt

Table I. cont.

Sample No.	No. of attempts	Latitude	Longitude	Water Depth m/Core length cm	Lithology, color and additional remarks
**73 S	1	57°34.90'	151°12.15'	66	Shelly s, sample contained large basalt boulder at 86% of volume, ash, g/s/shells=.5-3-11
**74 S	2	57°41.10'	151°00.40'	75	Shelly s, with cobbles and boulders, mode is rounded to sub-rounded b-c/g/s/sl-c/shell=80-4-2-tr-14
**75 S	1	57°45.80'	151°08.05'	70	Shell fragments, with lithics, shards, s mod. sorted, g/s/sl-c/ shells=1-16-tr-83
**76 S	1	58°06.20'	151°46.10'	95	S, dark green, shell fragments, well sorted, shards, s 98% shells 2%
**77 S	1	58°11.60'	151°37.00'	38	Shelly cobbles, some forams, shell hash, g/s/sl/shells=90-3-6-1
**78 S	2	58°11.41'	151°37.15'	70	Totally brittle stars; some, very little, shell hash.
**79 S	1	58°12.23'	151°38.07'	-	Brittle stars, shelly pebbles, lithic are rounded, few shards, g/s/sl-c/shells=36-6-tr-58
**80 S	1	58°01.50'	151°21.90'	81	Pebbly shelly s, forams, shards, s vcs-cs/ms/fs/vfs=2-1-92-5 dark, rounded
81 S	1	58°05.21'	151°14.55'	143	Sandy mud, green, rich in ash, ms/fs/vfs=tr-56-45, s/sl/c/shells= 88-10-tr-2
81 G	3	58°05.21'	151°14.55'	145	No recovery
**82 S	1	58°03.60'	151°15.90'	103	Sandy g, shards, lithics are sub-angular to rounded, g/s/sl/c/shells= 50-29-1-tr-20
**83 G	1	56°53.73'	151°29.84'	706/150	Coarse pebbly s with shells and mud.
84 G	1	56°55.06'	151°24.58'	859/175	Grey mud, some grit, strong H_2S odor
**85 S	1	57°45.00'	151°44.00'	55	Sandy shell hash, shards, forams; lithics are rounded to sub-rounded g/s/sl/c/shells=1-3-tr-96
**86 S	1	57°41.48'	151°34.70'	61	Shelly s, shards and forams; vcs/cs/ms/fs/vfs=1-1-2-90-6; g/s/sl-c/ shells=1-66-tr-33
87 S	1	57°36.50'	151°47.65'	132	Ash s 99%, very well sorted 98% fs. s/sl-c=99-1
87 G	2	57°36.50'	151°47.65'	137	No recovery
88 S	1	57°31.20'	151°38.00'	167	Ash s 76%, well sorted=fs-vfs=100%. s/sl/c/shells=76-23-tr-1
88 G	2	57°31.20'	151°38.00'	145	No recovery
-**89 S	1	57°28.50'	151°44.50'	70	Conglomerate, with shards, lithics sub-angular to sub-rounded, c-g/s/sl-c/shells=88-8-tr-4
**90 S	1	57°25.10'	151°51.90'	67	Sandy, shell hash, ms=75% of s, lithics are rounded to sub-rounded, s/sl-c/shells=2-tr-98

Table 1. cont.

Sample No.	No. of attempts	Latitude	Longitude	Water Depth m	/Core length cm	Lithology, color and additional remarks
**91 S	1	57°19.29'	152°04.82'	73		S 99% with shell has, well sorted vfs; sub-rounded. s/shell=99-1
92 S	2	56°56.50'	152°33.00'	167		Silty c, olivine-green color, H_2S odor, vfs. s/sl/c=1-3-96
-**93 S	1	56°53.45'	152°40.90'	128		Silty s, vfs, shards present, olive-grey color. s/sl/c=90-8-2
-**94 S	1	56°48.15'	152°52.60'	63		Shelly s, shards, olive-grey color; well sorted fs. g/s/sl-c/shells=49-36-tr-15
-**95 S	1	56°48.10'	153°21.35'	160		Conglomerate; shards; rounded to angular cobbles; g/s/sl-c/shells=90-10-tr-tr
96 S	1	56°41.46'	153°05.90'	146		Sandy mud, well sorted; shards, s-vfs. s/sl/c=5-35-60
97 S	1	56°40.10'	153°10.02'	150		Sandy mud, well sorted round to sub-rounded. s/sl/c=4-26-70
97 G	1	56°39.90'	153°11.10'	128	/100	Mud, greyish-olive, very little shell fragments
98 S	1	56°38.00'	153°16.00'	145		Silty, sandy mud, well sorted, well rounded, shards s/sc/c=3-20-77
98 G	1	56°37.80'	153°16.30'	144		Sandy mud, little recovery
99 D	2	56°24.50'	152°53.70'	55	/20	Siltstone, olive grey
100 D	1	56°24.00'	152°53.50'	50	/17	Siltstone, olive-grey
101 D	1	56°23.20'	152°54.10'	49	/9	Sandstone, very fine grained, medium dark-grey color, silty.
102 D	1	56°23.10'	152°53.90'	45	/16	Siltstone, olive-grey
103 D	1	56°22.70'	152°52.00'	50	/17	Sandstone, very fine grained, silty, olive-grey
104 D	1	56°22.00'	152°50.90'	75	/16	Sandstone, very fine grained, silty, olive-grey
105 S	1	56°19.04'	152°46.50'	178		No recovery
106 D	2	56°29.60'	152°43.70'	60	/1	Silt, very small recovery olive-grey color
107 D	1	56°30.15'	152°44.10'	56	/30	Siltstone, dark-grey
108 D	2	56°30.30'	152°44.90'	56	/25	Siltstone, dark-grey
109 D	2	56°30.80'	152°46.20'	58		No recovery
110 D	1	56°31.40'	152°46.70'	64	/47	Silt, medium dark-grey
111 D	1	56°31.70'	152°47.50'	65	/48	Sandy silt, olive-grey
**112 D	2	56°32.00'	152°48.20'	70	/22	Shell hash, pale-olive color forams cs/ms/fs/vfs=2-11-85-2; s/sl/c/shells=18-1-1-80
-**113 S	1	56°33.50'	152°27.20'	197		Pebbly s, color 5Y 3/2; shards; p/g/s/sl/c/shells=5-3-89-2-tr-tr
-**114 S	1	56°37.60'	152°34.00'	160		Sandy g, g are sub-angular to sub-rounded, forams, p/s/sl/c=40-55-2-3
**115 S	2	56°57.02'	152°06.28'	80		S, 5Y 4/4, sub-angular to rounded; shards, lithics; s/sl/c/shells=91-tr-tr-9

Table 'l. cont.

Sample No.	No. of attempts	Latitude	Longitude	Water Depth m/Core length cm	Lithology, color and additonal remarks
116 D	2	57°12.00'	151°51.10'	74/39	Sandy siltstone; medium dark grey, some pebbles
117 D	1	57°10.09'	151°50.70'	54/14	Sandy siltstone, dark-grey, with pebbles
118 D	1	57°11.00	151°50.00'	54/20	Sandy siltstone, dark-grey
**119 D	1	57°10.60'	151°49.10'	56/40	Coarse s, light olive-grey, shelly and pebbly
120 D	1	57°10.00'	151°48.40'	60/20	Sandy siltstone, dark-grey
121 D	2	57°09.25'	151°47.50'	70	Sandy siltstone, dark-grey
122 D	2	57°09.00'	151°46.90'	74	No recovery
123 D	2	57°08.75'	151°46.30'	76/34	Sandy siltstone, dark-grey
124 D	1	57°08.50'	151°45.60'	78/20	Fs, medium dark-grey
125 D	1	57°08.00'	151°45.00'	80/20	Fs ash, with dark sandy silt; well sorted s/sl/c=90-10-tr
126 D	2	57°07.40'	151°44.10'	80	No recovery
-**127 S	1	57°11.24'	151°29.59'	69	Pebbly s, shards, lithics-sub-angular to sub-rounded, vcs/cs/ms/fs/vfs=5-10-35-45-10 p/s/sl-c/shells=15-67-tr-28
**128 S	1	58°31.47'	149°21.90'	121	Muddy s, with pebbles; shells and forams, shards, p/s/sl/c/shells=2-30-4-2-62
-**129 S	1	58°35.85'	149°14.91'	95	Pebbly s; shards, lithics sub-rounded to rounded. p/s/sl-c/shells=70-8-tr-22
130 S	1	58°42.23	149°03.38	145	S 98%, well sorted, sub-angular, few shards; cs/ms/fs/vfs=1-2-90-7, some c.
**131 S	1	58°44.99'	148°58.18'	214	Silty s, sub-angular, lithics; shards; cs/ms/fs/vfs=1-4-85-10; p/s/sl/c/shells=3-76-15-5-1
132 S	1	58°49.24'	148°54.71'	236	Pebbly-silty s; shards sub-angular to sub-rounded; cs/ms/fs/vfs=5-25-65-5; p/s/sl/c/shells=10-80-44-2
133 G	1	58°54.41'	149°01.95	250/95	Sandy c, vfs; grey-green mud; s/sl/c=10-10-80
134 S	1	58°49.39'	149°14.22'	206	Pebbly s, boulders meta conglomeate and quartzite ss, mud green; p/s/sl/c/shells=11-73-6-8-2
-**135 S	1	58°40.39'	149°31.82'	136	S 93%; well sorted fs; sub-angular to sub-rounded; forams; s/sl/c/shells=93-2-4-1
136 S	1	58°34.90'	149°45.19'	125	S 97%, fs slightly green in color; coarser s towards bottom; sub-rounded; s/sl/c/shells=97-2-1-tr
-**137 S	1	58°29.46'	150°05.25'	93	Pebbly s; abundant forams; shards-bimodal sorting (due to washing?) sf; p/s/sl/c/shells=30-49-81-12

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Table 1. cont.

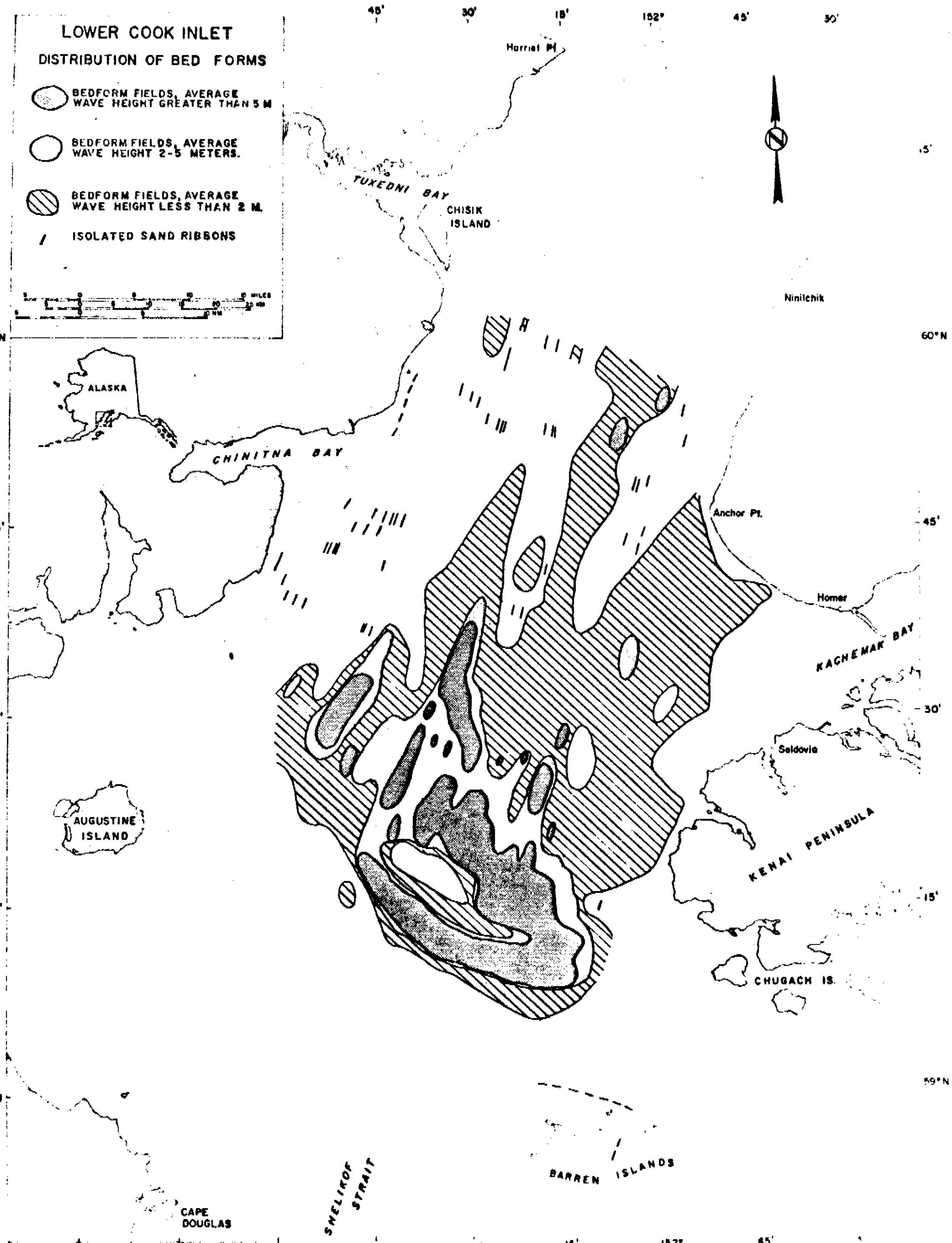
Sample No.	No. of attempts	Latitude	Longitude	Water Depth m/Core length cm	Lithology, color and additional remarks
**138 S	1	58°22.07'	150°24.07'	60	Sandy g; shell hash on top; g/s/sl/c=70-29-1-tr; shell hash removed
-**139 S	2	58°15.96'	150°15.30'	54	Shell incrustment on foot of one large sponge-no sample analyzed
-**140 S	1	58°22.20'	149°54.26'	83	Sandy pebbles; rounded to sub-rounded; p/s/sl/c/shells=70-8-tr-tr-22
**141 S	1	58°13.12'	149°11.85'	120	Pebbly s w/forams abundant; well rounded pebble; shards; p/s/sl/c shells=20-13-2-tr-65
**142 D	2	58°08.70'	149°04.70'	114/0	Smear recovery; pipe well dented; only noted a foram bearing c
143 D	1	58°08.00'	149°03.80'	104/0	Smear recovery; sandy silt; only enough to make smear slide; olive grey
-**144 D	1	58°05.92'	149°01.44'	88/23	Conglomerate; Top-olive grey foram bearing silty cs; Base-dark grey sandy siltstone; p/s/sl/c/shells=44-37-2-7-10
**145 D	1	58°06.59'	149°02.46'	90/10	Coarse s dark-grey to olive-grey; pebbly w/forams; g/s/sl/c/shells= 15-54-4-2-25
146 D	1	58°05.99'	149°01.25'	88	No recovery
**147 D	2 •	58°05.60'	148°01.00'	88/12	Silty s; dark to olive grey; abundant pebbles; forams; fine sands; p/s/sl/c/shelss=57-37-1-tr-5
**148 D	1	58°04.96'	148°59.95	90/8	Sandy pebbles; dark to olive grey; siltstone; forams; shards; lithics; p/s/sl/c/shells=51-21-tr-tr-28
149 D	2	58°04.60'	148°59.50'	98/0	Sandy silt; enough for smear only. dark grey
* 150 S	1	59°04.55'	152°49.50'	147	Muddy s 98%; well sorted fs; sub-angular forams; s/sl/c/shells= 98-1-tr-1
151 S	1	59°11.90'	152°09.50'	112	No recovery
-* 152 S	1	59°37.21	152°29.08'	70	S 99%; medium s well sorted; w/pebbles and shells=1% sub-angular; lithics rounded; vcs/cs/ms/fs/vf=tr-8-92-tr-tr
* 153 S	2	59°10.70'	152°31.55'	99	S 99% w/forams; well sorted fs; sub-angular to angular; s/sl-c/shells= 99-tr-tr-1
154 S	1	59°09.25'	153°05.63'	75	Muddy s 98%; fs, well sorted; sub-angular to sub-rounded; shards; s/sl/c/shells=98-tr-1

Table 2. Additional Biological Notes

* 14V1	some shell debris
** 61S1	brittle stars
** 63S1	mollusks, brittle stars, sand dollars
** 64S1	brittle stars
** 65S2	abundant brittle stars, crabs
** 67S3	many various fauna
** 68S2	clams, snails, shell hash
** 70S1	brittle stars
** 71S1	brittle stars
** 72S1	brittle stars
** 89S1	mollusks, shell fragments
** 93S1	mollusks, shells, small fish
** 94S1	shells, corals, pectens, mytilus
** 95S1	brachiopods, brittle stars, urchine
**113S1	forams
**114S1	mollusks, echinoids, starfish
**127S1	shells, brittle stars
**129S1	shells, brittle stars, brachiopods
**135S1	starfish
**137S1	brittle stars
**139S2	bryozoa
**140S1	bryozoa, shell fragments, brittle stars, crabs
**144D1	shells
* 152S1	clam shells

* located in lower Cook Inlet

** located on Kodiak Shelf



LOWER COOK INLET
DISTRIBUTION OF BED FORMS
BEDFORM FIELDS, AVERAGE WAVE HEIGHT GREATER THAN 5 M
BEDFORM FIELDS, AVERAGE WAVE HEIGHT 2-5 METERS.
BEDFORM FIELDS, AVERAGE WAVE HEIGHT LESS THAN 2 M.
ISOLATED SAND RIBBONS
Harriet Pt.
TUXEDNI BAY
CHISIK ISLAND
Ninilchik
60°N
ALASKA
CHINITNA BAY
Anchor Pt.
45'
Homer
KACHEMAK BAY
30'
Seldovia
AUGUSTINE ISLAND
KENAI PENINSULA
15'
CHUGACH IS.
59°N
BARREN ISLANDS
SHELIKOF STRAIT
CAPE DOUGLAS
153°
152°

FIGURE 1

APPENDIX I

GRAIN SIZE DISTRIBUTIONS OF SOME SURFICIAL SEDIMENTS FROM LOWER COOK INLET, ALASKA

GRAIN SIZE DISTRIBUTIONS OF SOME SURFICIAL SEDIMENTS FROM LOWER COOK INLET, ALASKA

Rapid sediment analyzer (RSA) results of a restricted number of samples from lower Cook Inlet were collected in order to have grain size data of the bulk samples obtained during the 1976 R/V SEA SOUNDER cruise. These bulk samples will be used for sediment dispersion studies to be conducted during the September 1977 cruise. The bulk samples will be coated with a fluorescent tracer to facilitate later observations. The location of the samples is given in Figure 1, and comparison with the figures in this report that display the distribution of bedforms shows that they are all from areas containing sand waves.

No statistical comparison was made between the samples or between RSA and sieve methods. All cummulative grain size distributions are on a linear scale as is customary when working with ϕ size groups rather than a metric system. Due to the strong sorting it may be preferable to use a probability scale along the ordinate, but the coarse and fine tails of each distribution are so small that such a scale will not give significant additional information.

The ϕ scale was introduced in 1922 by Wentworth and is logarithmic in nature in that each grade limit is twice as large as the next smaller grade limit. To relate ϕ-scale to a mm scale a few examples are given:

ϕ (phi) = - 1 is 2 mm (boundary between granule and very coarse sand)
ϕ = 0 is 1 mm (boundary between very coarse sand and coarse sand)
ϕ = 1.0 is 0.5 mm (boundary between coarse and medium sand)
ϕ = 2.0 is 0.25 mm (boundary between medium and fine sand)
ϕ = 3.0 is 0.125 mm (boundary between fine sand and very fine sand)
ϕ = 4.0 is 0.0625 mm (boundary between very fine sand and silt)

(The general formula for conversion from size in millimeters (d) to the ϕ-scale is $\phi = -\log_2 d$.)

The grain size distributions, displayed in Figures 2 - 14, show very compatible distributions and shapes with only limited shifts to coarse and fine. The mean phi size can be utilized as an adequate number to classify the sample. Mean phi sizes vary between 0.98 (fine size of coarse sand) to 2.35 medium fine sand), with the average in the medium sand size class. This variation is considerable for hydrodynamic studies but presently will give a good base for benthic studies. As soon as details are worked out we will be able to classify these samples in hydrodynamic groups which will be required for the 1977 dispersion studies. Detailed breakdowns on the size distributions are given in Tables 1 - 13.

SAMPLE NUMBER=S762,3 14LCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	3.50	3.52	3.52
0.50	2.50	2.51	6.03
0.75	2.50	2.51	8.54
1.00	18.50	18.59	27.14
1.25	23.00	23.12	50.25
1.50	17.00	17.09	67.34
1.75	21.00	21.11	88.44
2.00	7.00	7.04	95.48
2.25	0.50	0.50	95.98
2.50	2.50	2.51	98.49
2.75	0.00	0.00	98.49
3.00	0.00	0.00	98.49
3.25	0.50	0.50	98.99
3.50	0.50	0.50	99.50
3.75	0.50	0.50	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 1.26
SKEWNESS= -0.00
STANDARD DEVIATION= 0.45
KURTOSIS= 1.05
NORMALIZED KURTOSIS= 0.51

Table I.

SAMPLE NUMBER=S76-2,3 15 LCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	1.00	1.01	1.01
0.50	3.75	3.77	4.77
0.75	5.25	5.28	10.05
1.00	6.00	6.03	16.08
1.25	13.00	13.07	29.15
1.50	16.00	16.08	45.23
1.75	20.00	20.10	65.33
2.00	15.00	15.08	80.40
2.25	8.00	8.04	88.44
2.50	3.50	3.52	91.96
2.75	3.50	3.52	95.48
3.00	2.50	2.51	97.99
3.25	0.75	0.75	98.74
3.50	0.75	0.75	99.50
3.75	0.50	0.50	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 1.56
SKEWNESS= 0.02
STANDARD DEVIATION= 0.61
KURTOSIS= 1.22
NORMALIZED KURTOSIS= 0.55

Table 2.

SAMPLE NUMBER=S76-2,3 28LCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00
0.50	0.00	0.00	0.00
0.75	0.00	0.00	0.00
1.00	2.00	2.00	2.00
1.25	8.00	8.00	10.00
1.50	15.50	15.50	25.50
1.75	34.00	34.00	59.50
2.00	21.50	21.50	81.00
2.25	10.00	10.00	91.00
2.50	4.00	4.00	95.00
2.75	2.00	2.00	97.00
3.00	1.00	1.00	98.00
3.25	0.50	0.50	98.50
3.50	1.00	1.00	99.50
3.75	0.50	0.50	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 1.70
SKEWNESS= 0.13
STANDARD DEVIATION= 0.40
KURTOSIS= 1.31
NORMALIZED KURTOSIS= 0.57

Table 3.

SAMPLE NUMBER=S76-2,3 29LCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	1.00	1.00	1.00
0.50	0.25	0.25	1.25
0.75	0.25	0.25	1.51
1.00	0.15	0.15	1.66
1.25	0.10	0.10	1.76
1.50	0.25	0.25	2.01
1.75	2.50	2.51	4.52
2.00	13.00	13.05	17.56
2.25	37.50	37.63	55.19
2.50	34.50	34.62	89.81
2.75	8.00	8.03	97.84
3.00	1.30	1.30	99.15
3.25	0.45	0.45	99.60
3.50	0.40	0.40	100.00
3.75	0.00	0.00	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 2.21
SKEWNESS= -0.01
STANDARD DEVIATION= 0.26
KURTOSIS= 1.08
NORMALIZED KURTOSIS= 0.52

Table 4.

SAMPLE NUMBER=S76-2,3 30S1CI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00
0.50	0.50	0.50	0.50
0.75	1.00	1.00	1.50
1.00	3.25	3.25	4.75
1.25	11.75	11.75	16.50
1.50	24.60	24.60	41.10
1.75	39.15	39.15	80.25
2.00	10.00	10.00	90.25
2.25	7.00	7.00	97.25
2.50	1.00	1.00	98.25
2.75	0.75	0.75	99.00
3.00	0.50	0.50	99.50
3.25	0.50	0.50	100.00
3.50	0.00	0.00	100.00
3.75	0.00	0.00	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 1.55
SKEWNESS= 0.00
STANDARD DEVIATION= 0.33
KURTOSIS= 1.26
NORMALIZED KURTOSIS= 0.56

Table 5

SAMPLE NUMBER=S76-2,3 30 $aLCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	2.00	2.00	2.00
0.25	2.00	2.00	4.00
0.50	1.00	1.00	5.00
0.75	5.00	5.00	10.00
1.00	12.00	12.00	22.00
1.25	22.00	22.00	44.00
1.50	21.00	21.00	65.00
1.75	19.00	19.00	84.00
2.00	10.50	10.50	94.50
2.25	2.50	2.50	97.00
2.50	2.50	2.50	99.50
2.75	0.00	0.00	99.50
3.00	0.00	0.00	99.50
3.25	0.00	0.00	99.50
3.50	0.00	0.00	99.50
3.75	0.50	0.50	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 1.32
SKEWNESS= -0.04
STANDARD DEVIATION= 0.45
KURTOSIS= 1.06
NORMALIZED KURTOSIS= 0.52

Table.6

SAMPLE NUMBER=S76-2,3 31LCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00
0.50	0.00	0.00	0.00
0.75	0.75	0.76	0.76
1.00	0.00	0.00	0.76
1.25	0.25	0.25	1.01
1.50	4.00	4.04	5.05
1.75	39.00	39.39	44.44
2.00	42.50	42.93	87.37
2.25	10.50	10.61	97.98
2.50	0.50	0.51	98.48
2.75	0.75	0.76	99.24
3.00	0.25	0.25	99.49
3.25	0.00	0.00	99.49
3.50	0.50	0.51	100.00
3.75	0.00	0.00	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 1.78
SKEWNESS= 0.06
STANDARD DEVIATION= 0.21
KURTOSIS= 0.93
NORMALIZED KURTOSIS= 0.48

Table 7

SAMPLE NUMBER=S76-2,3 34 LCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00
0.50	0.00	0.00	0.00
0.75	0.00	0.00	0.00
1.00	0.00	0.00	0.00
1.25	0.00	0.00	0.00
1.50	0.00	0.00	0.00
1.75	0.00	0.00	0.00
2.00	9.00	9.00	9.00
2.25	29.00	29.00	38.00
2.50	37.75	37.75	75.75
2.75	13.50	13.50	89.25
3.00	4.25	4.25	93.50
3.25	2.75	2.75	96.25
3.50	1.75	1.75	98.00
3.75	0.25	0.25	98.25
4.00	1.75	1.75	100.00

MEAN PHI SIZE = 2.35
SKEWNESS= 0.19
STANDARD DEVIATION= 0.34
KURTOSIS= 1.43
NORMALIZED KURTOSIS= 0.59

Table 8

SAMPLE NUMBER=S76-2,3 44SHLCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	1.75	1.94	1.94
0.50	2.25	2.50	4.44
0.75	4.00	4.44	8.89
1.00	3.00	3.33	12.22
1.25	10.50	11.67	23.89
1.50	33.50	37.22	61.11
1.75	18.25	20.28	81.39
2.00	6.25	6.94	88.33
2.25	4.25	4.72	93.06
2.50	3.25	3.61	96.67
2.75	2.00	2.22	98.89
3.00	0.75	0.83	99.72
3.25	0.25	0.28	100.00
3.50	0.00	0.00	100.00
3.75	0.00	0.00	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 1.45
SKEWNESS= 0.07
STANDARD DEVIATION= 0.47
KURTOSIS= 1.84
NORMALIZED KURTOSIS= 0.65

Table 9

SAMPLE NUMBER=S76-2,3 44ΩLCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	3.00	3.00	3.00
0.00	2.00	2.00	5.00
0.25	4.00	4.00	9.00
0.50	3.00	3.00	12.00
0.75	4.00	4.00	16.00
1.00	3.00	3.00	19.00
1.25	5.50	5.50	24.50
1.50	33.50	33.50	58.00
1.75	29.00	29.00	87.00
2.00	6.00	6.00	93.00
2.25	2.00	2.00	95.00
2.50	2.00	2.00	97.00
2.75	1.00	1.00	98.00
3.00	0.00	0.00	98.00
3.25	0.00	0.00	98.00
3.50	2.00	2.00	100.00
3.75	0.00	0.00	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 1.30
SKEWNESS= -0.35
STANDARD DEVIATION= 0.58
KURTOSIS= 2.35
NORMALIZED KURTOSIS= 0.70

Table 10

SAMPLE NUMBER=S76-2,3 47LCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	3.50	3.50	3.50
0.50	3.00	3.00	6.50
0.75	17.50	17.50	24.00
1.00	33.00	33.00	57.00
1.25	22.00	22.00	79.00
1.50	12.00	12.00	91.00
1.75	5.25	5.25	96.25
2.00	2.15	2.15	98.40
2.25	0.20	0.20	98.60
2.50	0.00	0.00	98.60
2.75	0.40	0.40	99.00
3.00	0.00	0.00	99.00
3.25	0.10	0.10	99.10
3.50	0.20	0.20	99.30
3.75	0.70	0.70	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 0.98
SKEWNESS= 0.13
STANDARD DEVIATION= 0.38
KURTOSIS= 1.21
NORMALIZED KURTOSIS= 0.55

Table 11

SAMPLE NUMBER=S76-2;3 152LCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00
0.50	0.00	0.00	0.00
0.75	0.00	0.00	0.00
1.00	1.25	1.25	1.25
1.25	15.25	15.25	16.50
1.50	47.50	47.50	64.00
1.75	17.75	17.75	81.75
2.00	7.75	7.75	89.50
2.25	4.25	4.25	93.75
2.50	3.50	3.50	97.25
2.75	1.25	1.25	98.50
3.00	0.00	0.00	98.50
3.25	0.75	0.75	99.25
3.50	0.50	0.50	99.75
3.75	0.25	0.25	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 1.50
SKEWNESS= 0.40
STANDARD DEVIATION= 0.34
KURTOSIS= 1.45
NORMALIZED KURTOSIS= 0.59

Table 12

SAMPLE NUMBER=S76-2,3 153LCI

PHI SIZE	WEIGHT	WEIGHT %	CUMULATIVE %
-1.00	0.00	0.00	0.00
-0.75	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
-0.25	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00
0.50	0.00	0.00	0.00
0.75	0.00	0.00	0.00
1.00	0.00	0.00	0.00
1.25	1.00	1.00	1.00
1.50	0.75	0.75	1.75
1.75	2.75	2.75	4.50
2.00	11.50	11.50	16.00
2.25	29.00	29.00	45.00
2.50	47.50	47.50	92.50
2.75	4.50	4.50	97.00
3.00	2.25	2.25	99.25
3.25	0.00	0.00	99.25
3.50	0.75	0.75	100.00
3.75	0.00	0.00	100.00
4.00	0.00	0.00	100.00

MEAN PHI SIZE = 2.24
SKEWNESS= -0.19
STANDARD DEVIATION= 0.25
KURTOSIS= 1.09
NORMALIZED KURTOSIS= 0.52

Table 13

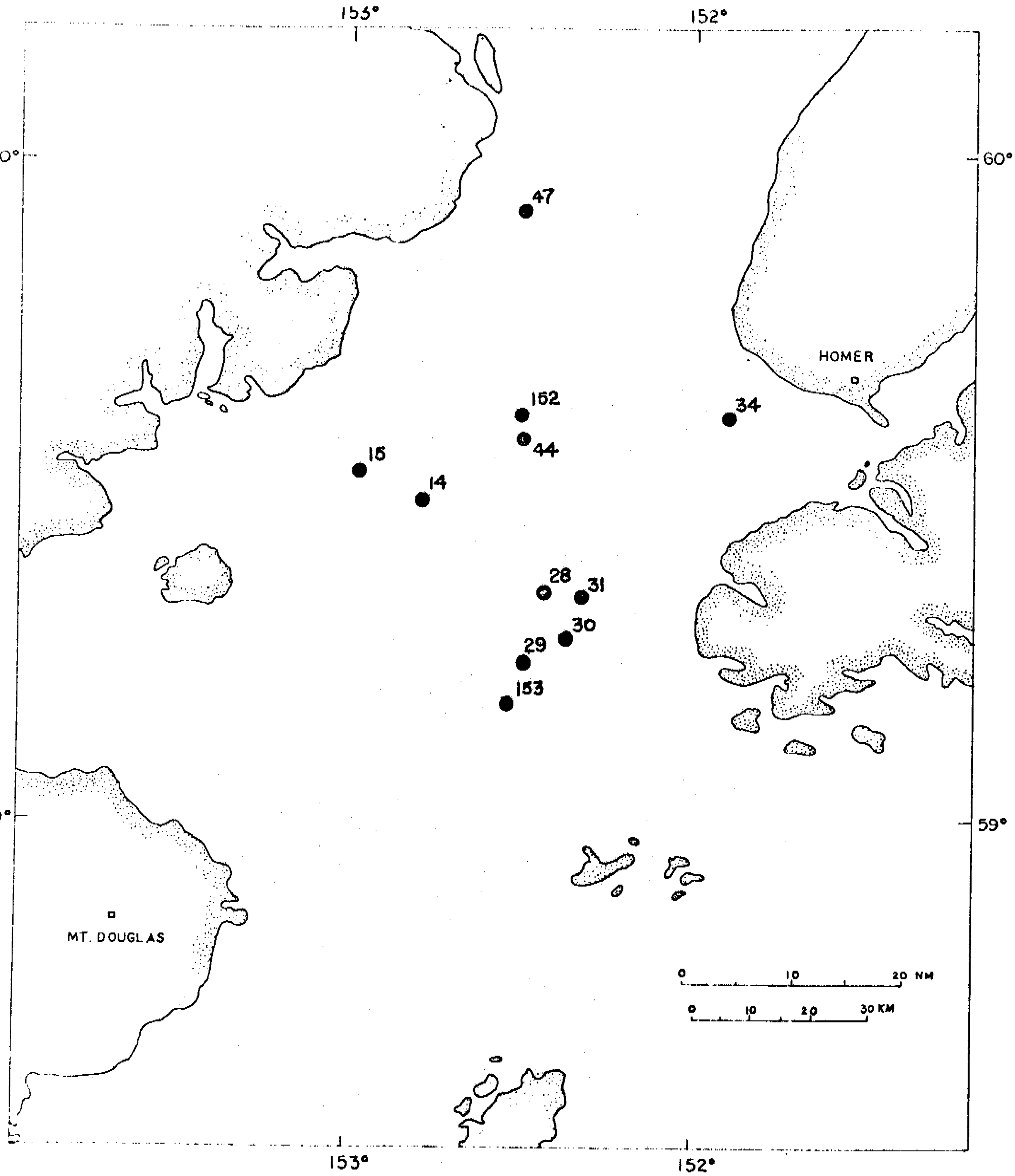


FIGURE 1. Locations of samples.

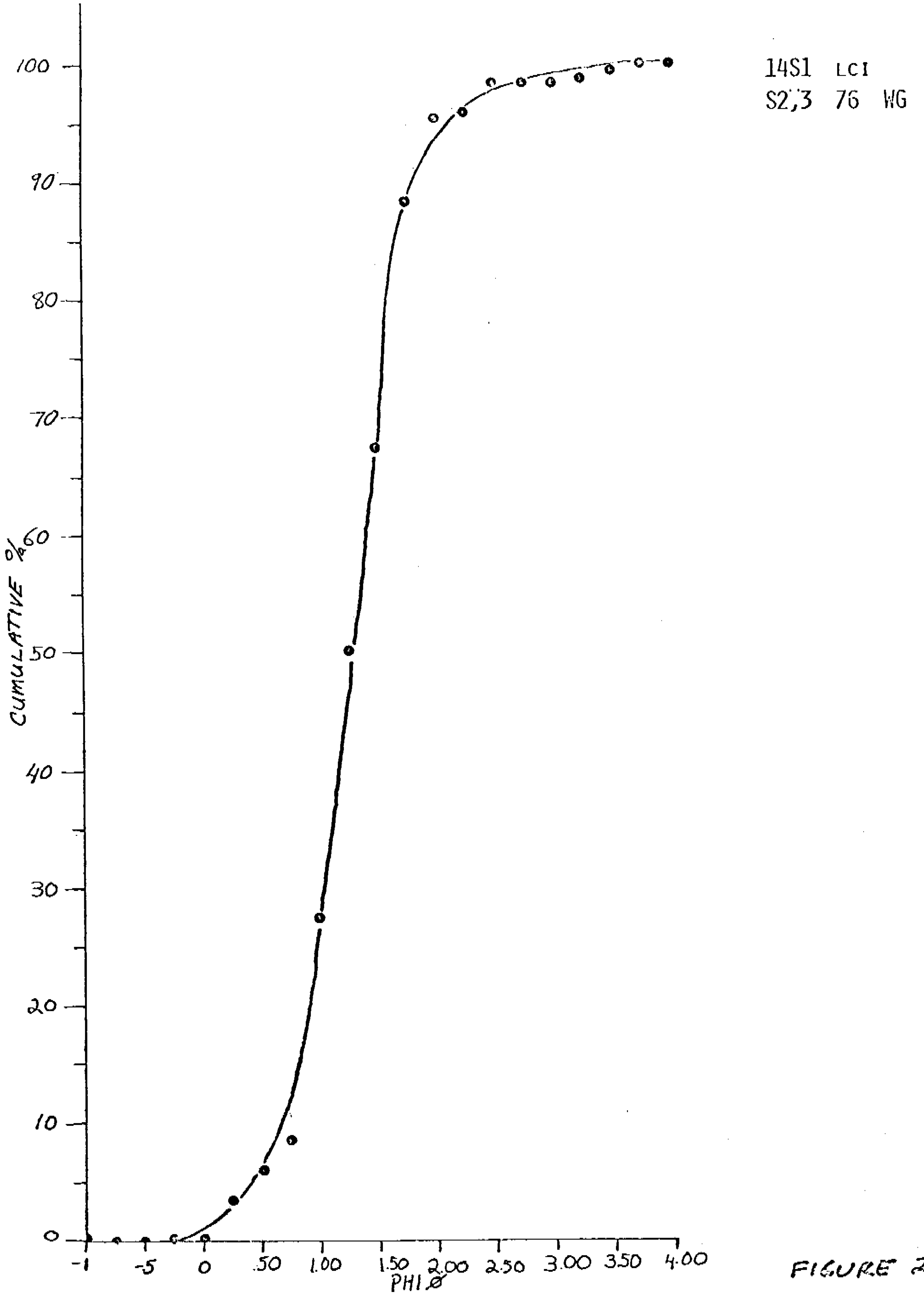

14S1 LCI
S2,3 76 WG
100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE %
-1
-5
0
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI Ø

FIGURE 2

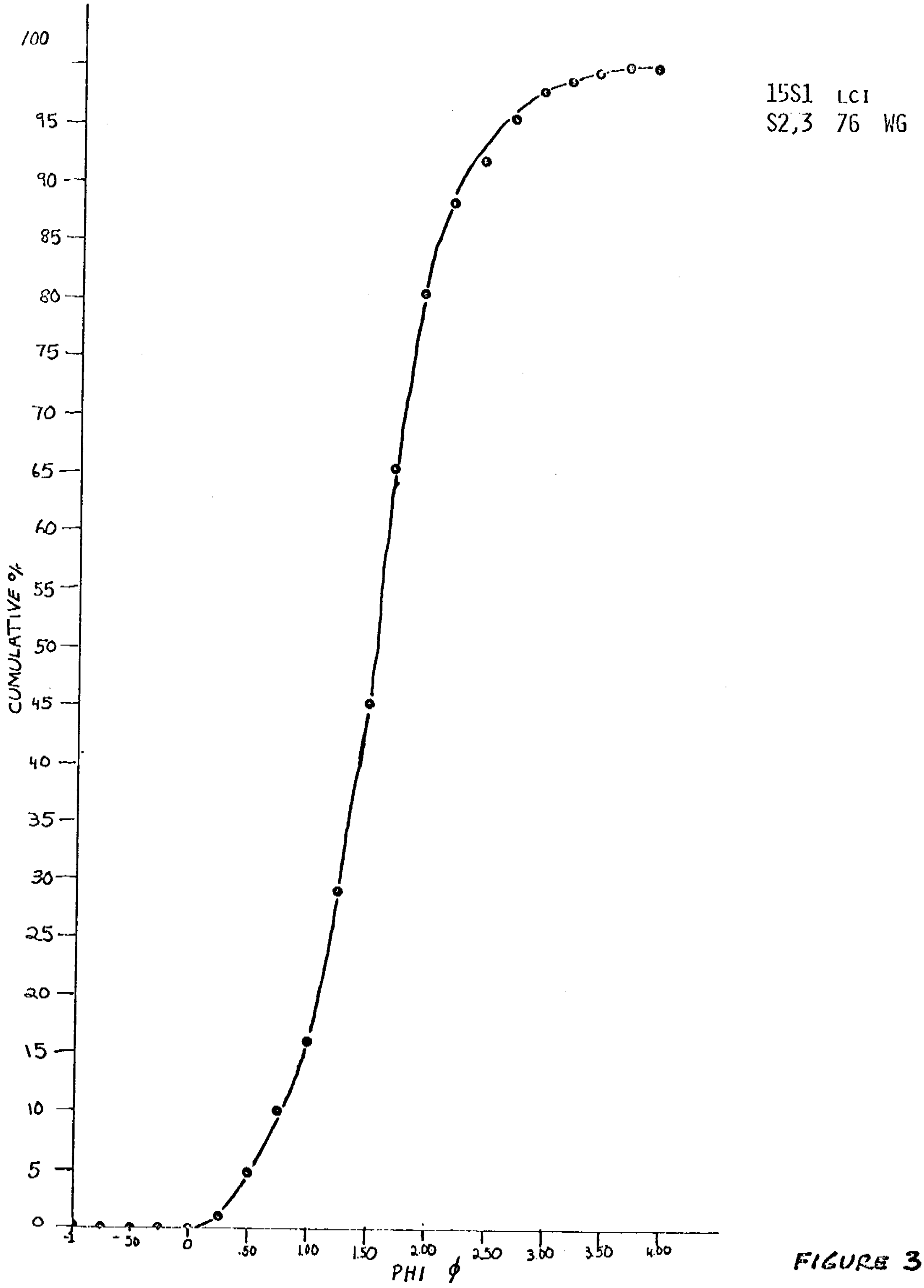

100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
CUMULATIVE %
-1
-.50
0
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI ϕ
15S1 LCI
S2,3 76 WG

FIGURE 3

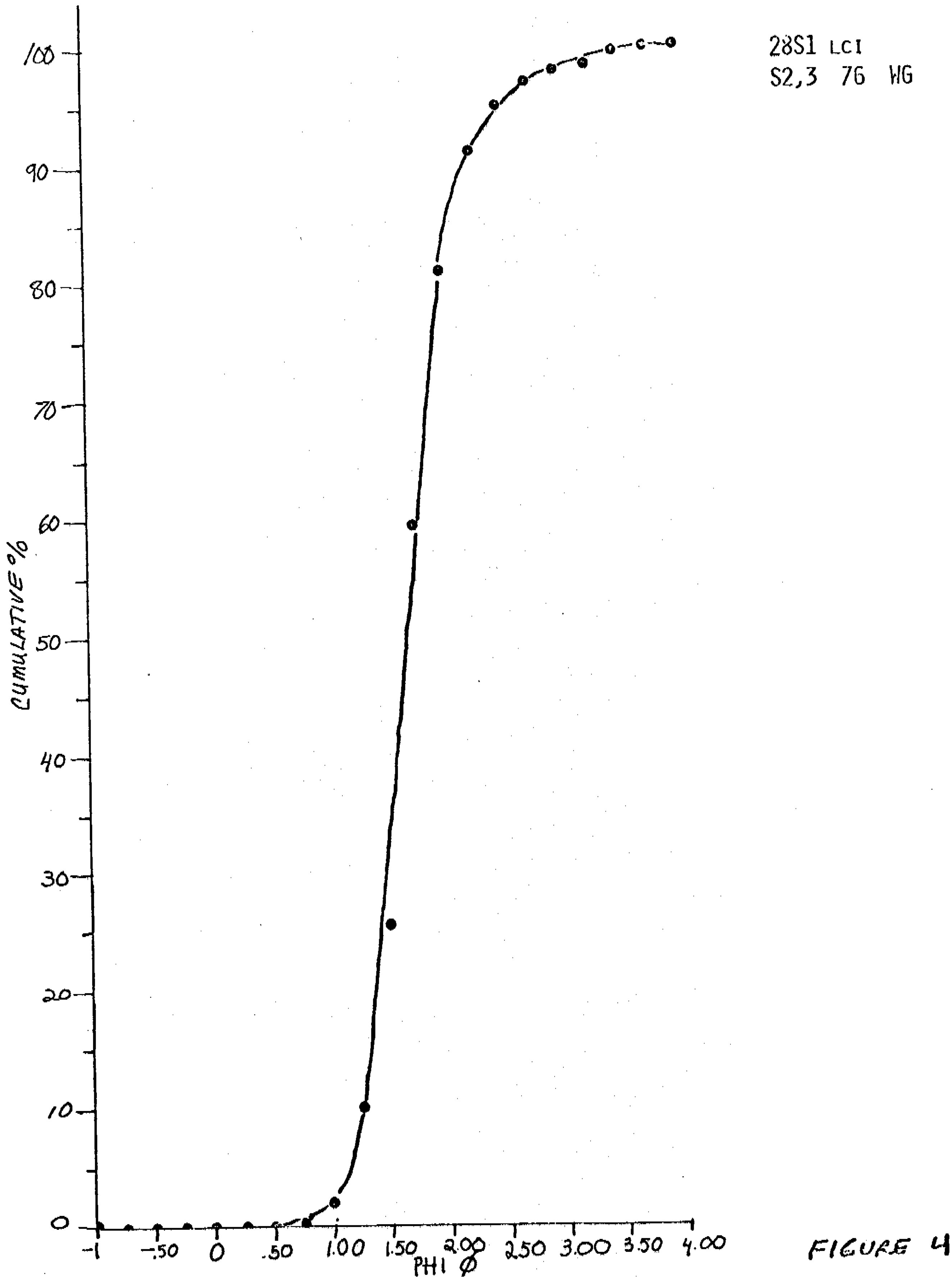
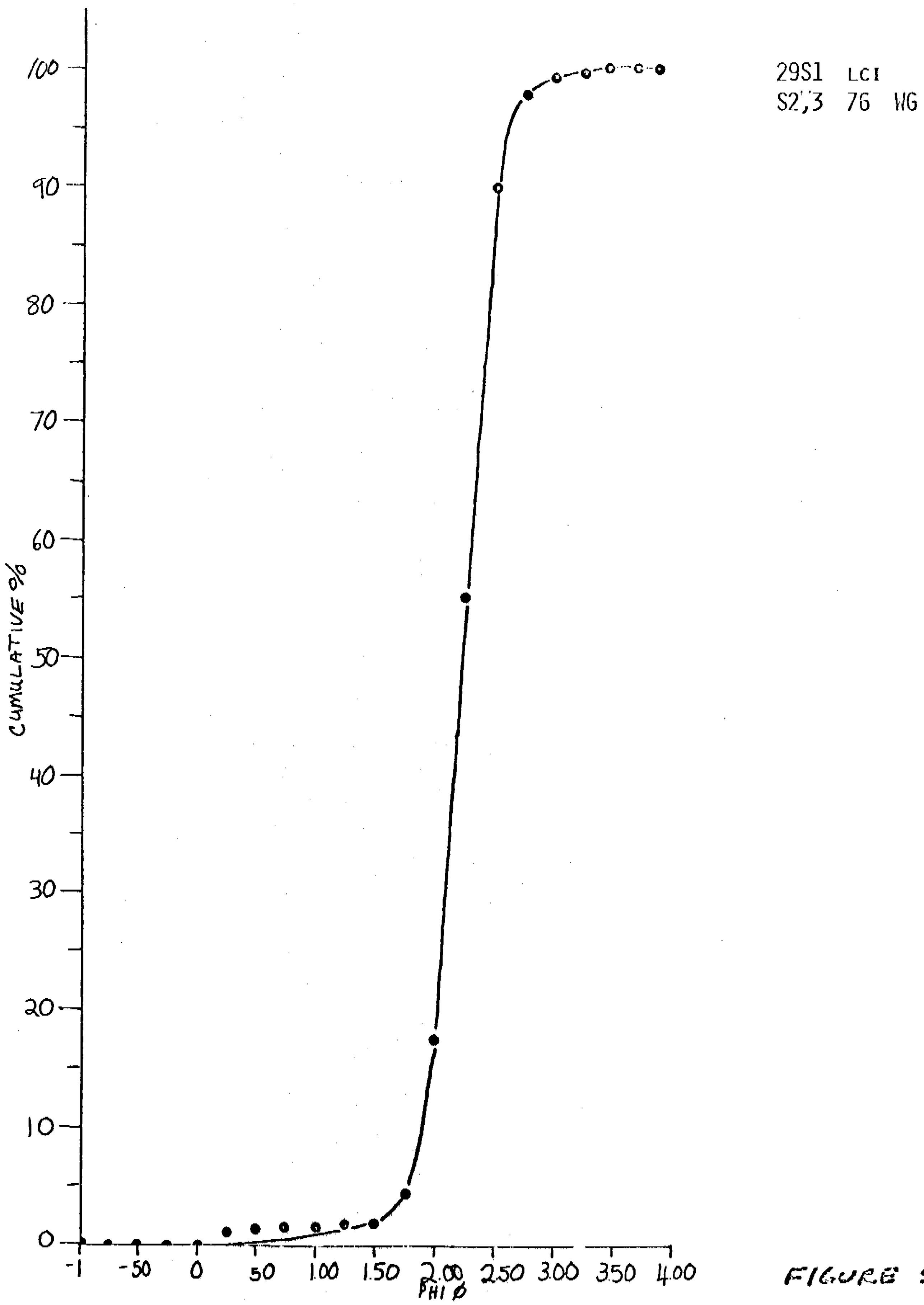
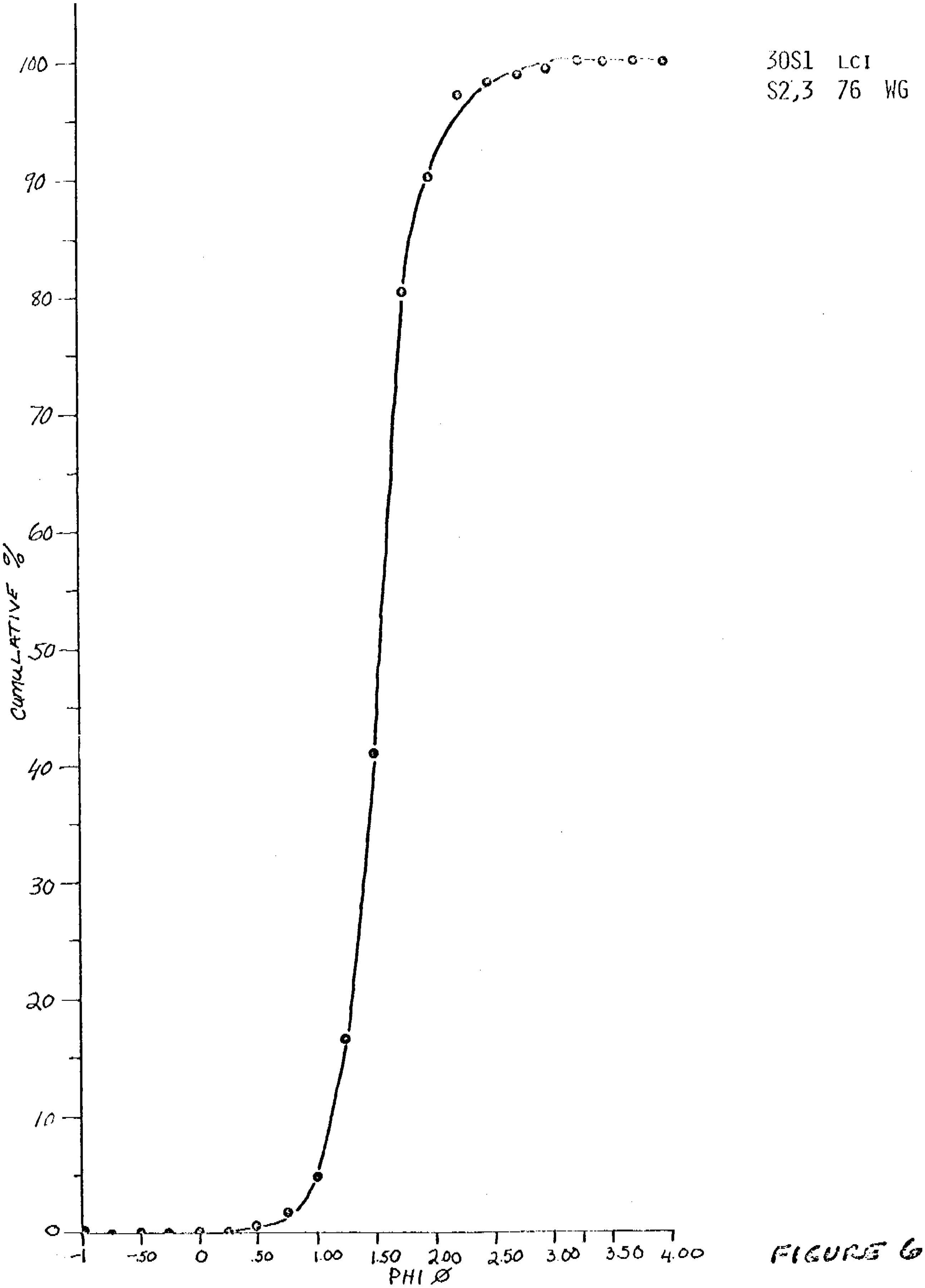

28S1 LCI
S2,3 76 WG
CUMULATIVE %
100
90
80
70
60
50
40
30
20
10
0
-1
-.50
0
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI Ø

FIGURE 4



100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE %
29S1 LCI
S2,3 76 WG
-1
-50
0
50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI ø

FIGURE 5



30S1 LCI
S2,3 76 WG
100
90
80
70
60
50
40
30
20
10
0
CUMULLATIVE %
-1
-.50
0
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI Ø

FIGURE 6

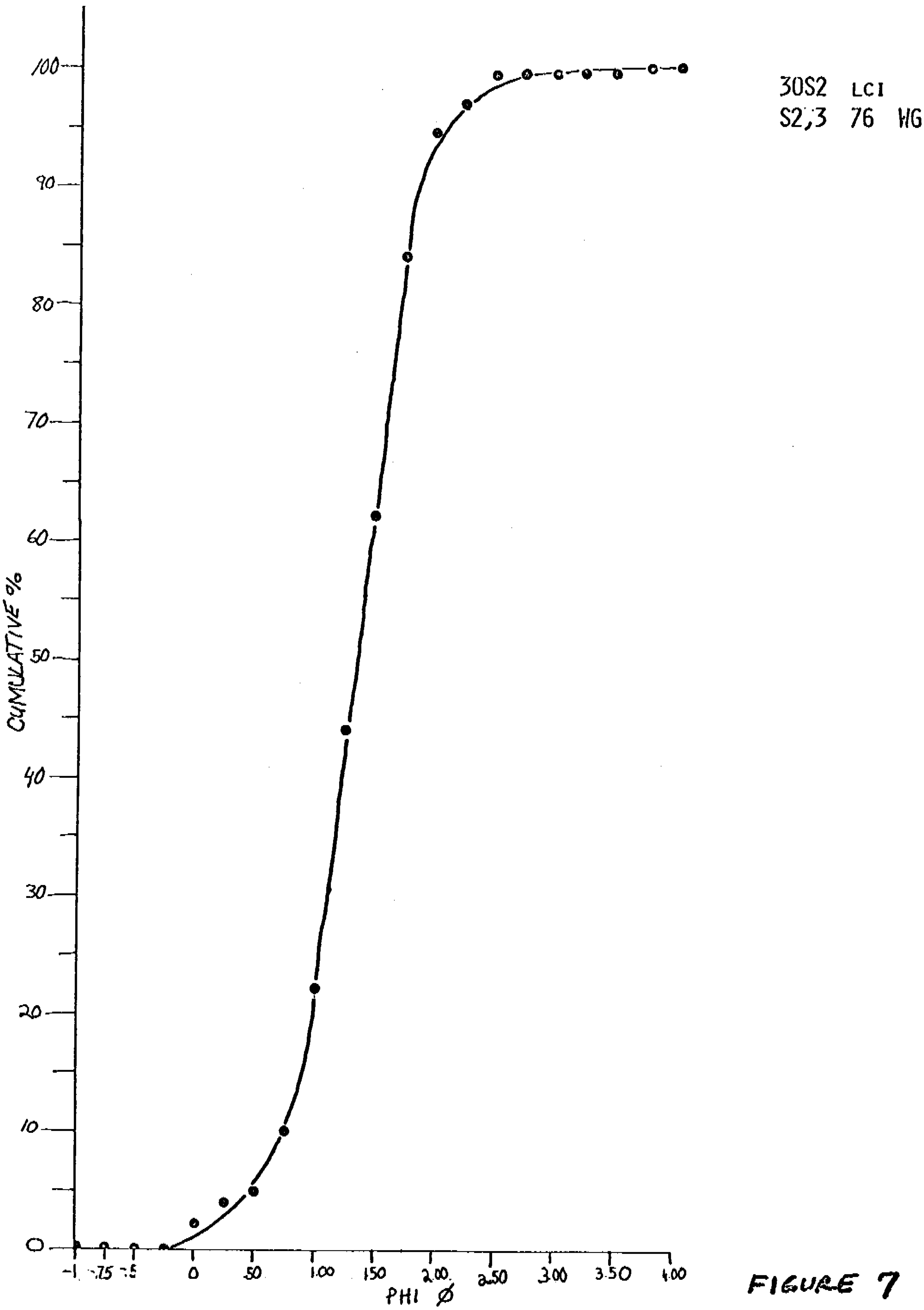
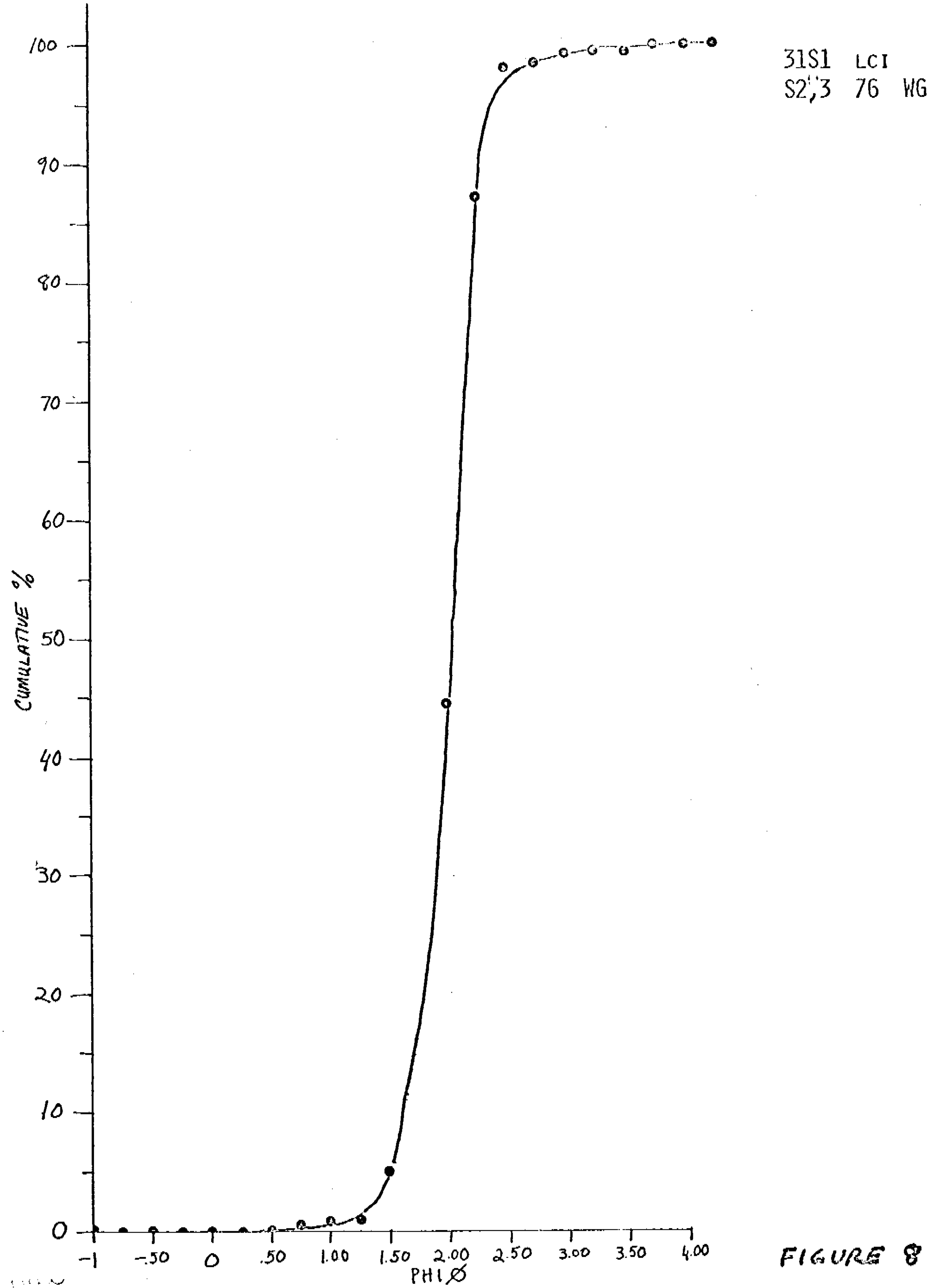
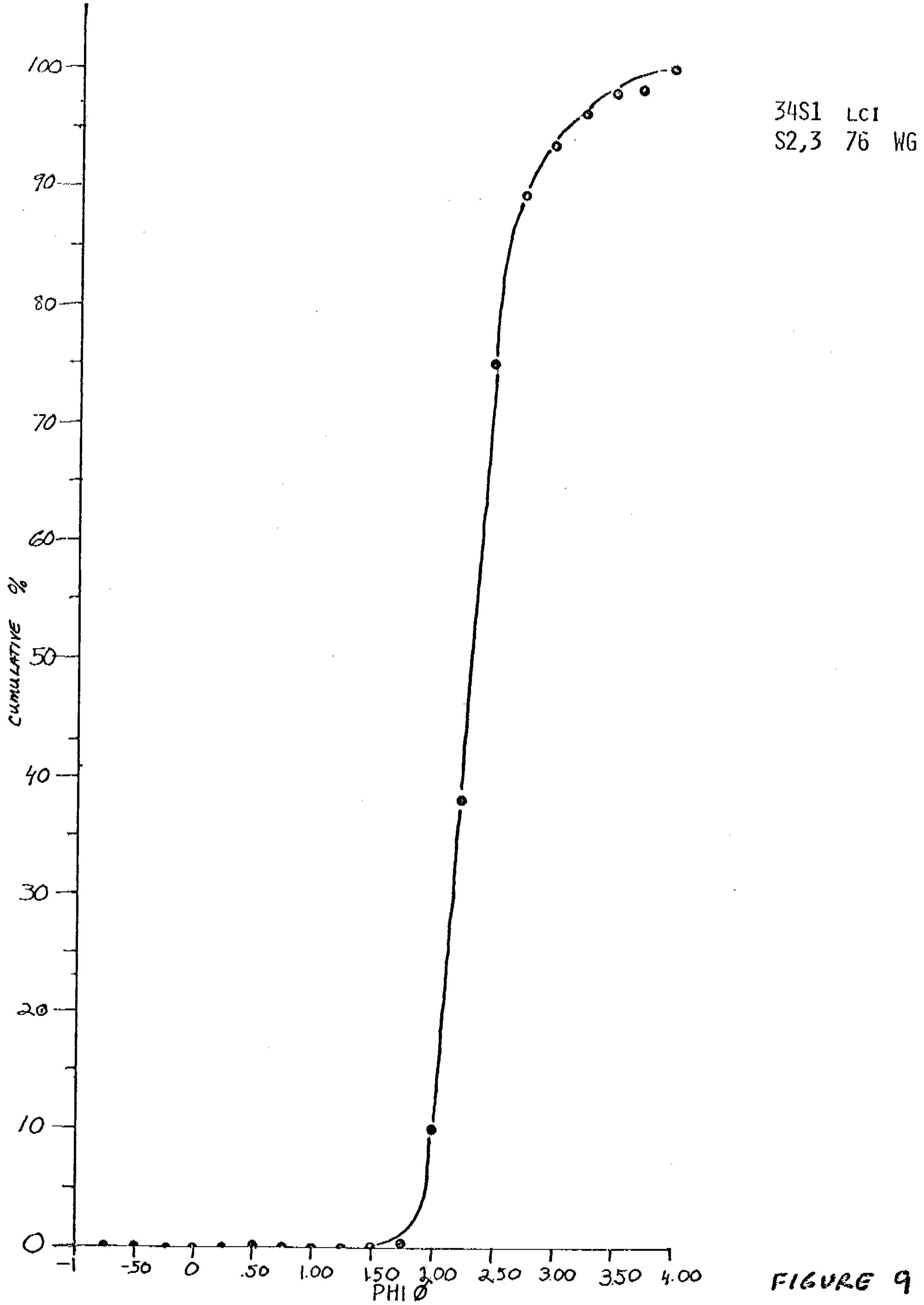

30S2 LCI
S2,3 76 WG
CUMULATIVE %
100
90
80
70
60
50
40
30
20
10
0
-1 -.75 -.5 0 .50 1.00 1.50 2.00 2.50 3.00 3.50 4.00
PHI Ø

FIGURE 7



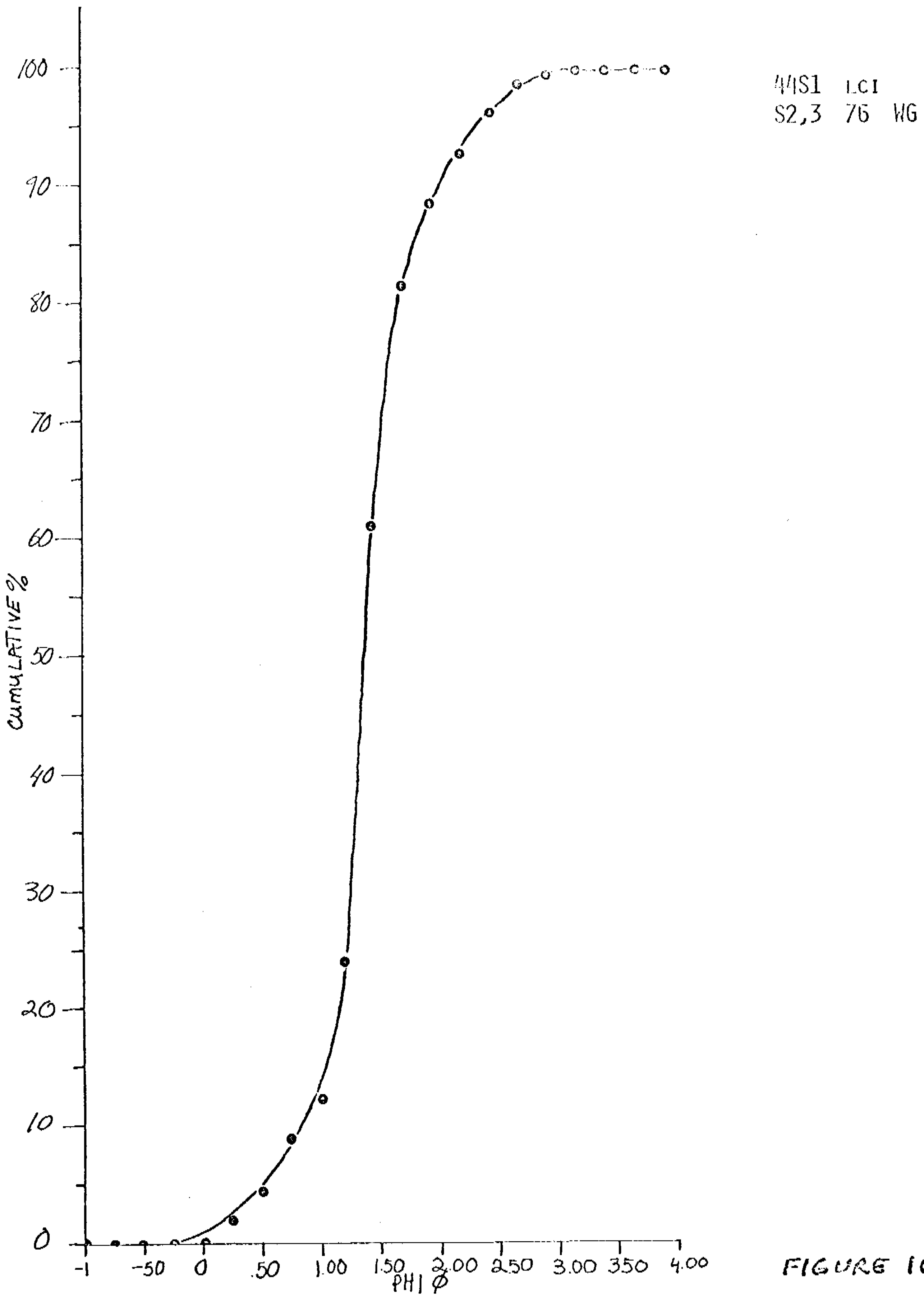
31S1 LCI
S2,3 76 WG
100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE %
-1
-.50
0
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI Ø

FIGURE 8



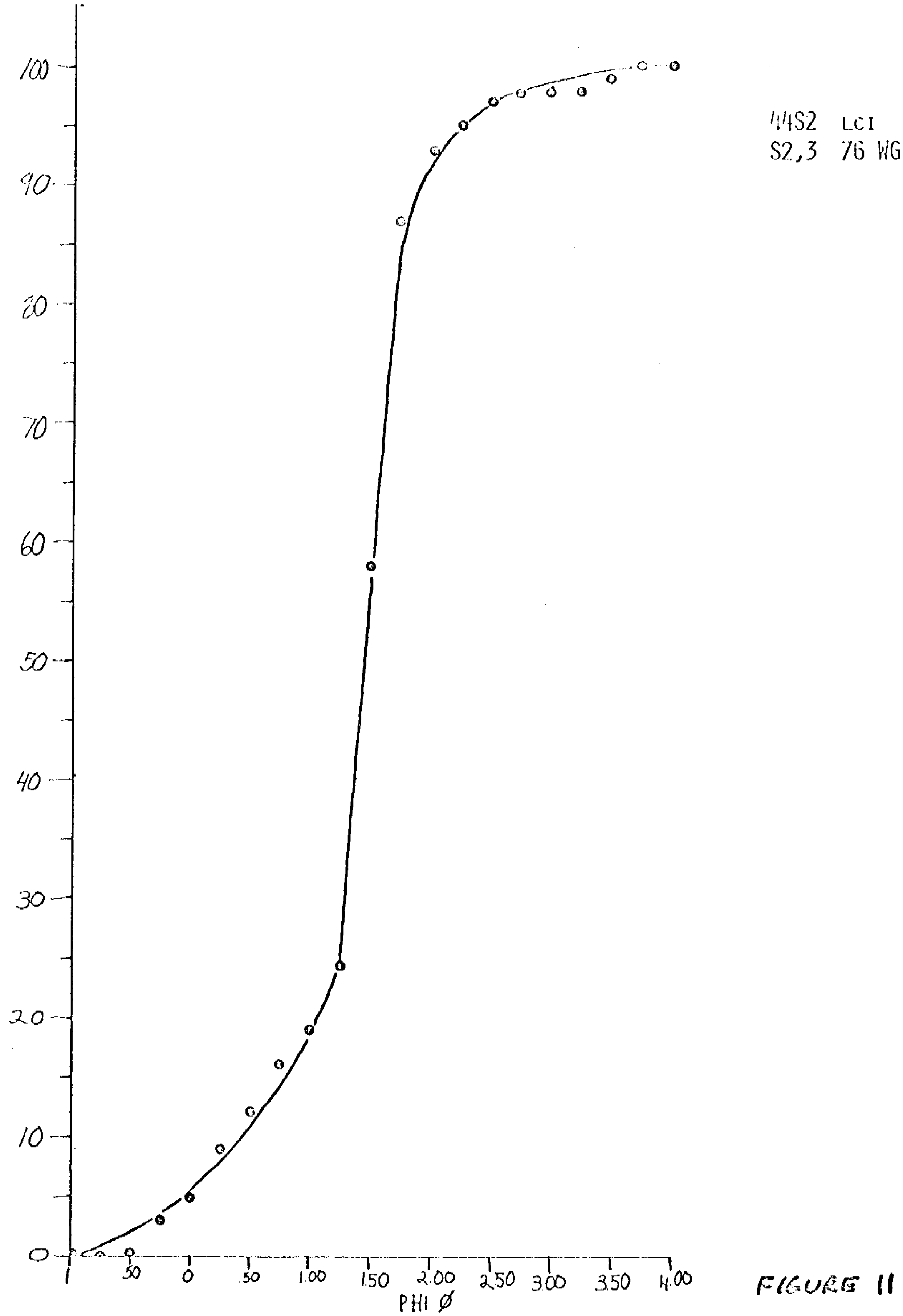
100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE %
-1
-50
0
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI Ø
34S1 LCI
S2,3 76 WG

FIGURE 9



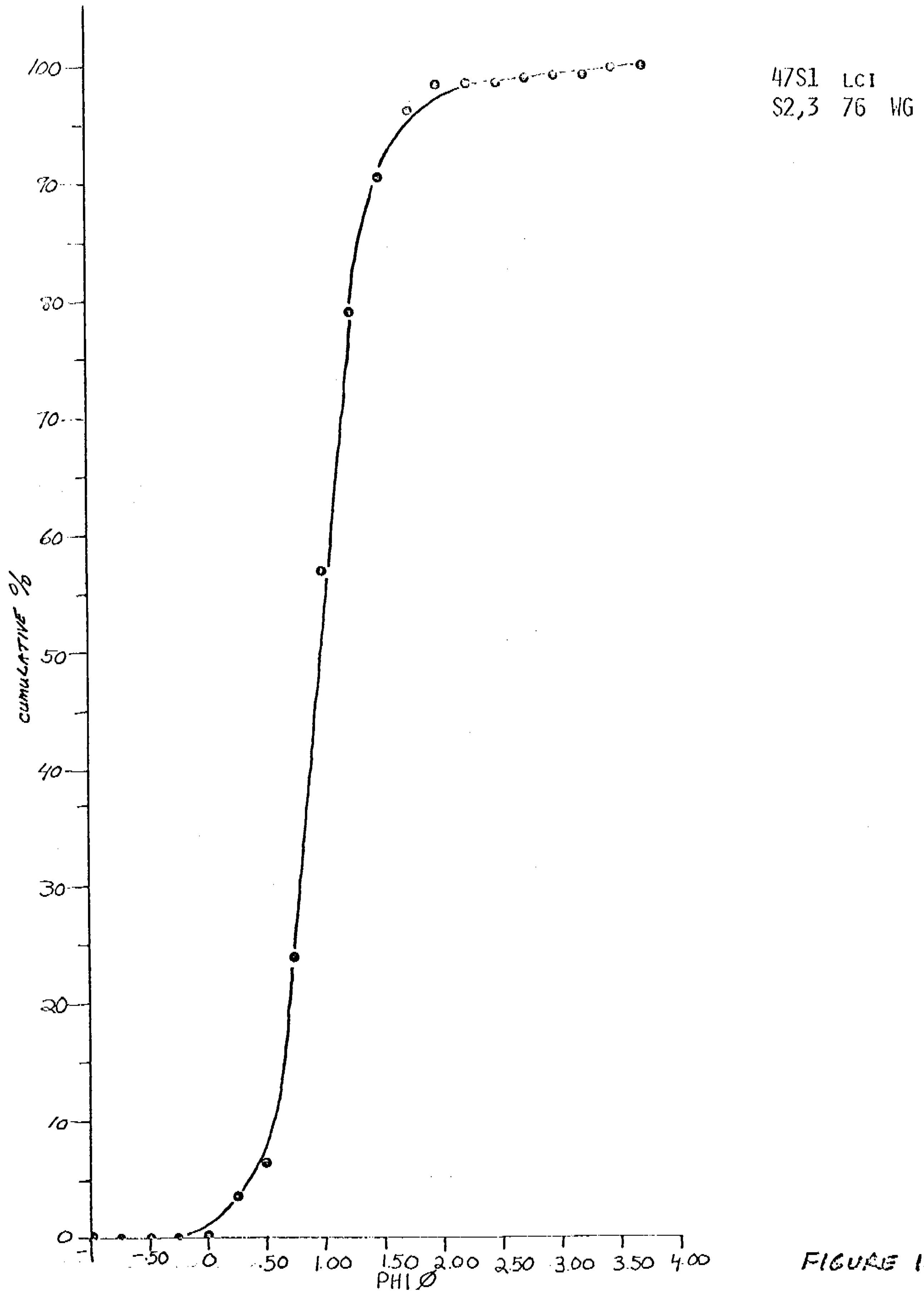
100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE %
-1
-50
0
.50
1.00
1.50
2.00
2.50
3.00
350
4.00
PHI Ø
44S1 LCI
S2,3 76 WG

FIGURE 10



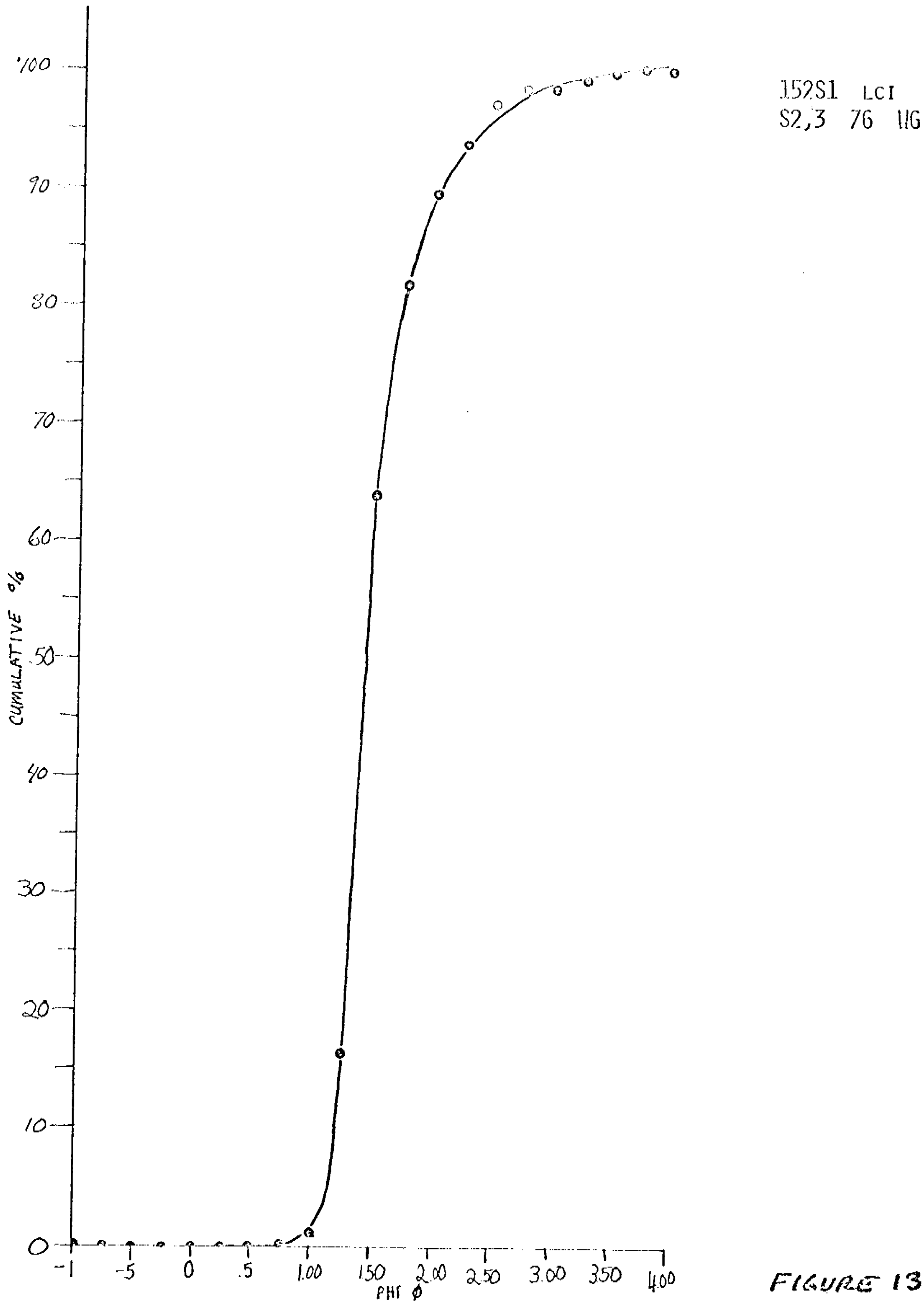
100
90
80
70
60
50
40
30
20
10
0
1
.50
0
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI Ø
44S2 LCI
S2,3 76 WG

FIGURE 11



47S1 LCI
S2,3 76 WG
100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE %
-.50
0
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI Ø

FIGURE 12



100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE %
-1
-5
0
.5
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI ϕ
152S1 LCI
S2,3 76 HG

FIGURE 13

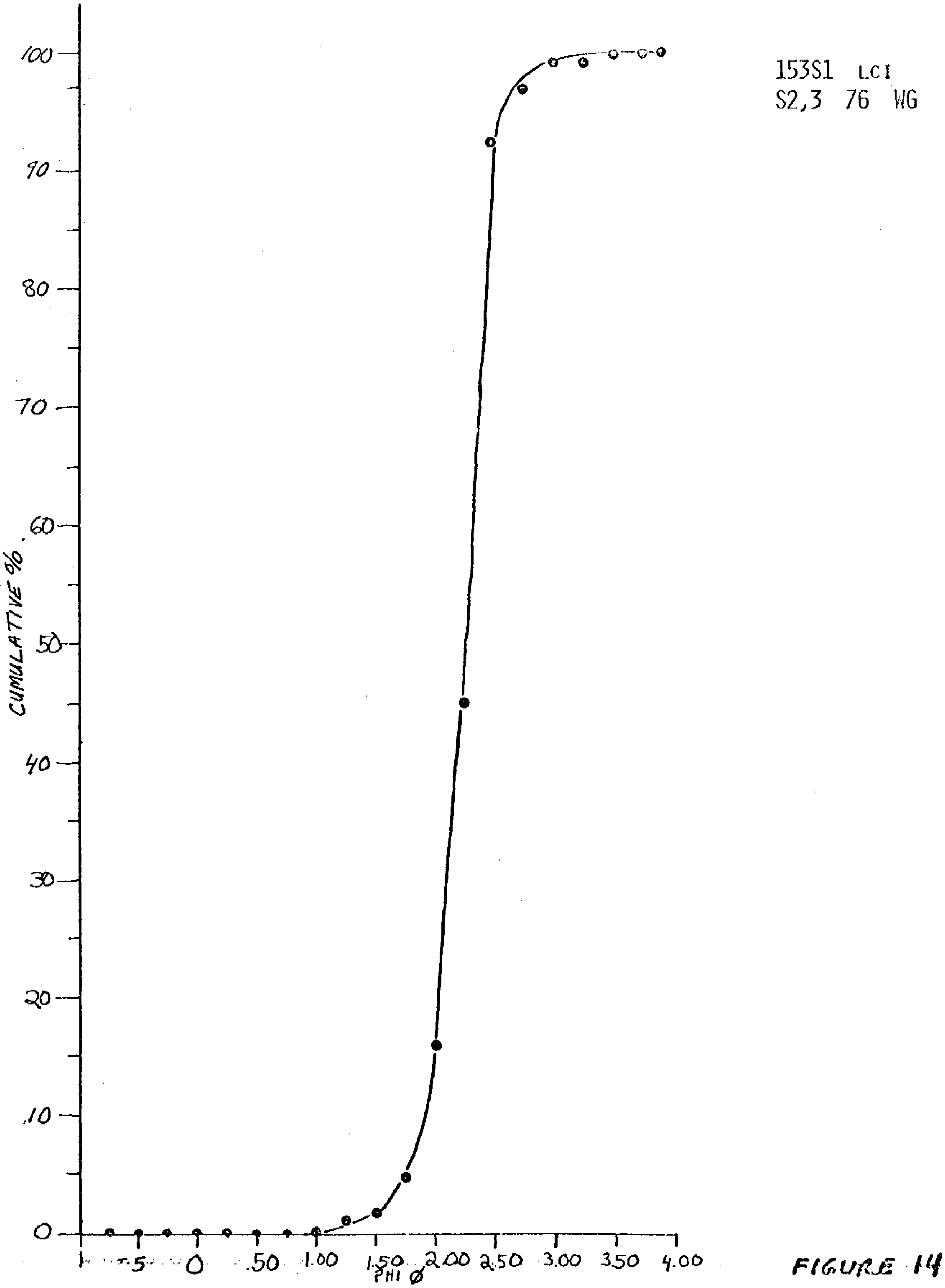

153S1 LCI
S2,3 76 WG
CUMULATIVE %
100
90
80
70
60
50
40
30
20
10
0
-.5
0
.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
PHI Ø

FIGURE 14

APPENDIX II

PRELIMINARY ANALYSIS OF SURFACE MICROTEXTURES ON QUARTZ GRAINS FROM LOWER COOK INLET, ALASKA

PRELIMINARY ANALYSIS OF SURFACE MICROTEXTURES ON QUARTZ GRAINS FROM LOWER COOK INLET, ALASKA

by

Monty A. Hampton, Arnold H. Bouma, and Michael E. Torresan, U.S. Geological Survey, Menlo Park, California 94025

ABSTRACT

The present-day distribution of unconsolidated sediment over the floor of lower Cook Inlet, Alaska, implies that an original blanket of Pleistocene deposits has been winnowed in northern areas and covered with redeposited sands to the south. Surface microtextures on sand-sized quartz grains typically reveal relict glacial features, in most cases modified by chemical or mechanical action.

The distribution of microtextures shows a central zone of intense bedload activity within a field containing large sand waves. Outside of this zone, where bedforms are small or absent, chemical alteration of grain surfaces is abundant, indicating relatively low-energy bedload activity. Grains from a few local areas in the north show nearly unaltered glacially influenced grains, implying that although these have been sites of winnowing, the remaining grains have been sheltered from intense overwhelming chemical or mechanical action.

The distribution of sediments in lower Cook Inlet appears to be approxiately in equilibrium with the present current regime. Significant net transport throughout the area does not appear to be taking place.

INTRODUCTION

Cook Inlet is a large tidal estuary in south central Alaska. In June and July, 1976, a marine environmental geologic survey was conducted in the lower part of the inlet (Fig. 1), aboard the R/V SEA SOUNDER. High-resolution seismic profiling and side-scanning sonar surveys were run, a limited number of underwater TV observations were made, and 50 samples were collected of the surficial sediments.

Examination of sand-size quartz grains with the scanning electron microscope (SEM) from 27 of the samples reveals surface microtextural features that have been suggested to be indicative of specific mechanical and chemical processes (e.g., see Krinsley and Margolis, 1971; Margolis and Kennett, 1971; Whalley and Krinsley, 1974). The distribution of distinctive groups of microtextural features, analyzed in conjunction with other aspects of the sedimentary deposits, provides insight into the sedimentary history and present-day sedimentary dynamics of lower Cook Inlet.

GEOLOGIC AND PHYSICAL OCEANOGRAPHIC SETTING

Cook Inlet is part of a larger structural and sedimentary basin containing volcanic and sedimentary rocks of late Paleozoic to Recent age (see Evans et al., 1972). The major morphologic elements of the area have been established since the end of the Tertiary, and Pleistocene glaciers repeatedly covered most of the inlet (Karlstrom, 1969) depositing blankets of unconsolidated sediment over folded and eroded bedrock.

Most of lower Cook Inlet is relatively shallow, with depths generally between 40 and 80 m. However, near the mouth of the inlet, approximately south of the latitude of Augustine Island, depths abruptly increase to 120-200 m.

Circulation in lower Cook Inlet is mainly controlled by tides and by the counter-clockwise Alaska current. Northward-moving flood currents flow predominantly up the eastern side of the inlet, whereas ebb currents flow south mostly on the western side. Strong tidal currents create a thorough mixing of the water column, and bottom flow is strong enough to move coarse sediment. The details of the circulation in lower Cook Inlet are complicated, and most of them are as yet unresolved.

Visual estimates of the grain-size distributions of the surficial sediment samples are presented in Figure 2. Sediments are relatively coarse, gravel to boulder-bearing sands in the north, grading to clean sands and then to muddy sands to the south. Local exceptions occur near some of the land masses. This distribution apparently reflects decreasing energy density of currents with increasing width and depth of the inlet toward the south.

Numerous fields of bedforms occur throughout lower Cook Inlet (Fig. 3), and a wide variety of bedform types have been observed including sand waves, dunes, sand ribbons, and perhaps sand ridges. The bedforms occur most abundantly in the central portion of the inlet, where the sediments are predominantly clean sands (see also Bouma et al., 1977a, b).

METHODS

The sediment samples were collected with a modified version of a Van Veen grab sampler, as designed by Andy Soutar of Scripps Institution of Oceanography. Subsamples were taken from the upper few centimeters and back in the laboratory they were wet-sieved to remove silt- and clay-sized material. The samples were boiled in 50% HCl for 10 minutes to remove fine-grained debris and carbonate coatings from the grain surfaces. The samples were dried, and heavy minerals were removed using bromoform. Splits of the 1,500 μm-500 μm and 500 μm - 355 μm size ranges were taken from the remaining light grains. Quartz grains were hand-picked from the coarser split and mounted on standard SEM stubs using transfer tape. If the coarser split did not yield enough suitable grains, the finer fraction was used.

A Cambridge Steroscan 180 scanning electron microscope was used in this investigation. Photographs were taken with a Polaroid 55 Pos/Neg film. More than 15 grains were studied from each sample to obtain sufficient data for qualitative assessments of relative abundances and variations.

GENERAL DESCRIPTION OF MICROTEXTURES

Most samples analyzed for this study show some combination of glacial, mechanical impact, and chemical solution/precipitation features (Fig. 4). Original grain morphology inherited from the parent rock may dominate in some cases.

The major features noted to be indicative of previous glacial activity include high surface relief, angularity of grains, conchoidal fractures of various sizes, parallel and sub-parallel steps, upturned plates, flat cleavage faces, and cleavage traces. Mechanical impact features include rounded edges of grains, abundant V-forms on rounder edges but also occurring on flat and even recessed areas of intensely abraded grains, breakage features, and upturned plates. Chemical features include smooth precipitation surfaces, thicker irregular overgrowths, solution pits, precipitated and etched upturned plates, and terminated quartz crystals. Photographs clearly illustrating all these features are presented in Krinsley and Doornkamp (1973).

Features interpreted to have a glacial origin cannot always be distinguished from features inherited from the source rock (see Krinsley and Doornkamp, 1973, p. 10), and some grains from lower Cook Inlet cannot be separated in this respect. However, it is likely that most surficial grains in lower Cook Inlet have experienced glacial transport (see Karlstrom, 1969) and most grains show convincing combinations of microtextures to support this. However, some samples close to land, for example sample 32, might have significant input of grains from Tertiary or Mesozoic bedrock that have not undergone glacial modification.

Chemical activity evidently has left its imprint during several stages of the Quaternary histories of many grains. Unmodified chemical overgrowths and etchings were observed, but mechanical impacts on chemical surfaces are common, as is breakage of these surfaces. Also, chemical smoothing or overgrowth of mechanically impacted surfaces occurs. Most chemical overgrowths are irregularly shaped, but at least two samples (29 and 32) contained grains with overgrowths showing good crystal form.

DISTRIBUTION OF MICROTEXTURES

The distribution of microtextures depicted in figure 4 can be divided into three main groups. Generally, glacial textures are most abundant only in a few samples from the northern area (samples 5, 9, 32, and 49), mechanical features with abundant glacial features are common in samples from the central area (samples 27, 28, 30, 33, 35, and 36), and chemical features are most abundant in other areas. Sample 41 in the mouth of Katchemak Bay, which shows an abundance of mechanical features but lies outside the central area, is an anomaly.

The distribution pattern shows some interesting relations to occurrence of bedforms, grain-size distributions, and bathymetry. Samples exhibiting mostly glacial features, in addition to being located to the north, were taken from sediments containing much material coarser than sand and from areas where bedforms are absent or small-scale. The two samples (5 and 9) occurring outside bedform fields contain abundant chemical features but only minor evidence of mechanical brasion. The other two samples (37 and 49) occur within bedform fields and show abundant mechanical impact features but only minor chemical alteration.

All but one of the samples exhibiting mechanical impact features as the most abundant microtextural type occur within the bedform fields. Chemical alteration is the least abundant type of feature in these samples. The samples that show most intense mechanical abrasion (27,28,30, and 33) occur in the more southerly fields, which include the largest sand waves. The large bedforms have smaller sand waves superimposed on their flanks, and our underwater TV observations show that bedload movement of sand is intense, with grain velocities up to about 30 cm/s.

The samples containing highly chemically attacked grains occur mostly outside the bedform fields, although a few samples came from within fields containing small bedforms near the edges of the overall bedform area. The deeper-water samples (22,23,25,150) are all characterized by the presence of chemical features. Most of these deeper-water samples also contain significant quantities of silt and clay (Fig. 2).

CONCLUSIONS

The association of certain microtextural types with certain bottom features points out several aspects of the sedimentary history and dynamics of lower Cook Inlet. After the final Pleistocene glacial recession, most grains on the floor of lower Cook Inlet probably exhibited an overwhelming dominance of glacial features (which can include significant chemical imprints; see Krinsley and Doornkamp, 1973; Whalley and Krinsley, 1974). Most samples examined in this study show ample evidence of a glacial history. Glacial features appear quite fresh and unaltered on some grains, but most typically they are either chemically etched or overgrown, or they are mechanically subdued. These alterations mostly reflect conditions that began during the post-Pleistocene shoreline transgression and have developed into the present-day setting.

The present distribution of grain sizes over the floor of lower Cook Inlet probably reflects the relation of current velocity to width and depth of the inlet. Current velocities are generally high in the narrow northern part of the area, and they tend to decrease as the inlet widens to the south. Poorly sorted glacial sediments that once blanketed the inlet have been redistributed by winnowing of sand, silt, and clay in the north, leaving behind a coarse-grained lag, and deposition of sand in the wider areas to the south. Currents evidently slacken enough to deposit some silt and clay in the deep areas in the southern part of the inlet, but most has been carried out to Shelikof Strait and perhaps to the Kodiak Shelf.

The bedforms have developed where sufficient sand and current velocities are available. The most active bedform areas, in terms of intensity of bedload movement, have imparted abundant mechanical features to the grains, subduing the original glacial features and effectively obliterating the effects of any chemical activity that might be taking place. (Note that sample 29, located in a narrow zone with a smooth bottom containing a few s 11 bedforms, and surrounded by very large bedforms, shows abundant chemical and glacial features but only minor evidence of mechanical action.)

In areas outside the bedform fields, and at a few places within fields of small-scale bedforms, transport activity apparently is minor, as indicated by the paucity of impact features, and the grains are subjected to substantial chemical activity. Most grains predominantly covered by chemical microtextures still show some signs of their glacial past.

A significant observation is that grains with a high density and abundance of mechanical impact features are rarely found outside of the central bedform area. This implies that the high density of mechanical features is imparted to grains within the zone of intense sediment dynamics, where they are found today. But, these grains are not being transported in significant quantities out of this zone. The grains may experience high instantaneous velocities due to tidal currents, but their net long-term motion is equal to that of the bedform field itself, which is extremely low and perhaps zero. Sand grains are not moved through the bedform fields on their way to being washed out of the inlet, but instead there seems to be an equilibrium state between circulation and bed material. The original winnowing pattern that removed sand from the narrow northern part of the lower inlet and redistributed it to the south may not be evolving significantly today.

It is possible, of course, that after grains are moved out of a zone of intense bedload movement, chemical activity erases many of the mechanically formed features and therefore, the previous residence time in the high energy zone is obscured. No evidence for this was seen, however. In particular, highly abraded grains typically show abundant V-forms on flat surfaces and even on some recessed surfaces. Analogous surfaces on grains outside the high energy area show no vestige of substantial impact features, even on surfaces that show no significant chemical alteration.

In summary, a few local areas in the northern part of lower Cook Inlet have sand grains with mostly relict glacial microtextures. These areas have served as sites of winnowing for grains moved farther south, and the remaining sand grains have been exposed only to moderate chemical or mechanical activity. Within the main zone of bedforms is a zone of intense to-and-fro, tidally controlled bedload motion. Grains within this zone have been highly mechanically abraded and apparently are more-or-less permanent residents of this zone. In the remaining parts of lower Cook Inlet, bedload activity apparently is of lower energy, as evidenced by the paucity of mechanical impact features, and grain surfaces are subjected to intensive chemical alteration.

Pleistocene sediments have been redistributed by tidal currents within the inlet. High-velocity currents in the narrow, northern area have winnowed sand and mud, and substantial amounts of this sand and minor amounts of mud, have been redeposited to the south. Substantial southward migration of sand does not appear to be occurring today, and the distribution of sediments may represent a relatively stable, equilibrium situation.

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Krinsley, D.H., and Margolis, S.V., 1971, Grain surface texture: in Carver, R.E.(ed.), Procedures in Sedimentary Petrology: New York, Wiley-Interscience p. 151-180.

Margolis, S.V., and Kennett, J.P., 1971, Antarctic glaciation during the Tertiary recorded in sub-Antarctic deep sea cores: Amer. Jour. Sci.:, v. 271, p. 1-36

Whalley, W.B., and Krinsley, D.H., 1974, A scanning electron microscope study of surface textures of quartz grains from glacial environments: Sedimentlology, v. 21, p. 87-105.

FIGURE CAPTIONS

Figure 1. Location map of the study area, lower Cook Inlet.

Figure 2. Grain-size distributions of surficial sediments, lower Cook Inlet.

Figure 3. Distribution of bedforms in lower Cook Inlet.

Figure 4. Microtextures on surfaces of quartz sand grains, lower Cook Inlet.

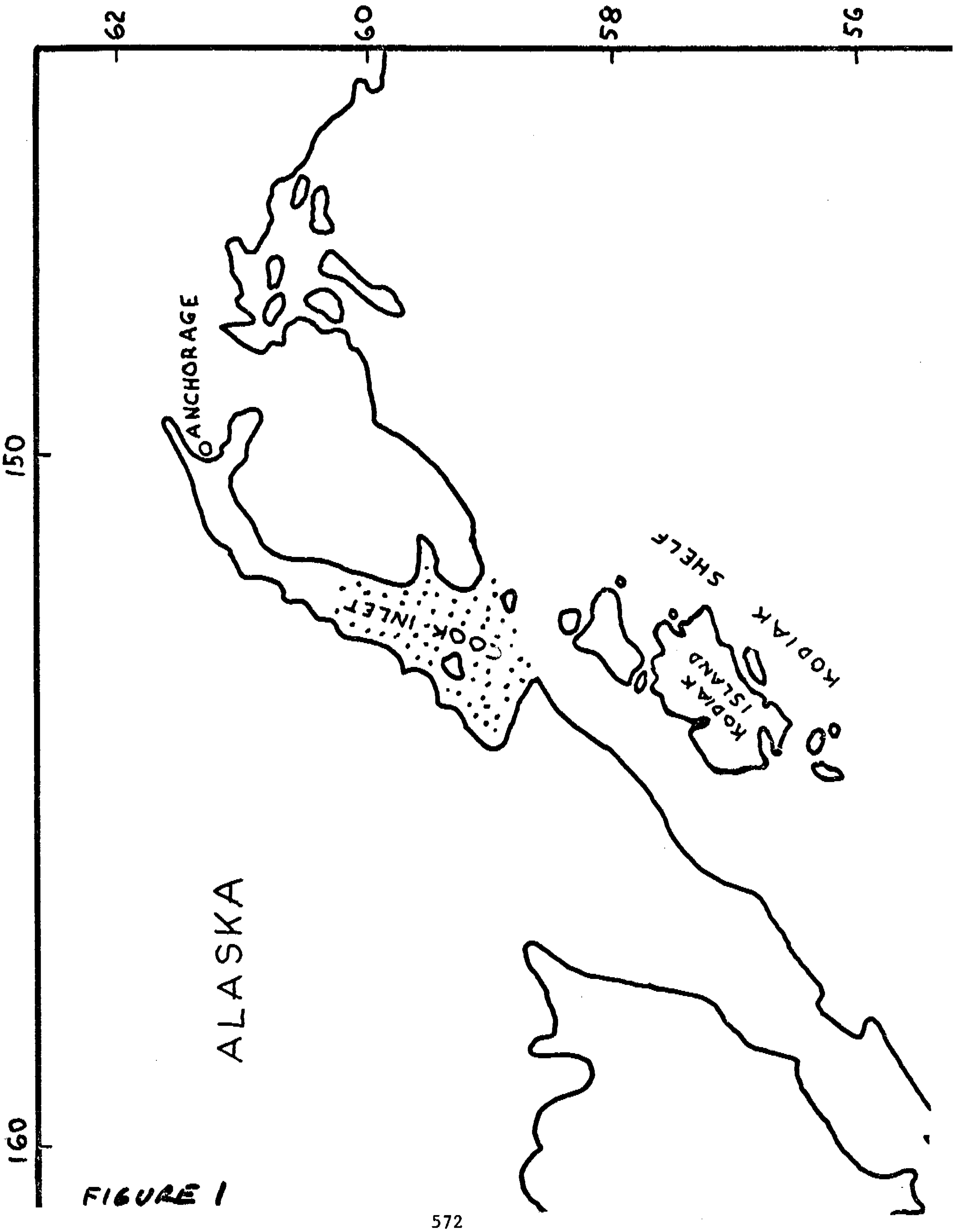

62
60
58
56
150
160
ALASKA
ANCHORAGE
COOK INLET
SHELF
KODIAK ISLAND
KODIAK

FIGURE 1

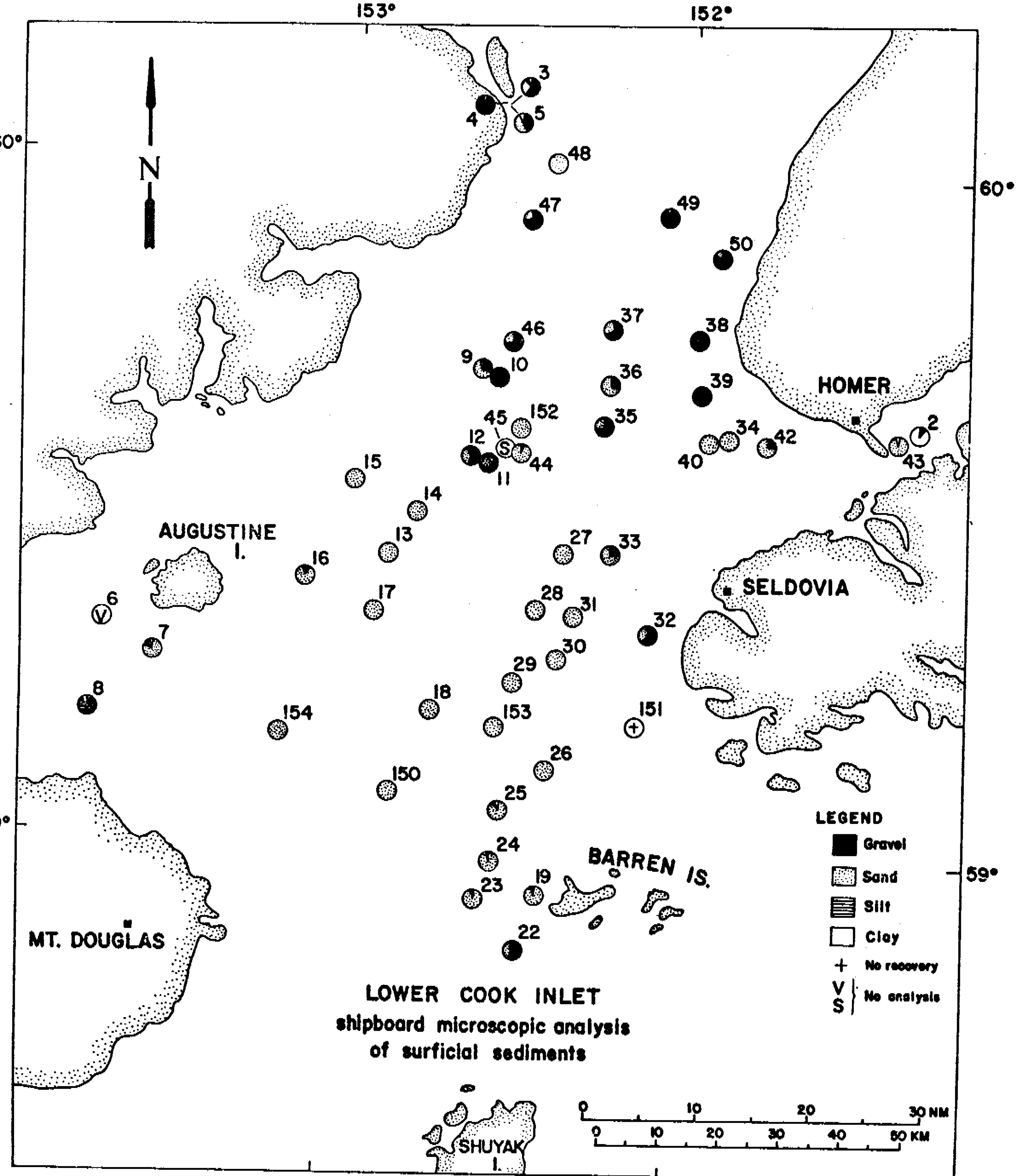
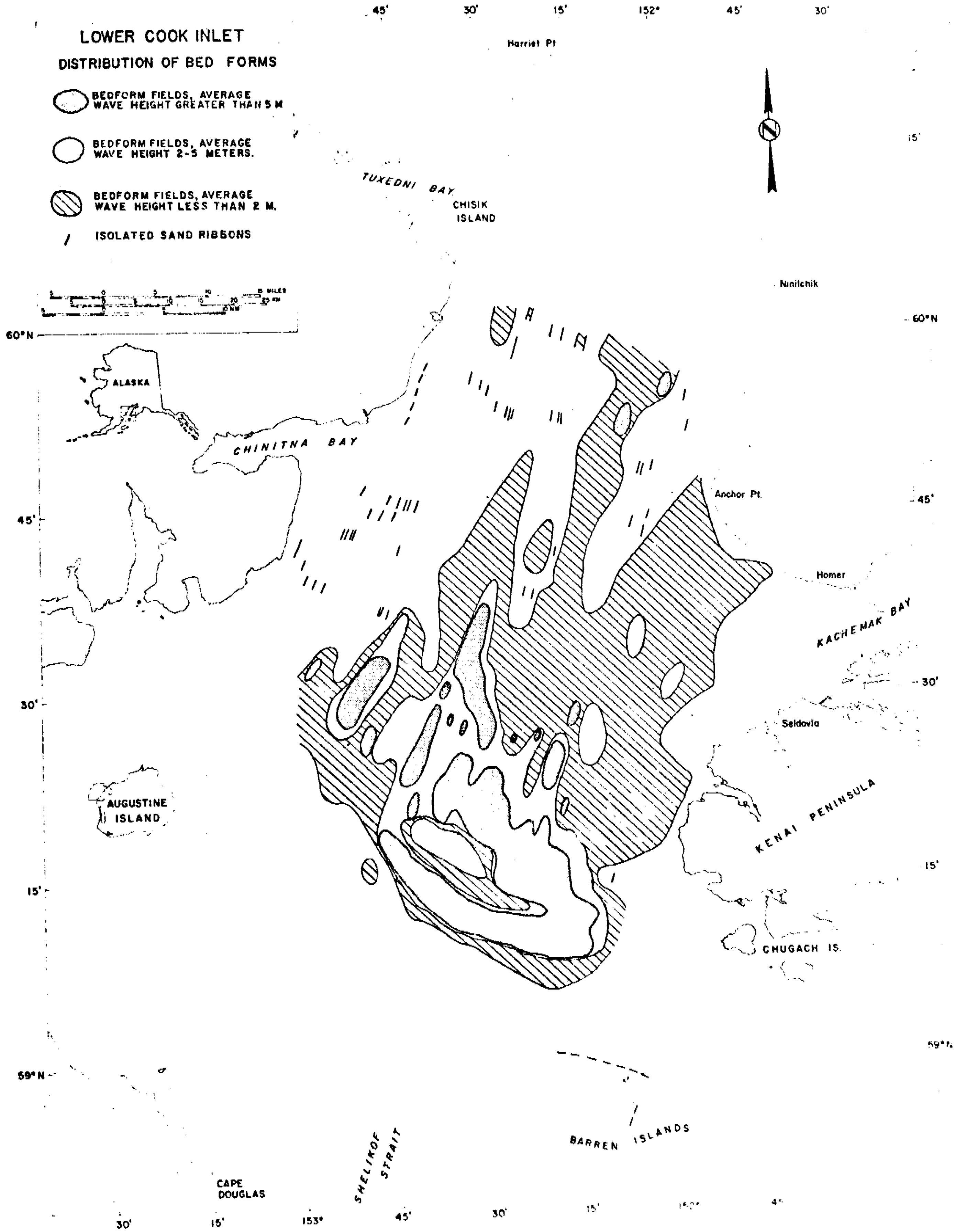


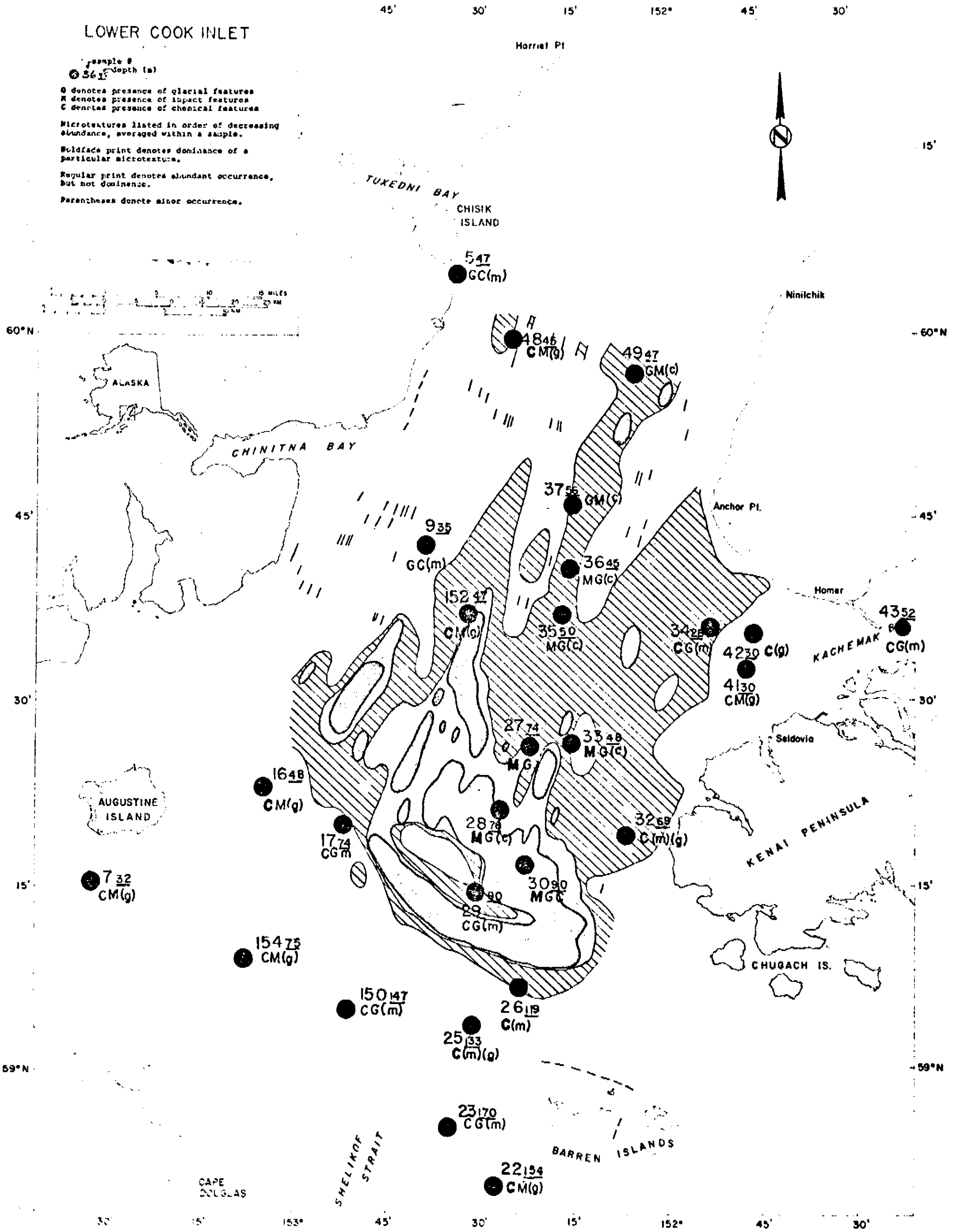
PLATE 6

FIGURE 2



LOWER COOK INLET
DISTRIBUTION OF BED FORMS
BEDFORM FIELDS, AVERAGE WAVE HEIGHT GREATER THAN 5 M
BEDFORM FIELDS, AVERAGE WAVE HEIGHT 2-5 METERS.
BEDFORM FIELDS, AVERAGE WAVE HEIGHT LESS THAN 2 M.
ISOLATED SAND RIBBONS
Harriet Pt
TUXEDNI BAY
CHISIK ISLAND
Ninilchik
60°N
ALASKA
CHINITNA BAY
Anchor Pt.
45'
Homer
KACHEMAK BAY
30'
Seldovia
AUGUSTINE ISLAND
KENAI PENINSULA
15'
CHUGACH IS.
59°N
BARREN ISLANDS
SHELIKOF STRAIT
CAPE DOUGLAS
153°
152°

FIGURE 3



LOWER COOK INLET
sample #
depth (m)
G denotes presence of glacial features
M denotes presence of impact features
C denotes presence of chemical features
Microtextures listed in order of decreasing abundance, averaged within a sample.
Boldface print denotes dominance of a particular microtexture.
Regular print denotes abundant occurrence, but not dominance.
Parentheses denote minor occurrence.
45'
30'
15'
152°
60°N
59°N
Harriet Pt
TUXEDNI BAY
CHISIK ISLAND
Ninilchik
ALASKA
CHINITNA BAY
Anchor Pt.
Homer
KACHEMAK
Seldovia
AUGUSTINE ISLAND
KENAI PENINSULA
CHUGACH IS.
BARREN ISLANDS
SHELIKOF STRAIT
CAPE DOUGLAS
153°
5 47 GC(m)
48 46 CM(g)
49 47 GM(c)
37 55 GM(c)
9 35 GC(m)
36 45 MG(c)
152 47 CM(g)
35 50 MG(c)
34 28 CG(m)
42 30 C(g)
43 52 CG(m)
41 30 CM(g)
27 74 MG
33 48 MG(c)
16 48 CM(g)
17 74 CGm
28 78 MG(c)
32 69 C(m)(g)
7 32 CM(g)
30 90 MGC
29 90 CG(m)
154 75 CM(g)
150 147 CG(m)
26 119 C(m)
25 133 C(m)(g)
23 170 CG(m)
22 154 CM(g)

FIGURE 4

APPENDIX III

DISTRIBUTION OF CLAY MINERALS IN COOK INLET AND KODIAK SHELF SEDIMENT

DISTRIBUTION OF CLAY MINERALS IN COOK INLET AND KODIAK SHELF SEDIMENT

by

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INTRODUCTION

Twenty-five surface samples from lower Cook Inlet and forty-three from Kodiak shelf were analyzed for clay mineralogy (Fig. 1). Also, mineralogy was determined on three bedrock samples (110D2, 111D1, and 116D2) from the Kodiak shelf. Methods of sample preparation and clay mineral identification are provided by Hein, Scholl, and Gutmacher (1976). A brief outline of the procedure is: Carbonate and organic matter is removed. The less than 2 μm fraction is isolated by centrifugation. This clay size fraction is Mg-saturated, glycolated, and heat treated (550°C). An X-ray diffractogram is taken after each treatment. If the presence of vermiculite is indicated on these diffractograms, then, Ba-saturated samples are X-rayed to confirm its presence. Peak areas are measured and the clay mineral percentages are calculated from them. Biscayes' (1965) weighting factors are used; kaolinite, chlorite, illite, and smectite are summed to equal 100 percent. In general, percentages are reproducible to within three percent of the value given, and values rarely change by as much as five percent. Percentages of chlorite and kaolinite are obtained by a slow scan of the 24 to 26° 2θ region (Biscaye, 1964). Kaolinite is a minor component of Cook Inlet and Kodiak shelf sediment (Table 1). The kaolinite plus chlorite percentage values will be used for discussions (Tables 1 and 2) because an accurate determination of kaolinite is difficult when it is present in small quantities. Expandable layers in mixed-layer smectite/illite are determined from the charts of Perry and Hower (1970) and Reynolds and Hower (1970). Illite crystallinity (Y) is measured as the ratio of the 10Å peak width at mid-height to the peak height.

Distribution of Clay Minerals in Cook Inlet

Sample locations and the distribution of clay minerals are shown in Figures 1 through 4. Clay mineral percentages are also listed in Table 1. Chlorite and illite are the dominant clay minerals in Cook Inlet. They average 52% (+kaolinite) and 45% respectively (Table 2). Smectite averages 3%. There is a major difference in the clay mineralogy from lower Cook Inlet (near the Barren Islands) across the inlet to Kamishak Bay and farther to the north. In general, illite increases in abundance in northwestern and northern lower Cook Inlet, whereas chlorite + kaolinite dominates the clay mineral suite near the Barren Islands (Figs. 2 and 3). Chlorite + kaolinite is also abundant in Kachemak Bay. Smectite percentages are lowest in central Cook Inlet and increase both to the northwest and southeast; it is most abundant in Kachemak Bay. Illite has a higher crystallinity (lower numbers) in samples from Kachemak Bay and northwestern and northern lower Cook Inlet than it does in samples near the Barren Islands (Fig. 4).

Distribution of Clay Minerals on Kodiak Shelf

Clay mineral percentages from Kodiak shelf sediment samples can show large variations over relatively short distances. However, in general, three trends are apparent. First, most samples to the south and east of the east end of Afognak Island have a clay mineral assemblage representative of the average for the Kodiak shelf taken as a whole, such as, about 60% chlorite + kaolinite, 33% illite, and 6% smectite (Tables 1 and 2). The smectite value is most variable, whereas, the chlorite + kaolinite values are exceedingly uniform through this area. Second, in general, clay mineral percentages on southern, middle and northern Albatross Banks are similar, but, these values are distinctive from those determined for samples from the intervening troughs. Samples from these topographic lows contain relatively more illite and less chlorite + kaolinite. Third, dart cores were taken on bedrock ridges (sample numbers in Table 1 followed by the letter D; see Fig. 5 and Bouma and Hampton, 1976). The clay mineral percentages from the upper part of these dart cores are different from those of other shelf samples. The illite crystallinity is especially distinctive and averages 0.15 (sample 125D not included) as compared to 0.38 for the shelf in general (Table 2). This value of 0.15 is essentially the same as the average value for lower Cook Inlet, 0.16. Local variation in the clay mineralogy on a bank or within a single trough can be attributed to small scale topography. For example, sample 115 has a distinctive clay mineral assemblage; it was taken from a broad outer shelf basin superimposed on the middle Albatross Bank.

Comparison of Cook Inlet and Kodiak Shelf Clay Mineralogy

Overall, Cook Inlet has an illite-dominated clay mineral suite in contrast to the chlorite-rich suite on Kodiak shelf (Table 2). Illite crystallinity is much higher (lower values) in Cook Inlet as compared to the shelf. Samples from southeastern Cook Inlet have a clay mineral suite more like Kodiak shelf than like the rest of Cook Inlet (Table 2); for example, chlorite + kaolinite is the same as on the shelf and illite and illite crystallinity show values intermediate between average shelf and inlet samples. Thus, samples from northwestern Cook Inlet are very rich in illite, such as about half of the clay mineral suite is illite. Chlorite + kaolinite (55%) and illite (38%) values on the outer shelf ridges, however, are intermediate between those average values for the shelf and for Cook Inlet.

Regional Distribution of Clay Minerals

Average values for the clay mineral composition of suspended sediment from the Copper River, bottom samples from the Copper River delta, and bottom samples from the continental shelf in the northern Gulf of Alaska are listed in Table 2. Copper River samples are comparable to those from the shelf seaward of the river; chlorite + kaolinite is diluted and illite enriched in the offshore bottom samples. In general, the samples offshore of the Copper River have the same clay mineral percentages as samples from southeastern Cook Inlet, and values that are closely comparable to Kodiak shelf samples (Table 2).

Bottom samples from upper Cook Inlet, including Knik Arm and Turnagain Arm are illite rich. Most commonly, illite is greater than 50 percent of the clay mineral suite (N.R. O'Brien, personal communication, 1977). This illite-rich suite is derived from the Susitna River and is widely distributed in upper Cook Inlet.

Interpretation: Sources and Dispersal Patterns of Clay Minerals

The Copper River is the primary supplier of sediment to the northern Gulf of Alaska. We infer from the regional distribution of clay minerals that currents flowing parallel to the Alaskan coast carry Copper River sediment west and southwestward. This sediment is the main source of clay minerals found on the continental shelf and perhaps the upper slope from the Copper River west to at least the western limit of Kodiak Island. This Copper River clay mineral suite is also carried into Cook Inlet, maintains its identity around the Barren Islands, and can be traced north to as far as Homer and into Kachemak Bay. Near Homer, the chlorite-rich Copper River suite mixes extensively with the illite-rich Susitna River or upper Cook Inlet suite. Apparently, currents flowing out of Cook Inlet hug the northwestern shore and deposit the Susitna River suite there in lower Cook Inlet south of Homer. This illite suite is evident as far south as Kamishak Bay, where our sampling stops. The fate of this characteristic suite is unknown. Shelikof Strait, and Cook Inlet, from Homer north to the Susitna River, must be sampled to further delineate the current patterns and to confirm our speculations about the available data. Apparently the Susitna River suite doest not enter the Pacific through Stevenson Trough because this area contains the characteristic Copper River clay mineral suite.

The origin of clay minerals on the Kodiak shelf is speculative. In general, the Copper River clays collect on the banks. But, on outer-shelf bedrock ridges, a mixture of locally derived bedrock clays (Quaternary(?) mudstone) and transported Copper River clays is likely. Further, local basins on banks and bedrock knobs protruding through the sediment-filled troughs complicate the interpretation of any single sample. Apparently, some small-scale basins are filled with clays eroded from local bedrock outcrops. There may be some contribution of clays to the shelf from erosion on Kodiak Island. Sediment-filled fiords on the southern coast could easily be churned during storms resulting in the movement of fine-grained sediment seaward onto the shelf. Kodiak Island fiords should be sampled to verify this conclusion. Seismic records show that Kodiak shelf troughs are partly filled with sediment (Bouma and Hampton, 1976). Clay mineralogy suggests that the fine fraction of this trough fill is primarily derived from the Copper River suite. The clays are probably swept into the troughs from the adjacent banks and are mixed partly with Kodiak Island derived clays or clays eroded from shelf bedrock outcrops.

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Table 1. Clay Minerals In Bottom Sediments From Southern Cook Inlet And Kodiak Shelf, Alaska.

Sample No.	K + C	Kaol.	Chlor.	Illite	Smectite	Others	X*	Y+
				COOK INLET				
2 top	55%	14%	41%	38%	7%		70	0.11
2 bot.	56	12	44	39	5		75	0.11
4	42	10	31	56	3		95	0.08
5	43	13	29	53	4		90	0.08
7	44	11	31	55	2		80	0.12
8	47	7	40	45	6		80	0.13
9	43	7	36	54	4		95	0.12
9V1	37	6	31	61	2		70	0.17
12	43	6	36	55	3		95	0.11
14V1	49	9	40	49	2		75	0.14
15	47	10	37	49	4		85	0.10
16 top	43	8	35	55	2		90	0.10
16 bot.	45	14	30	55	0		-	0.10
17	57	8	49	41	2		100	0.14
19	59	14	45	39	3		75	0.12
22S	58	8	49	40	3		75	0.38
23	61	18	42	39	1		80	0.13
24S1	60	10	51	38	2		70	0.24
25	60	7	53	38	2		75	0.21
26	64	0	64	35	1		?	0.26
29	59	15	43	41	0	Sepiolite	-	0.22
34	53	11	42	44	3		70	0.15
36	54	13	41	45	1	Sepiolite	?	0.28
37S1	55	8	46	45	1		70	0.20
43	49	10	39	32	19		90	0.10
48	40	9	31	59	2		95	0.15
150	58	9	49	39	3		85	0.24
				KODIAK SHELF				
1	66	15	52	28	6		80	0.21
52	62	16	46	37	1		70	0.28
54	63	14	49	36	2		70	0.31
55	63	9	54	29	7		75	0.25
56S	63	13	49	27	10	Sepiolite	80	0.28
56S1	64	17	47	32	4	Vermiculite	75	?
58	63	12	51	34	3		85	0.24
60	61	13	48	33	6	Sepiolite	85	0.39
61	60	14	46	29	11		75	0.50
63	64	13	51	34	2		70	0.25
64	62	14	48	33	5		80	0.35
66	62	13	50	35	3		75	0.21
67	60	16	45	36	4		80	0.28
68S2	59	8	52	37	4		70	0.36
69	58	16	42	27	15		80	0.96
70	72	14	59	25	2		70	0.51
75	69	39	30	30	1	Sepiolite	?	0.87
82	56	13	42	34	11		80	0.20
85	66	0	66	33	1		75	0.57
87S1	66	9	57	29	3		95	0.58
88	52	7	45	42	6		85	0.28
91	63	13	50	30	8		70	0.35

Table 1 cont.

Sample No.	K + C	Kaol.	Chlor.	Illite	Smectite	Others	X*	Y+
92	57	11	46	38	5		80	0.28
93	59	11	48	37	4		80	0.30
96	52	11	40	43	6		85	0.33
98	64	13	51	34	3		75	0.23
103D	41	7	38	34	24		70	0.09
110	54	11	44	38	7		75	0.14
110D2	56	12	44	39	5		75	0.19
111D1	58	9	49	38	4		70	0.15
113B	58	10	48	35	7	Sepiolite	75	0.17
114	61	17	45	38	1		?	0.39
115	72	20	53	19	9		70	1.70
116D2	56	8	48	38	6		70	0.12
117D	59	8	51	41	0		-	0.17
120D	54	8	46	37	9		65	0.13
125D	40	?	?	30	30		55	1.37
127	58	12	46	34	8		75	0.36
128	60	14	46	33	7		85	0.29
130	62	13	49	33	5		80	0.48
132	64	13	51	33	4		80	0.21
133G	60	9	52	33	6		75	0.15
134	60	11	48	35	5		75	0.30
136	62	12	50	33	5		80	0.24
141	66	13	53	29	5		80	0.23
147D	60	8	52	36	4		70	0.18

* Percent expandable layers in the smectite/illite mixed layer phase.

+ Illite crystallinity.

Table 2. Average And Range Of Clay Mineral Percentages From Lower Cook Inlet, Kodiak Shelf, Southeastern Cook Inlet*, Copper River And Delta, And The Shelf Off The Copper River**.

	Cook Inlet		Kodiak Shelf		SE Cook Inlet		Copper River & Delta		Shelf Off Copper R.	
	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
K + C	51	37-64	60	40-72	60	57-64	68	61-73	62	44-70
Kaol.	10	0-18	13	0-39	10	0-18	12	6-17	9	7-10
Chlor.	41	29-64	48	30-66	49	42-64	56	53-64	53	37-60
Illite	46	32-61	33	19-43	39	35-41	31	27-39	38	30-56
Smectite	3	0-19	6	0-30	2	0- 3	<1	0- 1	<1	0- 1
X^+	82	70-100	76	55-95	80	70-100	?	?	?	?
Y^+	0.16	0.08-0.38	0.38	0.09-1.70	0.22	0.12-0.38	0.27	0.18-0.33	?	?

* Includes samples 17, 19, 22, 23, 24, 25, 26, 29, and 150.

**Number of samples analyzed from each area is, 25, 43, 9, 5, and 19 respectively. Data for Copper River and delta and for the shelf off the Copper River are unpublished data of James R. Hein, and B.F. Molnia and P.T. Fuller 1977).

$^+$ X = percent expandable layers in the smectite/illite mixed layer phase; Y = illite crystallinity.

FIGURE CAPTIONS

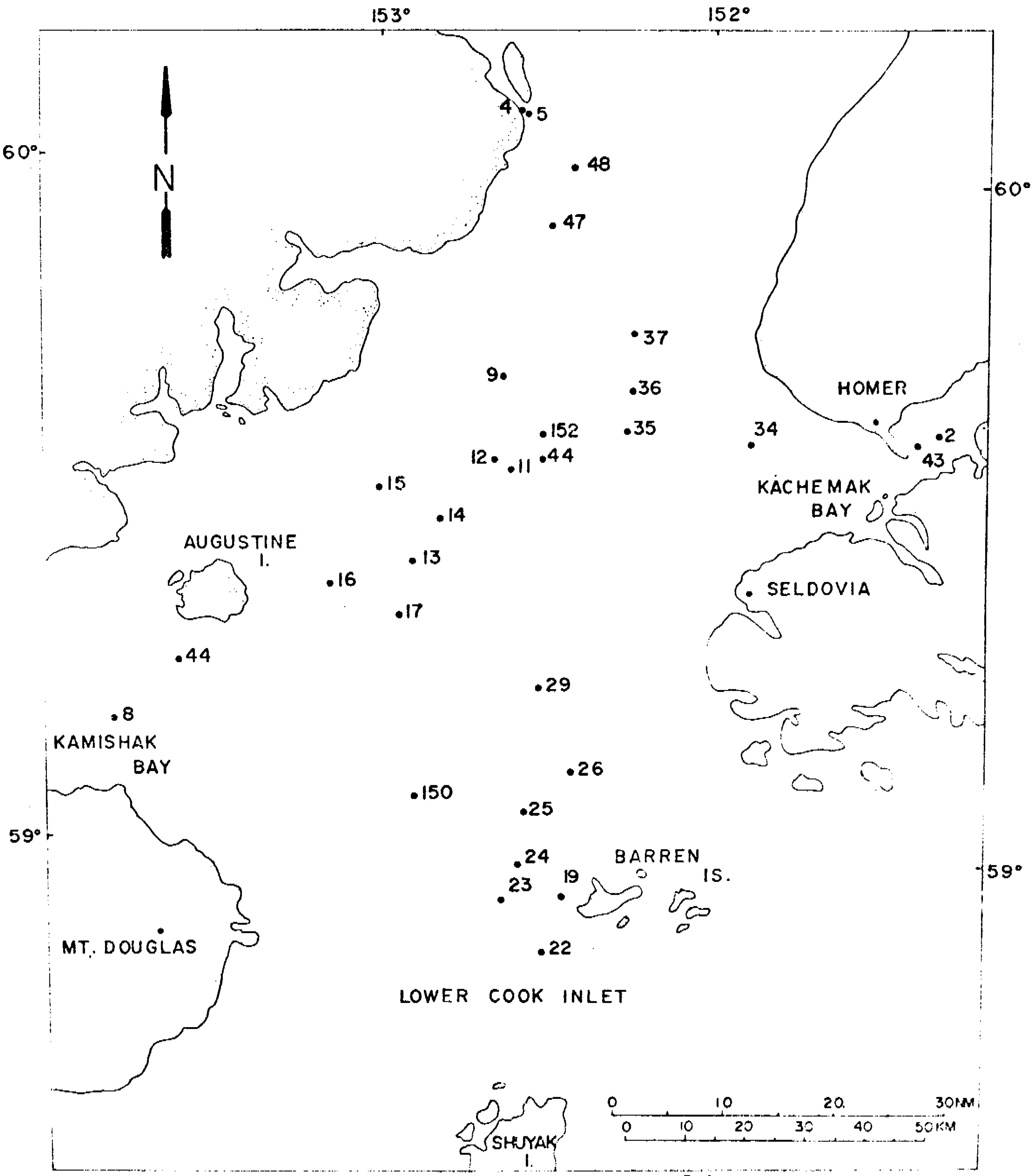
Figure 1. Distribution of samples analyzed for clay mineralogy and sample numbers from lower Cook Inlet.

Figure 2. Distribution of chorite+kaolinite in lower Cook Inlet. Numbers are the percentage of chlorite+kaolinite in the clay mineral suite. The percentage values are contoured at a five percent interval.

Figure 3. Distribution of illite in lower Cook Inlet. Numbers are the percentage of illite in the clay mineral suite. The percentage values are contoured at a five percent interval.

Figure 4. Variation of the crystallinity of illite in lower Cook Inlet sediment samples. Contour interval is 0.05.

Figure 5. Generalized physiography and distribution of samples analyzed for clay mineralogy on Kodiak shelf. Sample numbers are listed next to the station locations.



153°
152°
60°
59°
N
4
5
48
47
37
9
36
152
35
34
HOMER
2
43
12
11
44
15
KACHEMAK
BAY
14
AUGUSTINE
I.
13
16
SELDOVIA
17
44
29
8
KAMISHAK
BAY
26
150
25
24
BARREN
IS.
23
19
MT. DOUGLAS
22
LOWER COOK INLET
0
10
20
30NM
0
10
20
30
40
50KM
SHUYAK
I.

FIGURE 1

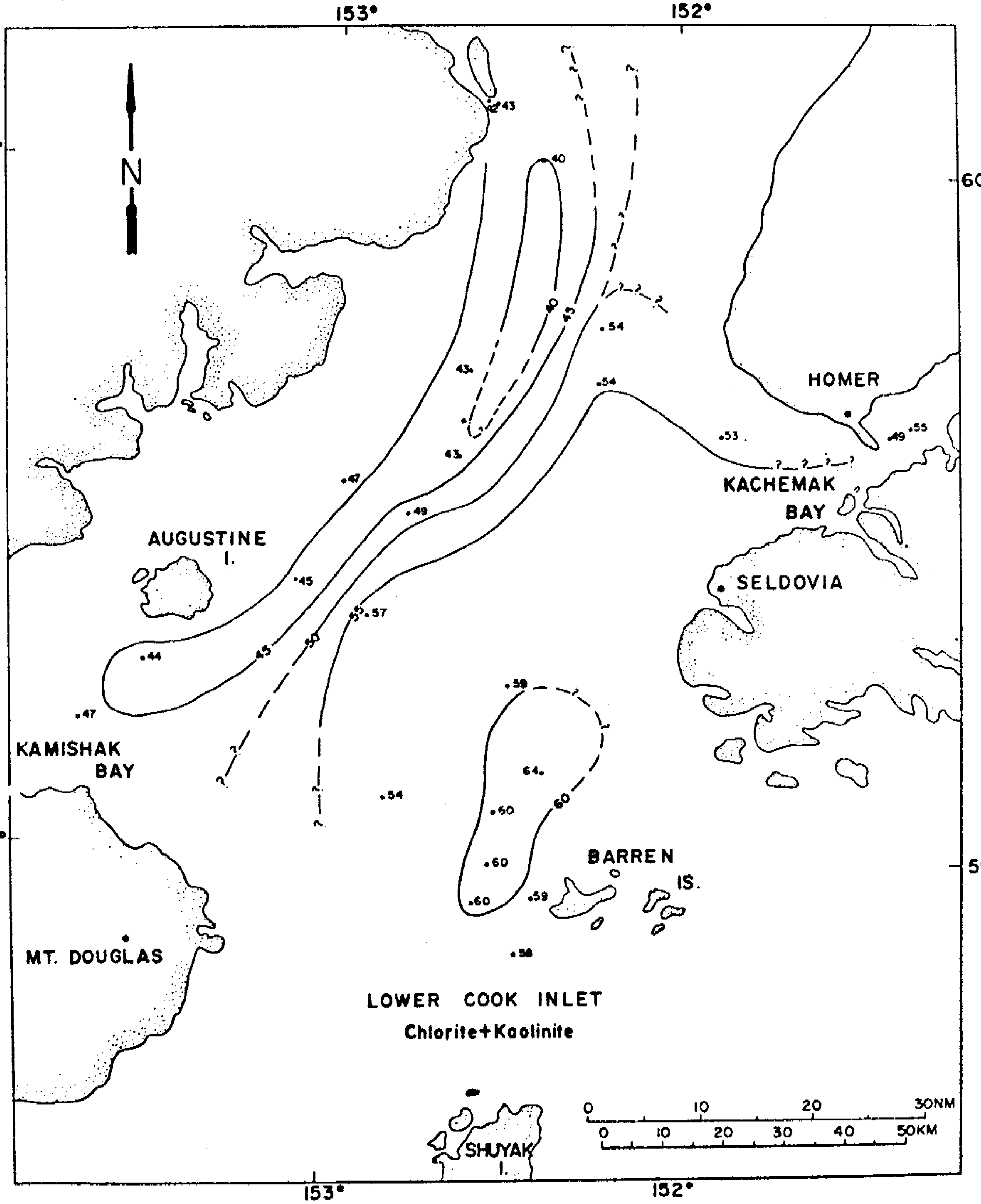
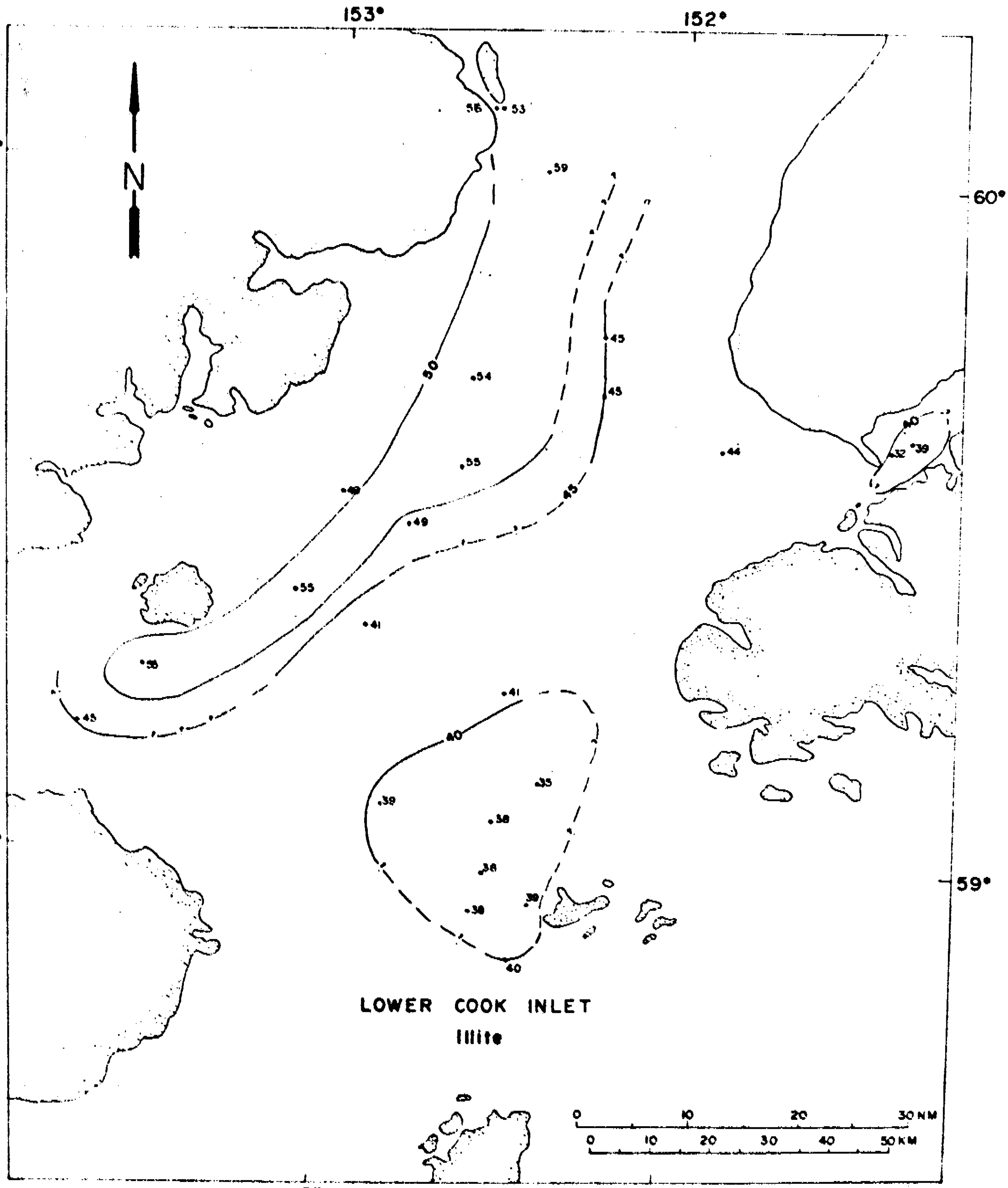

153°
152°
60°
59°
N
HOMER
KACHEMAK
BAY
SELDOVIA
AUGUSTINE
I.
KAMISHAK
BAY
MT. DOUGLAS
BARREN
IS.
SHUYAK
I.
LOWER COOK INLET
Chlorite+Kaolinite
0 10 20 30NM
0 10 20 30 40 50KM

FIGURE 2



153°
152°
60°
60°
N
59°
69°
LOWER COOK INLET
Illite
0
10
20
30 NM
0
10
20
30
40
50 KM
153°
152°

FIGURE 3

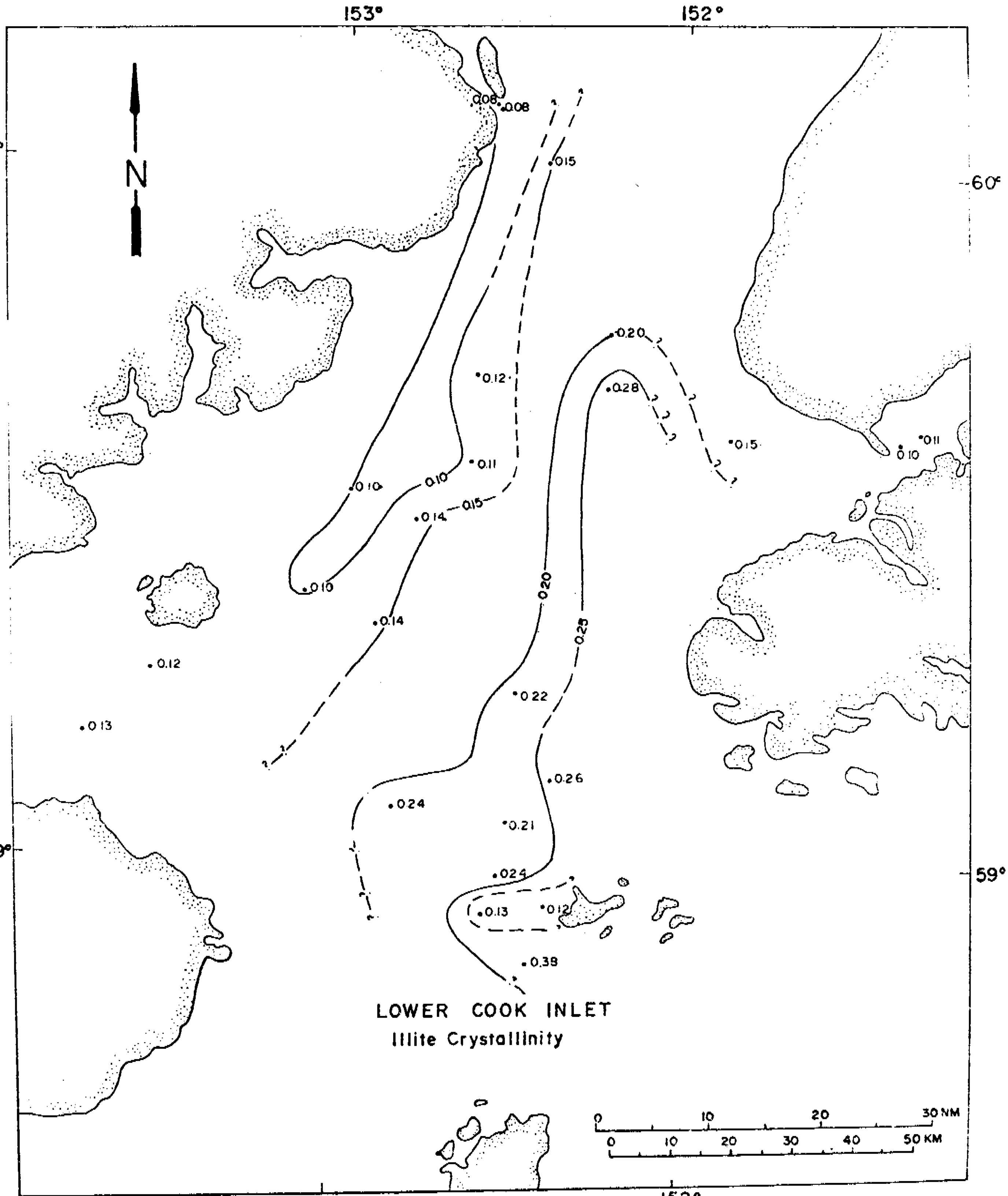

153°
152°
60°
60°
N
0.08
0.08
0.15
0.20
0.12
0.28
0.15
0.11
0.10
0.11
0.10
0.10
0.14
0.15
0.10
0.14
0.20
0.25
0.12
0.22
0.13
0.26
0.24
0.21
59°
59°
0.24
0.13
0.12
0.38
LOWER COOK INLET
Illite Crystallinity
0 10 20 30 NM
0 10 20 30 40 50 KM
153°
152°

FIGURE 4

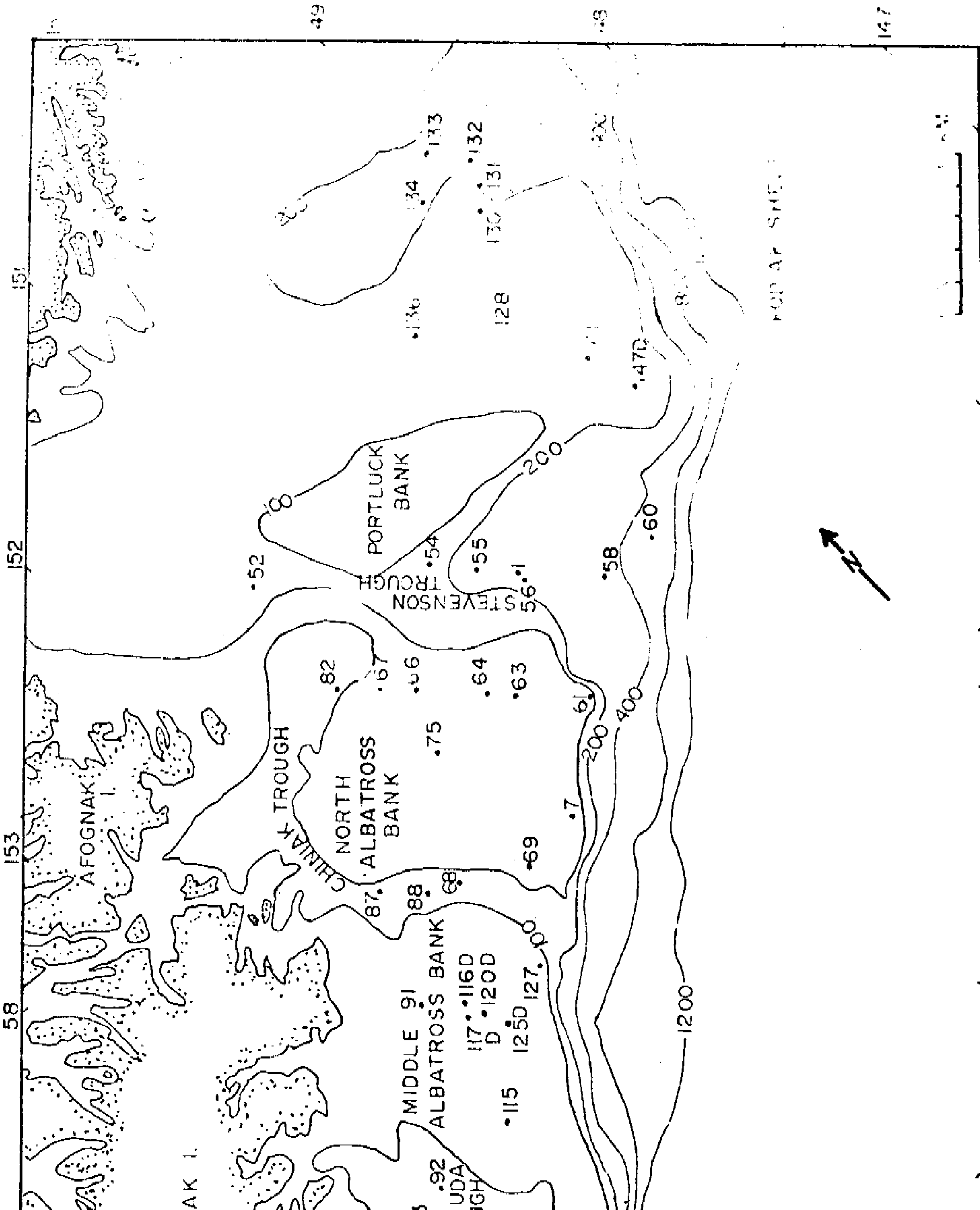

KODIAK I.
AFOGNAK I.
PORTLUCK BANK
STEVENSON TROUGH
CHINIAK TROUGH
NORTH ALBATROSS BANK
MIDDLE ALBATROSS BANK
KILIUDA TROUGH
SOUTH ALBATROSS BANK
200
400
800
1200

FIGURE 5

APPENDIX IV

VOLCANIC ASH IN SURFICIAL SEDIMENTS OF THE KODIAK SHELF - AN INDICATOR OF SEDIMENT DISPERSAL PATTERNS

VOLCANIC ASH IN SURFICIAL SEDIMENTS OF THE KODIAK SHELF - AN INDICATOR OF SEDIMENT DISPERSAL PATTERNS

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ABSTRACT

Surficial sediments of the Kodiak shelf, Gulf of Alaska, contain various amounts of volcanic ash whose physical properties indicate that it originated from the 1912 Katmai eruption. High contents of ash occur in Kiliuda and Chiniak Troughs and also in the deeper part of Amatuli Trough. The sediments of Stevenson Trough contain low to moderate amounts of ash. Low to moderate amounts of ash also are typical on Albatross and Portlock Banks, but high ash contents occur in several shallow depressions found on these banks.

The distribution of ash does not reflect the original depositional pattern from the volcanic event but instead represents redistribution by oceanic circulation of the shelf. Therefore, the ash distribution can be used as an indicator of present-day sediment dispersal patterns.

No significant modern sources of sediment exist for the Kodiak shelf, which is mostly covered with Pleistocene glacial deposits. The coarse-grained sediments on the shallow, flat parts of Albatross and Portlock Banks apparently are sites of winnowing, with the removed fine material being deposited in the shallow depressions on the banks and in Kiliuda, Chiniak, and Amatuli Troughs. Stevenson Trough seems to experience a relatively high-energy current regime, with little deposition of fine material. The surficial sediments of Stevenson Trough are mostly clean sands, and a field of large, seaward-facing sand waves occurs near the mouth.

INTRODUCTION

An environmental marine geologic study of the Kodiak shelf, western Gulf of Alaska, was conducted aboard the R/V SEA SOUNDER during June and July, 1976 (Fig. 1). As part of this study, 63 samples were collected from the unconsolidated surficial sediments of the shelf and adjacent upper continental slope. Shipboard examination of the sediments revealed that they contain various amounts of volcanic ash. Petrographic and morphologic laboratory studies of the ash were made, and the amount of ash in 59 of the samples was determined. Assuming that the hydraulically mobile ash particles have been moved by ocean currents after originally settling from the atmosphere, the distribution of ash has been studied in order to detect trends of modern sediment dispersal on the Kodiak shelf.

METHODS

Sampling

Samples were collected with a Van Veen sampler as modified by Andy Soutar of Scripps Institution of Oceanography. This sampler is capable of taking an undisturbed surficial sediment sample with maximum dimensions of about 45x60x20 cm. In most cases the undisturbed top two cm were sampled for ash content analysis but in cases where washing of the sample was a problem (usually due to incomplete closing of the jaws of the sampler) bulk samples from the unwashed central portion of the sampler were taken.

In most instances the ash appeared to be more-or-less evenly distributed throughout the sample, though in at least one instance (sample 56) ash occurred in discrete layers intercalated with sand or silty sand.

Samples of pure ash are pale yellowish brown (10 YR 9/1) to very pale orange (10 YR 8/2) in color. High concentrations of ash proved difficult to penetrate with any type of coring device due to extreme angularity and interlocking. The angularity of the particles gives ash-bearing samples an abrasive feel when rubbed between the fingers.

LABORATORY

A practical method of volcanic ash separation from samples with high concentrations of ash has been developed based on the procedure presented by Huang and others (1975) for sediments with low ash contents. Small samples of about 6 cm^3 from the Soutar-Van Veen sampler are washed through a 2 μm sieve to remove coarse materials, then rinsed in distilled water to remove salt and next centrifuged to settle all suspended particles. Concentrated hydrochloric acid is then added to dissolve shell material, which in some samples is as high as 75% by weight. Acid is added at intervals until no visible reaction is observed upon further addition. Examination of the ash with an optical microscope revealed no evidence of chemical etching. The samples are then washed and centrifuged three times to remove excess HCl.

After drying, the samples are disaggregated and passed through a 1 μm sieve. Material not passing through is pulverized with mortar and pestle until all material passes through.

The samples are then split to obtain a 0.50 - 0.75 g sample for heavy liquid separation of the ash from the other components. Siliceous planktonic particles are separated with a heavy liquid with a density of 2.30g/cm^3, on which most siliceous skeletons will float.

The volcanic ash in the samples is restricted to a density range of about 2.35-2.45 g/cm^3. The most efficient heavy liquid found to separate the ash with the least amount of contamination of non-ash components has a density of 2.450 ±0.002 g/cm^3.

The heavy liquid technique of Huang and others (1975) has been modified to provide maximum separation of glass. Each sample (between 0.50-0.75 g) is pured into a 250 ml separatory funnel containing 75-100 ml of acetylene tetrabromoform with a density of 2.450 ±0.002 g/cm^3, stirred, and allowed to settle for several hours. The separate and residue (floating and sinking portions, respectively) are then poured off, and each fraction is again subjected to heavy liquid separation, though they are allowed to settle for 2 days. The resulting two light fractions are then combined, washed in acetone, dried, and weighed, as are the resultant heavy fractions. The weight percent of material with a density less than 2.45 g/cm^3, which consists mostly of volcanic glass, is then calculated.

Visual estimates of efficiency of ash separation are as high as 95%, averaging about 80%. This efficiency is undoubtedly due to the very high ash content (up to 100% by weight) and the coarse grain size. It was found that the efficiency decreases slightly with decreasing ash size. Reproducibility tests on several samples yielded results within a range of 0.5-2.3%.

PREVIOUS WORK

Oceanographic studies of the Kodiak shelf have shown it to consist of several flat, shallow banks, generally from 80 to 120 m deep, that are cut by broad troughs that trend transverse to the shelf (Fig. 2). A series of structural arches trending along much of the outer shelf form physiographically high areas, both on the banks and in the troughs, near the shelf break. Typically, the arches have been eroded to expose bedrock.

Prior to 1976, the sediments and sedimentation patterns on the Kodiak shelf were only known in general terms. The USC&GS Boat Sheets, compiled from data gathered in the 1920's, give indications as to sediment type from samples recovered while taking lead-line soundings. These data show the sediments to be heterogeneously distributed mixtures of gravel, sand, mud and shells.

Gershanovich (1968), in a summary of Soviet work in the northern Pacific, constructed generalized sediment maps of the Bering Sea and Gulf of Alaska. His maps show the Kodiak shelf to be covered by glacially derived, volcanogenic, and shell-rich sediments.

Nayudu (1964) discussed the occurrence of volcanic ash in sediments of the Gulf of Alaska. He identified three layers of ash in core samples. The uppermost layer was concluded to have been derived from the 1912 Katmai volcanic eruption, whereas the sources of the lower two layers is unknown. Nayudu's map of the distribution of Katmai ash showed the entire area of the present study to have been covered by deposits from the 1912 events. According to a map presented by Wilcox (1959), the area received a thickness of from about 0.6 cm (0.02 ft) to more than 15 cm (0.5 ft) of Katmai ash.

In a summary of available knowledge of the western Gulf of Alaska by the University of Alaska (1974), dispersal of sediment on the Kodiak shelf is said to be particularly influenced by stor waves which, in depths of less than 100 m (i.e., on the banks) w .now finer material and deposit it in deeper areas (i.e., in the troughs). This dispersal pattern produces a normal depth-graded pattern of sediment grain sizes. As stated by von Huene and others (1976), no major accumulations of post-glacial sediments are likely to exist on the shelf, due to a lack of modern sediment sources. The sedimentary regime apparently is dominantly one of reworking of Pleistocene glacially derived sediments.

SEDIMENT DISTRIBUTION - 1976 DATA

On board ship, estimates were made of the grain-size distributions of the terrigenous material in the surficial sediment samples (Fig. 3, and Bouma and Hampton, 1976). Volcanic ash and biogenic material were excluded from these estimates. Sediments on the shallow banks are coarse grained, containing sand and coarser material with only a few samples containing measurable amounts of mud. (Note that constituents present in amounts less than 1% are not shown on Fig. 3). Foraminifera tests and broken shells of megafauna are abundant constituents of many bank sediments.

Sediments in troughs generally are finer-grained than those on the banks, and a few samples in Kiliuda Trough are composed entirely of silt and clay. The sediments of Stevenson Trough are mostly clean sands, with local occurrences of coarser material; mud is conspicuously absent from those samples.

The two gravity cores collected on the upper continental slope, seaward of middle Albatross Bank, consist of silty mud with scattered pebbles. In contrast, two grab samples collected seaward of the mouth of Stevenson Trough are composed of pebbly sand with essentially no fine-grained material.

DESCRIPTION OF VOLCANIC ASH

Volcanic ash from the surficial sediments of the Kodiak Shelf and from one 25 cm thick ash layer on Kodiak Island were studied using transmitted light and scanning electron microscopes to determine its petrographic and morphologic characteristics. The ash is generally very fine-grained - most particles are less than 75 μm though some samples contain abundant pumice up to about 800 μm in diameter. The ash is generally light brown (10 YR 9/1), though there are minor variations in color. Microscopically, the ash consists of very clear glass, though a few shards have very fine grained alteration products (probably clays) enclosed in unbroken vesicles. Mineral inclusions were not observed in any of the samples. The refractive index of the glass is uniform across the entire area, 1.485 ±0.001 which corresponds to a silica content of 74% (George, 1924). There are three morphologic types of ash present: pumice shards, bubble-wall shards, and small flat to slightly curved plates. The most abundant type of the three varieties is the more-or-less elongate pumice shard with very thin pipe-shaped vesicles, separated by thin walls. The long axis of the shard is generally parallel to the vesicles and breakage of the shard is controlled by vesicle shape. Present in lesser amounts are pumice shards with spheroidal to ellipsoidal vesicles, and in a few shards rounded vesicles grade into the more common pipe vesicles.

Generally less abundant, and commonly finer grained than the pipe-vesicle pumice are shards broken from vesicle walls. These shards range in size up to about 300 μm. They are typically Y-shaped, though very complex forms are also abundant. Most were broken from pumice shards with spherical to ellipsoidal vesicles, though elongate vesicle remnants are common. The spheroidal and ellipsoidal vesicles range in size up to 150 μm in diameter whereas the pipe vesicles are commonly 0.5 to 25 μm in diameter and up to about 400 μm long. The subspherical vesicles also tend to have thicker walls than the pipe vesicles.

The finest grained portion of ash consists of small flat or curved plates that originally formed the walls between adjacent vesicles. This morphologic variant ranges in size from about 50 μm to submicroscopic.

Areal distribution of the mean grain size of the ash seems to show two gross trends: a general coarsening from northeast to southwest and towards Kodiak Island, and a tendency to be somewhat finer grained in the troughs and local depressions than on the bathymetric highs.

The ash from the surficial sediments on the Kodiak shelf is identical in its petrographic and morphologic characteristics to the ash studied by Nayudu (1964) from Kodiak Island and the Gulf of Alaska, which he correlated with the 1912 Katmai eruption. The ash also fits the descriptions given by Heiken (1972, 1974) for samples from the Valley of Ten Thousand Smokes, near Katmai. Other volcanic ash found in Gulf of Alaska sediments is distinctly different from Katmai Ash (Nayudu, 1964; Pratt et al., 1973).

DISTRIBUTION OF VOLCANIC ASH

The abundances of volcanic ash in surficial sediments, relative to the sand-size terrigenous material, is shown in Fig. 4. Inspection of this diagram reveals some relationships between the distribution of volcanic ash and the physiography of the shelf. Most samples of surficial sediments in Kiliuda and Chiniak Troughs have high ash percentages, to the near exclusion of epiclastic debris. Samples 95 and 113 in Kiliuda Trough are exceptions. The samples from Stevenson Trough have low to moderate concentrations of ash, except for samples 58 and 81, and the three samples from Amatuli trough have increasing ash percentage with depth. The samples from Alabatross and Portlock Banks generally show moderate values, between 20% and 60¢, but several samples have higher percentages. Thus, the general ash distribution of the sea floor of the Kodiak shelf shows high concentrations in Kiliuda, Chiniak and Amatuli Troughs and lower concentrations in Stevenson Trough and on most parts of the banks.

Most of the samples that are exceptions to the above generalizations are located in minor irregularities within the larger physiographic features. Sample 95, for example, was taken closer to land than most samples, within an irregular depression on the seaward flank of a shallow local feature that probably is either a moraine or a bedrock high. It can be seen in Figure 3 that sample 95 is abnormally coarse-grained for this trough. Sample 113, near the mouth of Kiliuda Trough, is located seaward of a bedrock high that forms the landward of two shelf breaks in this area (see also Hampton and Bouma, 1977).

Sample 58 was collected from a shallow depression a short distance landward of the shelf break at the mouth of Stevenson Trough. It has an abnormally high ash content. Note that samples 59 and 60, which also have higher ash contents than average for Stevenson Trough, were taken beyond the shelf break, on the uppermost continental slope. Sample 81, also containing a high ash content for Stevenson Trough, was taken from the deepest part of a small depression in the upper reaches of the trough.

All samples from the banks that show anomalously high contents of ash are within shallow depressions that exist on the banks (i.e., samples 66, 91, 115, 128, 140 and 141) or seaward of the shelf-break high that occurs most places on the banks (i.e., sample 72). All other samples from the banks having low to moderate percentages of ash were taken from shallow, flat, morphologically typical areas of the banks.

CONCLUSIONS

The bulk of the volcanic ash in the surficial sediments undoubtedly is from the 1912 Katmai eruption. The original blanket of ash that was spread across the Kodiak shelf must have been of a more-or-less uniformly varying thickness (e.g., see Wilcox, 1959). This fact, coupled with the close relationship of the present distribution to physiography, leads to the conclusion that the ash has been redistributed since 1912 by ocean currents. The low density and high surface area of the ash particles implies that they are hydraulically mobile and should respond readily to currents that impinge on the shelf. Therefore, the ash distribution can be used to draw inferences about modern sediment dispersal patterns and about modern current regimes on the Kodiak shelf.

The typically high contents of ash in Kiliuda, Chiniak, and the deeper part of Amatuli Trough implies that these are quiet areas of deposition and that bottom currents strong enough to flush ash out of the troughs do not exist. Seismic profiling records show the presence of physiographically high structural arches near the mouths of Kiliuda and Chiniak Troughs, which could act as sills that contribute to the quiet setting. The presence of gravel and coarser material in some of the grab samples, which probably reflects relict Pleistocene sediment, suggests that net accumulation in the troughs has not been sufficient since the last marine transgression to completely bury this material.

Few data exist for Amatuli Trough, but it appears to be a quiet site of deposition in its deeper parts.

The distribution of ash on Albatross and Portlock Banks, and its relation to physiography, implies that sediments are winnowed from the shallow, flat parts of the banks (low to moderate ash contents) and that the small depressions (high ash content) serve as local sites of accumulation.

The small depressions on the banks are rather subtle, typically being a few miles wide and only 20 to 30 m deep. To date not enough samples are available to see whether the ash content is consistently high throughout an individual low area, but such sampling is planned for the next field season.

The epiclastic and pyroclastic material winnowed from the banks logically would be the source of fine-grained sediment in Kiliuda, Chiniak, and Amatuli Troughs. According to what is known of the current regime on the shelf (Univ. Alaska, 1974), storm waves probably are the main winnowing agent of bank sediments.

The low to moderate ash contents in Stevenson Trough, similar to those on the shallow parts of the banks, suggest that this trough experiences a relatively high-energy current regime compared to the others. This is substantiated by the lack of silt- and clay-size epiclastic material (Fig. 3) and by the presence of a field of large, seaward-facing sand waves, with wave heights up to 7 m and wave lengths of about 150 m, that occurs in the outer portion of the trough in about 200 m of water. A structural arch, similar to the ones observed in Kiliuda and Chiniak Troughs, is present in the mouth of Stevenson Trough, but it has at least two gaps that may provide pathways for currents that sweep the bottom. Furthermore, sandy sediments similar to those within the trough are present on the adjacent continental slope (e.g., samples 59 and 60; Fig. 3), indicating that transfer of sediment seaward out of the trough is taking place. In contrast, sample 113, located seaward of the sill across Kiliuda Trough has a significantly lower content of ash than the samples within the trough landward of the sill. It also contains less silt- and clay-size material than is typical within the trough. Transfer of surficial material seaward out of this trough does not seem to be taking place.

At station 56 within the bedform field in Stevenson Trough, a layer of nearly pure ash was noted about two inches beneath the surface of the grab sample, indicating that movements of sand has taken place since 1912. The ash layer may be from the original emplacement of Katmai ash, or more likely, it represents a buried concentration originally deposited in the trough of a sand wave.

A few samples do not fit the scheme presented above. For example, some samples from low areas contain low amounts of ash (sample 95 taken in probably morainal material close to land, and samples 130 and 131 taken on the edge of Amatuli Trough). In contrast, sample 72, which contains an abnormally high amount of volcanic ash compared to most bank sediments, is located on the seaward side of a physiographic high area but landward of the shelf break. This is not a low area in the same sense as used for other areas of the banks, but perhaps the physiographic high acts as a barrier to current movement, with deposition of winnowed material occurring on its seaward side. It does not contain significant amounts of terrigenous mud, however.

In summary, the Kodiak shelf appears to have received little input of terrigenous sediment since the last marine transgression, due to a lack of sediment sources. The modern sedimentary regime is one of reworking of Pleistocene glacial and/or glacial marine sediments. The low abundance of volcanic ash in surficial sediments, along with the coarse-grained nature of the epiclastic debris, indicates that the flat, shallow areas of Albatross and Portlock Banks are presently sites of winnowing, with the products being deposited in shallow depressions on the banks and in Kiliuda, Chiniak, and Amatuli Troughs. The surficial sediments of Stevenson Trough contain low percentages of ash and terrigenous mud relative to the other troughs. This, along with the occurrence of sand waves within the trough and an apron of sandy sediments on the adjacent continental slope suggests that a unique sedimentary environment for this area exists within Stevenson Trough. In particular, it experiences more sediment transport and a more dynamic current regime than the other major troughs that transect the shelf. The seaward asymmetry of the sand waves and the sediment apron on the continental slope imply that net transport is seaward out of the trough.

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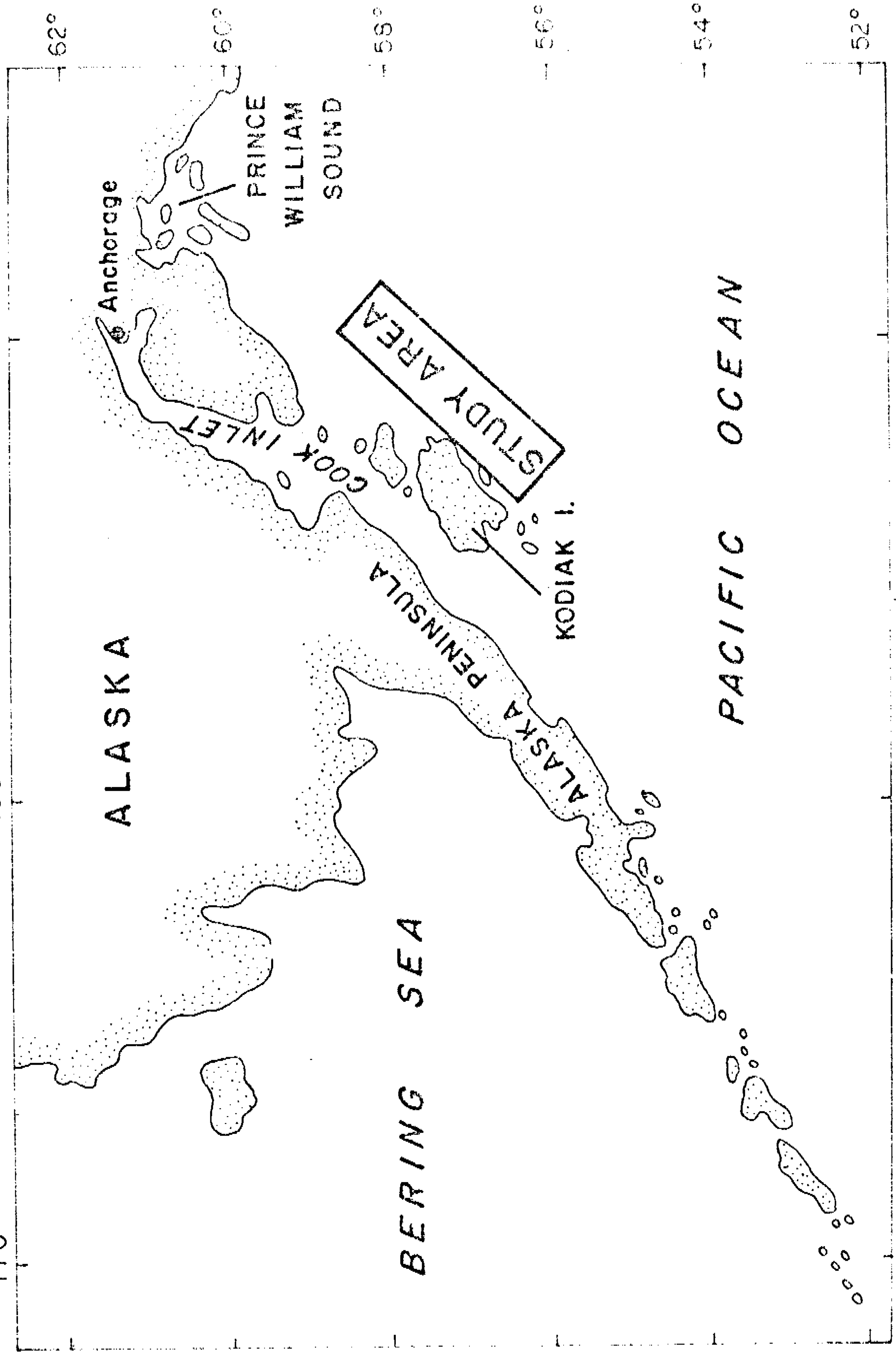
FIGURE CAPTIONS

1. Index map of the study area, Kodiak Shelf.
2. Physiography of the Kodiak Shelf.
3. Textures of surficial sediments, Kodiak Shelf.
4. Distribution of volcanic ash, sand size and finer fractions, in surficial sediments of the Kodiak Shelf.



62°
60°
58°
56°
54°
52°
150°
160°
170°
Anchorage
PRINCE
WILLIAM
SOUND
STUDY AREA
COOK INLET
KODIAK I.
ALASKA
ALASKA PENINSULA
PACIFIC OCEAN
BERING SEA

FIGURE 1

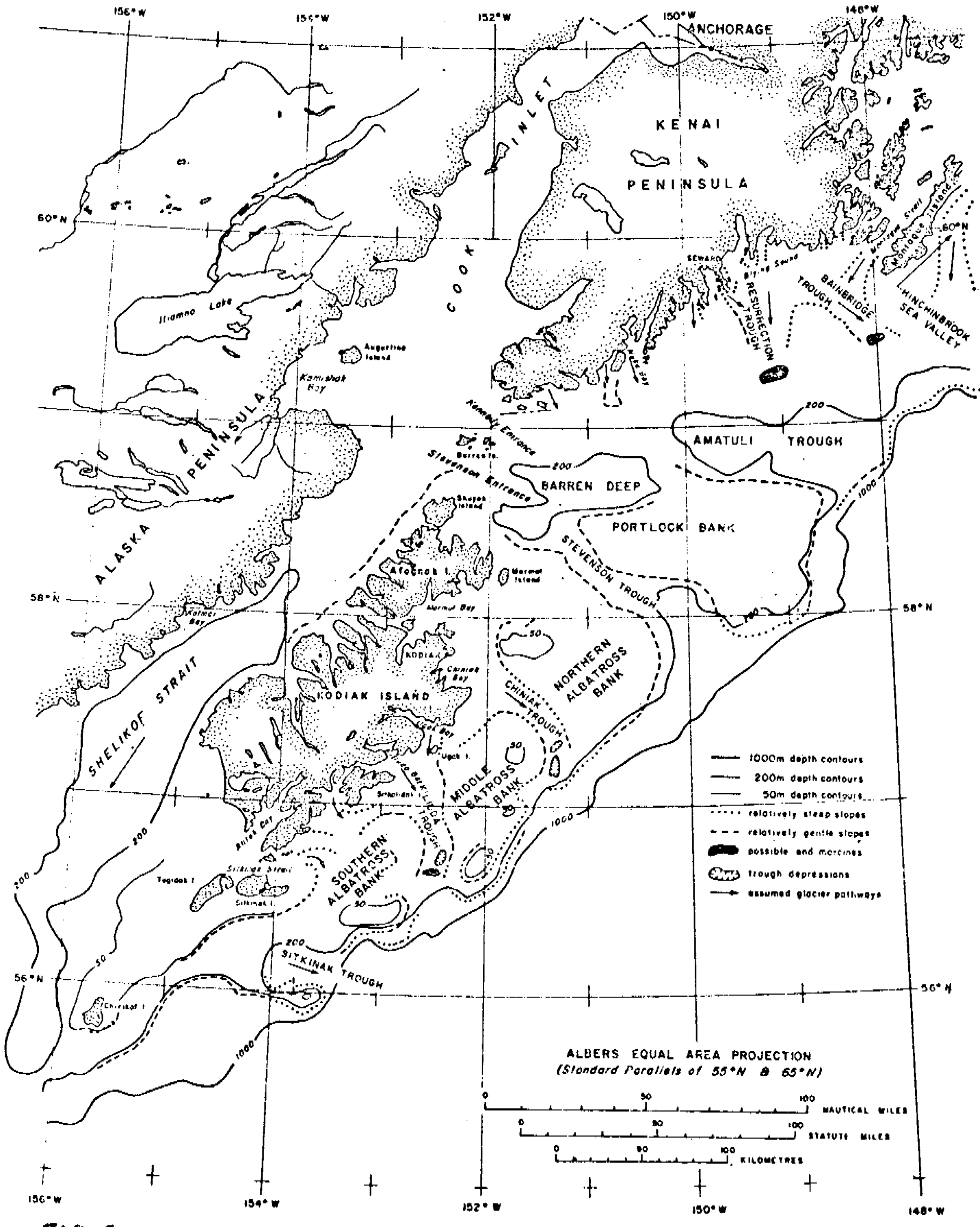
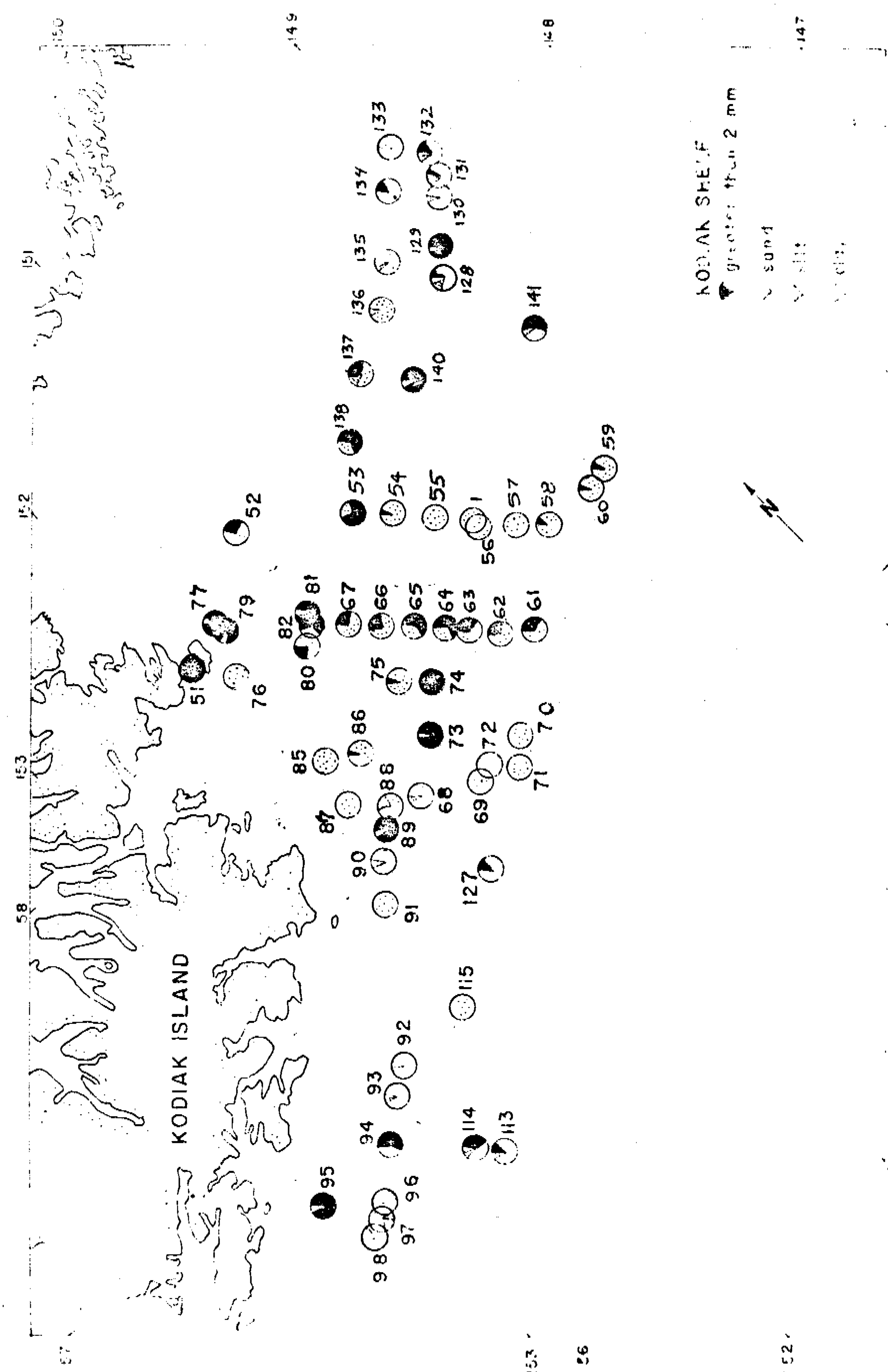


FIG. 2. Generalized physiographic map of Kodiak Shelf


KODIAK ISLAND
KODIAK SHELF
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52
53
54
55
56
57
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60
61
62
63
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65
66
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68
69
70
71
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FIGURE 3

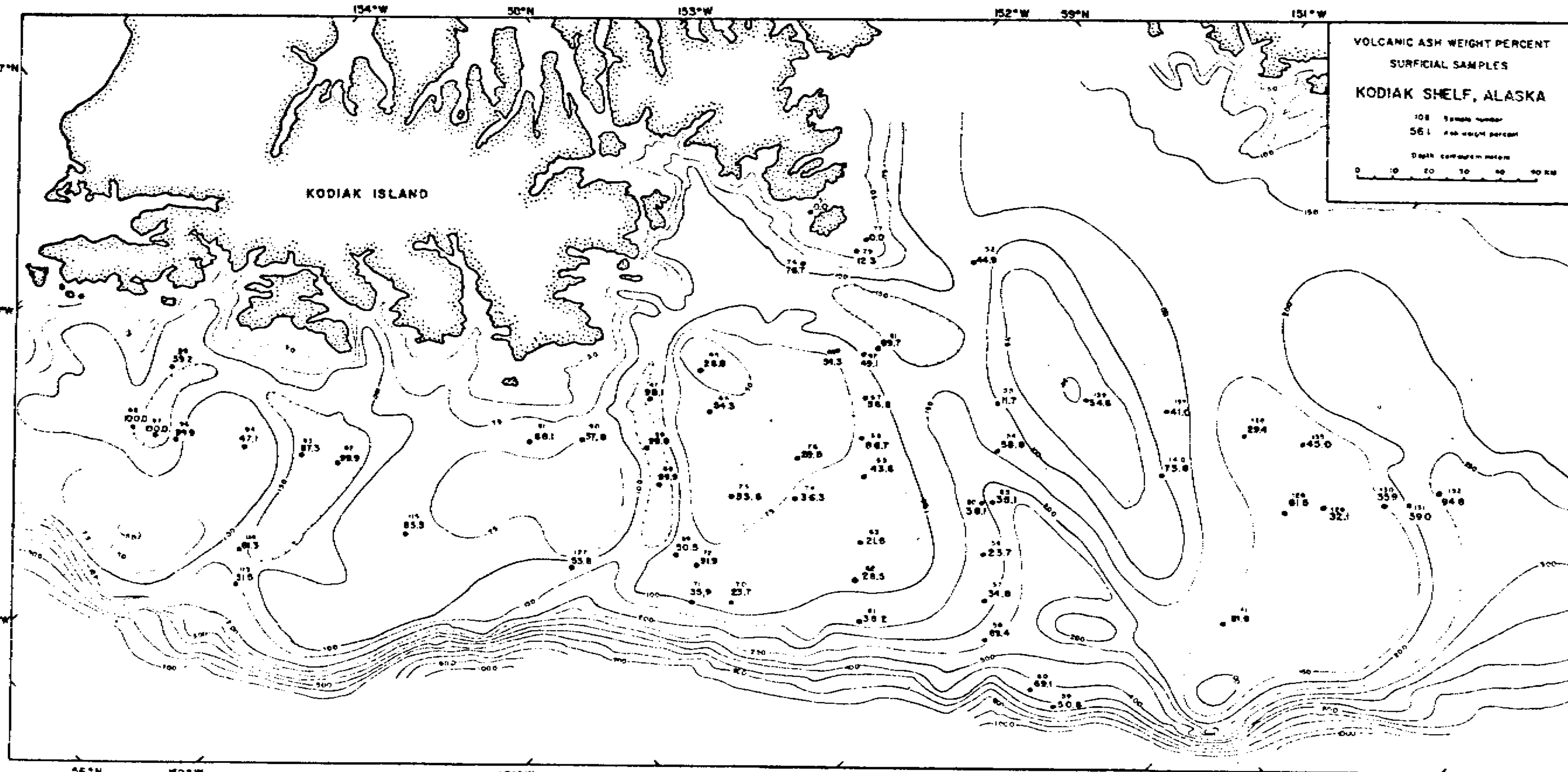
VOLCANIC ASH WEIGHT PERCENT
SURFICIAL SAMPLES
KODIAK SHELF, ALASKA
108 Sample number
56.1 Ash weight percent
Depth contours in meters
0 10 20 30 40 50 KM
KODIAK ISLAND
154°W
58°N
153°W
152°W
59°N
151°W
57°N
56°N
150°W
149°W
148°W

FIGURE 4

APPENDIX V

SLOPE INSTABILITY NEAR THE SHELF BREAK, WESTERN GULF OF ALASKA

SLOPE INSTABILITY NEAR THE SHELF BREAK, WESTERN GULF OF ALASKA

by

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ABSTRACT

The uppermost continental slope in the western Gulf of Alaska, from southern Albatross Bank to Portlock Bank, includes two broad areas where large submarine landslides occur and one intervening area where they are absent. The areas containing large slides show evidence for active near-surface folding and consequent slope steepening, which apparently is the ultimate control on this sliding. Evidence is absent for similar active steepening in the area containing no large slides, where slope gradients are relatively gentle.

Relatively small, shallow slides, fundamentally different from the larger ones, occur in all three areas on slopes that are not necessarily actively steepening. These slides probably are stratigraphically controlled, with failure occurring along weak subsurface strata.

Strong earthquakes and the related accelerations probably are responsible for the actual triggering of many of the large and small slides. As long as the tectonic setting remains as it is today, future large-scale sliding should remain confined to the two broad areas in which it presently exists. However, relatively small-scale and shallow slides might occur in any of the three areas.

INTRODUCTION

Slides and related forms of gravity-induced slope instability are widespread features of the continental slope. Seismic profiles of the slope reveal areas of hmmocky surface geometry, abrupt scarps, deformed and discontinuous subbottom reflectors, rotated sedimentary units, and/or shallow extensional surface fractures. These areas are interpreted to have experienced slope instability.

The causative factors of instability seldom are evident on seismic reflection records. The relative steepness of the continental slope--an average of 4.17^{o} according to Shepard (1973)--compared to other areas of the ocean floor, and the typically high rates of fine-grained sedimentation, probably are ultimately responsible for the abundance of sliding. Earthquakes and abnormally high pore pressures are thought to be common triggering mechanisms (see also Kelling and Stanley, 1976, p. 412-413).

Seismic reflection records gathered in June and July, 1976 aboard the R/V SEA SOUNDER and R/V S.P. LEE show several areas of instability on the uppermost continental slope in the western Gulf of Alaska, off the Kodiak island group (Fig. 1). The survey lines, which had been designed mainly for an environmental geologic study of the continental shelf, did not extend far beyond the shelf break (Fig. 2) (Bouma and Hampton, 1977; Hampton and Bouma, 1976), but previous records show features interpreted as slides down to the junction of the continental slope with the Aleutian Trench (von Huene, 1972).

Inspection of our seismic reflection records allows identification of areas where slides are present on the uppermost slope and other areas where they are absent. Two fundamentally different types of slides have been distinguished, and the habitats of each type have been defined. The records also show ample evidence as to the major controls on instability.

METHODS

Continuous seismic reflection records were collected with intermediate- and high-frequency instruments including Teledyne 160 kilojoule and 90 kilojoule sparker, EG&G uniboom and Raytheon 3.5 kilohertz systems. Ship's speeds commonly were about 5 1/2 knots, but varied between 4 and 8 knots.

Navigation was by Magnavox and Marconi integrated satellite - Loran C systems. A Motorola Mini-Ranger unit, using land-based transponders, was the principal navigational tool where surveying was within 50 to 80 miles of the transponders.

Two grab samples and two gravity cores were collected beyond the shelf break, giving limited information as to the nature of the upper slope sediments.

GEOLOGIC SETTING

General

The western Gulf of Alaska continental margin is located on the edge of the North America plate near the zone of subduction associated with the Aleutian Trench. Active tectonism is demonstrated by frequent seismic and volcanic events in the general area.

The most recent major seismic activity to affect the western Gulf was the 1964 Alaska earthquake. A maximum uplift of about 7 m near the shelf break as computed from pre- and post-earthquake soundings by von Huene et al. (1972). Since the turn of the centruy, more than 80 earthquakes of greater than Richter magnitude 6.0 have occurred in the region from the tip of the Alaska Peninsula to Prince William Sound (von Huene et al., 1976; John Lahr, U.S. Geological Survey, unpublished data). Sixteen volcanoes in this same region have been active within the past 10,000 years.

Structure

The structure of the continental margin reflects major tectonic activity (von Huene and Shor, 1969; von Huene, 1972; von Huene et al., 1972). A zone of intense faulting and deformation occurs along and offshore of the Pacific Coast of the Kodiak islands. Seaward of this zone is a broad, gently deformed basin containing middle and upper Tertiary sediments. A broad arch, which apparently is discontinuous at shallow to moderate depths, exists along the shelf break and forms the seaward flank of the basin. The arch is breached in several places, and a few rocks of Miocene and Pliocene age have been recovered by dredging (von Huene and Shor, 1969).

Seismic records suggest that the continental slope is composed of steeply dipping and folded sediments overlain by a blanket of terrigenous sediments (von Huene, 1972), but the structure is less well known than for the adjacent shelf.

Physiography

The surface physiography of the shelf off the Kodiak islands consists of everal flat, relatively shallow areas cut by transverse valleys (Fig. 3). This physiography reflects the erosive action of glaciers and waves as well as some bedrock structural control. The shelf-break arch commonly forms a physiographic high area, with a shallow trough behind it. Hogback ridges, reflecting breaching of the shelf-break arch, occur at several places on the outer parts of the shallow banks. Surficial scarps, implying recent faulting, occur throughout the shelf area (Bouma and Hampton, 1976; Hampton and Bouma, 1976).

The continental slope can be divided into three broad physiographic areas: the relatively smooth upper slope, the benchlike middle slope, and the steep, rough lower slope (von Huene, 1972).

Sediments

Surficial sediments on the shallow banks of the shelf are sands that contain coarser material up to boulder size. They rarely contain significant quantities of silt and clay (Bouma and Hampton, 1976). Foraminifera tests and crushed shells of megafauna constitute major portions of many of these sediments. The surficial sediments in the transverse troughs typically are finer grained than those on the banks, and a few are composed almost entirely of silt- and clay-size material. Local occurrences of gravel and coarser clasts are common. Volcanic ash is an abundant constituent of most surficial trough sediments.

The two gravity cores collected on the uppermost continental slope, seaward of middle Albatross Bank (Figs. 2, 3) consist of silty mud with scattered pebbles. The cores came from an area of general sliding (Fig. 3). The two grab samples, collected seaward of the mouth of a transverse valley, in an area that contains only minor evidence of slumping, are composed of pebbly sand with essentially no fine-grained material.

DESCRIPTIONS OF SEISMIC REFLECTION DATA

The following descriptions begin at the southwestern end of the study area and progress northeast. On southern and middle Albatross Bank, most sparker records (lines 63 through 154, Fig. 2) show evidence of sliding (Fig. 4). Slides are not evident, or are questionable, on lines 59, 60, 61 and 608. Perhaps some of these lines did not extend far enough onto the continental slope to encounter slides. In the best examples, such as lines 64 and 610, the slides appear as high-relief hummocks that reach heights of about 60 m. These features have the general appearance of large rotational slumps (Varnes, 1958), having relatively small displacements relative to the size of the displaced units and having generally curved slide planes, where visible. Truncation of strata at lines 63, 154 and 610 but not on others such as 609.

A minimum thickness of 200 m of slumped material can be estimated on line 154 by extending the 5 1/2° gradient of the upper slope above the headwall, out over the area of sliding and by measuring the distance down to the inferred slide plane. Estimates of thickness made on other lines are similar. The slide block visible in lines 154 is about 95 m thick and has moved about 300 m downslope.

Complexly distorted bedding exists to great depths in some of the slide areas. Past the major course change marked on line 610, for example, deformation is evident below the surface for about 0.8 sec. of one-way travel time. About 0.38 sec. of deformed sediment is visibile at the end of line 63, and about 0.18 sec. on line 55. Some irregular deformation also appears on line 60, which is parallel to the slope and crosses the trough between southern and middle Albatross Banks. The folding apparently is oblique to the main tectonic trend. The slope gradient normal to line 60 is about 6 1/2°.

The slides between lines 607-608 are subtle on the sparker records (Fig. 4) but show up well on the uniboom records (Fig. 5). They appear as a series of low-relief hummocks up to about 5 m high. Continuous reflectors are visible below the slides, giving a limiting maximum thickness of about 30 m of displaced material. These slides appear to be debris slides or block glides (Varnes, 1958), involving movement of a few or several units along relatively planar slide surfaces.

The debris slides described above moved over a gradient of about 3°. In contrast, the larger slumps moved over generally steeper gradients of 3°-9°, averaging about 5 1/2°. Gradients on the upper continental slope where sliding is not observed range from about 2° to 4 1/2°, averaging about 3°.

The nature of the shelf break is highly variable along southern and middle Albatross Banks. For example, the shelf break is abrupt on lines 609 and 610, whereas it is broad on lines 59 and 154 (Fig. 4). The depth of the shelf break, measured at the first significant change in gradient, varies from about 45 m (line 59) to about 365 m (line 610). Part of the variation in depth is related to the presence of troughs between the banks. The shape and depth of the shelf break does not seem to vary consistently with the presence or absence of slides, except that all abrupt shelf breaks are followed by sliding on the adjacent upper slope.

The geologic structure in this part of the study area shows considerable evidence of recent tectonics. A large, breached anticline is present near the shelf break on most lines (e.g., line 61, Fig. 4). An apparent graben occurs near the large anticline on line 64, and may be present in a more subdued form on nearby line 63 as well as partially on line 61. The graben is probably related to extension above the general arching that seems to be taking place.

A smaller anticline appears seaward of the large one on some of the lines. For example, a small subsurface flexure that is draped by very slightly deformed slope sediments appears on line 61 (Fig. 4). Line 610, the next line to the northeast, shows a larger, but analogous, anticline; one that has grown sufficiently to form a new shelf break beyond the landward one. The second crossing of the seaward anticline on line 610, past the major course change where the ship turned and headed back toward land, shows this anticline to be larger and forming a shallower shelf break (280 m versus 365 m) than on the previous crossing. The shelf break is a discontinuous, "en echelon" feature in this area, as depicted on Figures 2 and 3.

Ponded sediments occur between the two anticlines on lines 610 (Fig. 4). The increased dip of these sediments deeper in the section implies growth of at least the seaward anticline during deposition (von Huene, 1972).

The central part of the study area, along northern Albatross Bank (lines 190 to 31, Fig. 2), is devoid of slides on the uppermost continental slope (Fig. 6) except for some relatively small features on lines 605-606. As seen on the uniboom record (Fig. 7), these slides are similar to the debris slides on lines 607-608. They occur on a slightly steeper gradient of about 4 1/2° and appear to be about 25 m thick. Irregular subsurface deformation is apparent on lines 605-606 and 190 (Fig. 6) near the boundary with the southwestern part of the study area.

The gradient of the upper continental slope is gentle throughout most of the central area, in the range from 1/4° to 4 1/2°, averaging about 2°. The debris slides occur on the steepest observed slope (4 1/2°), where the shelf break is also most abrupt. The shelf break throughout the rest of the area ranges from sharp (e.g., line 34) to gradual (e.g., line 603). Its depth lies between 100 m and 175 m.

The geologic structure of the central region is in distinct contrast to that to the southwest. The shelf break anticline is present on most lines, but is typically a broad feature with gently dipping limbs (e.g., lines 31, 34, 39, 604, Fig. 6). The seaward limb normally conforms to the gentle gradient of the upper slope, and seismic reflectors generally are planar under the slope (e.g. lines 32, 33, 37, and 38, Fig. 6). A tight, breached anticline is present on line 49 (Fig. 6), but it is well landward of the shelf break. A relatively small subsurface anticline occurs on line 606 but does not appear on adjacent lines.

Large-scale sliding resumes in the northeastern part of the study area, which encompasses Portlock Bank and the adjacent trough to the southeast (lines C to 610, Fig. 2). Large slumps are present on many of the track lines. On line 81 the slide plane is visible below the slide mass, which is about 175 m thick and has moved about 950 m downslope (Fig. 8). An older seismic record, nearly coincident with line 81 but extending to the base of the continental slope (line 6, Fig. 9), shows this same slide block in its entirety. It is about 3700 m long and is succeeded downslope by at least one more similar slide.

Debris slides, similar to those on lines 607-608, appear on line 601 near the shelf break (Fig. 10). The continuous reflectors below the slide blocks place a maximum thickness of 70 m. The gradient is 3°. The analogous location on the return crossing of the shelf break, beyond the major course change marked on line 601, shows no slide blocks.

In addition to the presence of large slumps, the northeastern area has many other similarities to the southwestern area. The shelf break is abrupt in some places and broad in others. Gradients of the upper slope are from 2° to 9 1/2° and depths of the shelf break are from 110 m to 510 m.

The geologic structure near the shelf break also is similar to that of the southwestern area. Broad, breached anticlines appear on many lines (e.g. 77, 79, Fig. 8), and a large graben is well shown on line 81. Irregular subsurface deformation also occurs (e.g. lines C, 6, and 67, Figs. 8, 9).

Multiple shelf breaks, reflecting a similar situation as on lines 61 and 610 (Fig. 4), appear on lines 77, 175 and 601 (Fig. 8). On line 77, a subsurface anticline is draped by slope sediments. This anticline deforms the sea floor to form a new shelf break on the next line to the northeast (line 601) and a shallower, more pronounced break on the next one (line 175). Large slumps are present on the steep slope beyond this shelf break.

DISCUSSION AND CONCLUSIONS

The occurrence of large slides in areas where there is evidence for active growth of structures on the shelf break and uppermost continental slope, and the absence of such slides where tectonic deformation is relatively minor, indicates a relationship between slope instability and tectonics. The upper continental slope apparently is being tectonically steepened in places by growth of structural arches near the shelf break. The tectonic steepening probably is the ultimate control of the large slides in the study area, although earthquakes associated with the tectonism might actually be the triggering mechanism Von Huene (1972) also has suggested a relationship between tectonic steepening and sliding in this area.

Active tectonic steepening is perhaps most convincingly demonstrated where multiple shelf breaks exist. The seaward shelf break represents the physiographic expression of a shallow anticlinal fold. As most clearly shown on lines 77, 601, and 175 (Fig. 8), the axis of the anticline is inclined gently toward thesouthwest. On line 77 the anticline apparently once existed as a physiographic high, with slope sediment onlapping it. Present-day slope sediments are unaffected by the anticline, suggesting that its growth at this location is now slow or nonexistent. On lines 601 and 175 the anticline has higher elevations on crossings successively to the northeast and appears from its physiographic expression to be active at present. A similar case can be constructed for the seaward anticline and shelf break on lines 61 and 610 (Fig. 4). Seismic reflection records of all crossings of multiple shelf breaks along the Kodiak shelf (lines 175, 601, and 610) show large slides on the actively steepening seaward flank of the outer anticline.

Irregular subsurface deformation is common in the general areas where large-scale slides occur. This deformation (e.g., line 60 on Fig. 4 and lines C, 67, 81, and 176 on Fig. 8) undoubtedly represents buried slides in some places, but in others it may be due to gravity folding, diapirism, or movements along deep slide planes. All of these could be basically controlled by tectonic slope steepening, and in this way the complex deformation could be genetically related to the large slides.

The debris slides occur in a different environment from the larger slides and generally are found on more gentle gradients. The debris slides most likely are not all principally controlled by slope steepening. On line 601 (Figs. 8, 10) for example, the slides occur near the landward shelf break, behind the seaward break and its associated rotational slumps. The gradient on which these smaller slides occur is probably decreasing with time, because the seaward shelf break is apparently being uplifted faster than the landward break, with sediments ponding in the interconnecting depression. Where small slides occur along line 605 (Figs. 6, 7), the gradient probably is not increasing significantly, because this line is located in the central region of gentle deformation. The small slides on line 607 (Figs. 4, 5) are near a zone of rotational slumps (see line 55, Fig. 4), and this is one instance where the local slope may be steepening. In all of these examples, the more-or-less planar geometry of the slide plane indicates ultimate stratigraphic control of the instability, whereby sliding occurs along a weak layer of sediment. Failure of the weak layer might be triggered by accelerations and/or abnormal core pressures related to earthquakes, and in this way tectonism probably does exert some influence.

According to the ideas developed in this paper, future large earthquakes and the related tectonic steepening will probably continue to generate large-scale slides in the two areas where they occur today (i.e., the upper slope off southern-middle Albatross Bank and off Portlock Bank). The third area, off northern Albatross Bank, that does not contain large-scale slides seems unlikely to experience such slope instability as long as tectonic steepening remains dormant. All three areas contain the smaller, stratigraphically controlled debris slides and are therefore susceptible to shallow instability.

ACKNOWLEDGEMENTS

We are grateful for the cooperation and assistance given by Capt. Allan McClenaghan, officers and crew of the R/V SEA SOUNDER during our cruise in 1976. Roland von Huene contributed data collected aboard the R/V S.P. LEE and from earlier cruises, and provided stimulating discussions about this study. The manuscript was reviewed by George Plafker and Roland von Huene. Funding was partially through the BLM/NOAA Outer Continental Shelf Environmental As Assessment Program.

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FIGURE CAPTIONS

1. Generalized location map of the study area.

2. Locations of seismic reflection profiling lines. Parentheses indicate portions of records shown in Figures 4-10.

3. Locations of slumps on the upper continental slope, and physiography of the adjacent Kodiak shelf.

4. Sparker seismic reflection records from the southwestern part of the study area. Horizontal scale in nautical miles; vertical scale in seconds of two-way travel time. s = slides; s.b. = shelf break.

5. Uniboom seismic reflection record of part of lines 607-608. Horizontal scale in nautical miles; vertical scale in seconds of two-way travel time. s = slide.

6. Sparker seismic reflection records from the central part of the study area. Horizontal scale in nautical miles: vertical scale in seconds of two-way travel time. s = slide.

7. Uniboom seismic reflection record of part of lines 605-606. Horizontal scale in nautical miles; vertical scale in seconds of two-way travel time. s = slide.

8. Sparker seismic reflection records from the northeastern part of the study area. Horizontal scale in nautical miles; vertical scale in seconds of two-way travel time. s = slide; s.b. = shelf break.

9. Sparker seismic reflection record of part of line 6. Horizontal scale in nautical miles; vertical in seconds of two-way travel time. s = slide.

10. Uniboom seismic reflection record of part of line 601. Horizontal scale in nautical miles; vertical scale in seconds of two-way travel time. s = slide.

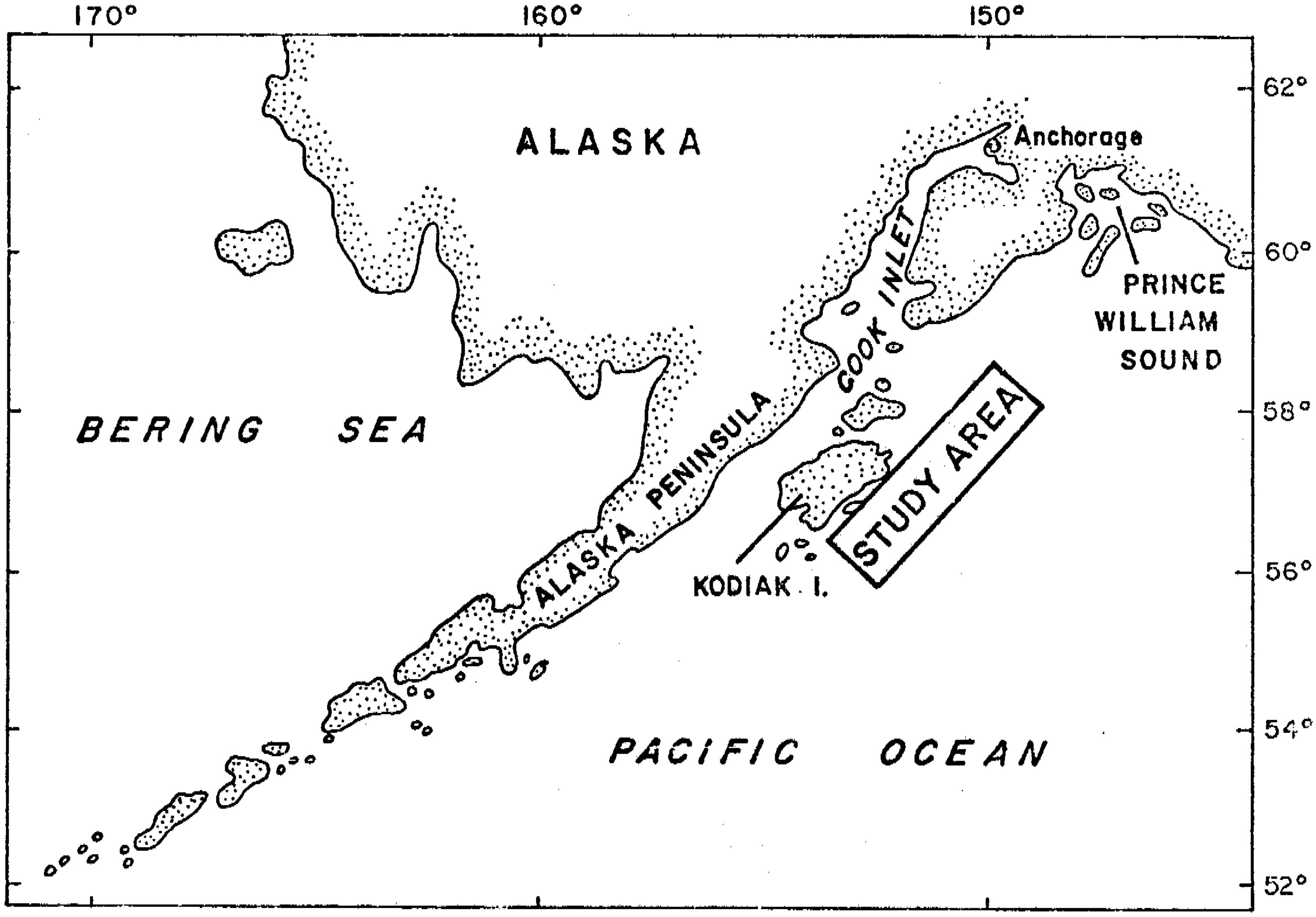
170°
160°
150°
62°
60°
58°
56°
54°
52°
ALASKA
Anchorage
COOK INLET
PRINCE
WILLIAM
SOUND
BERING SEA
ALASKA PENINSULA
STUDY AREA
KODIAK I.
PACIFIC OCEAN

FIGURE 1

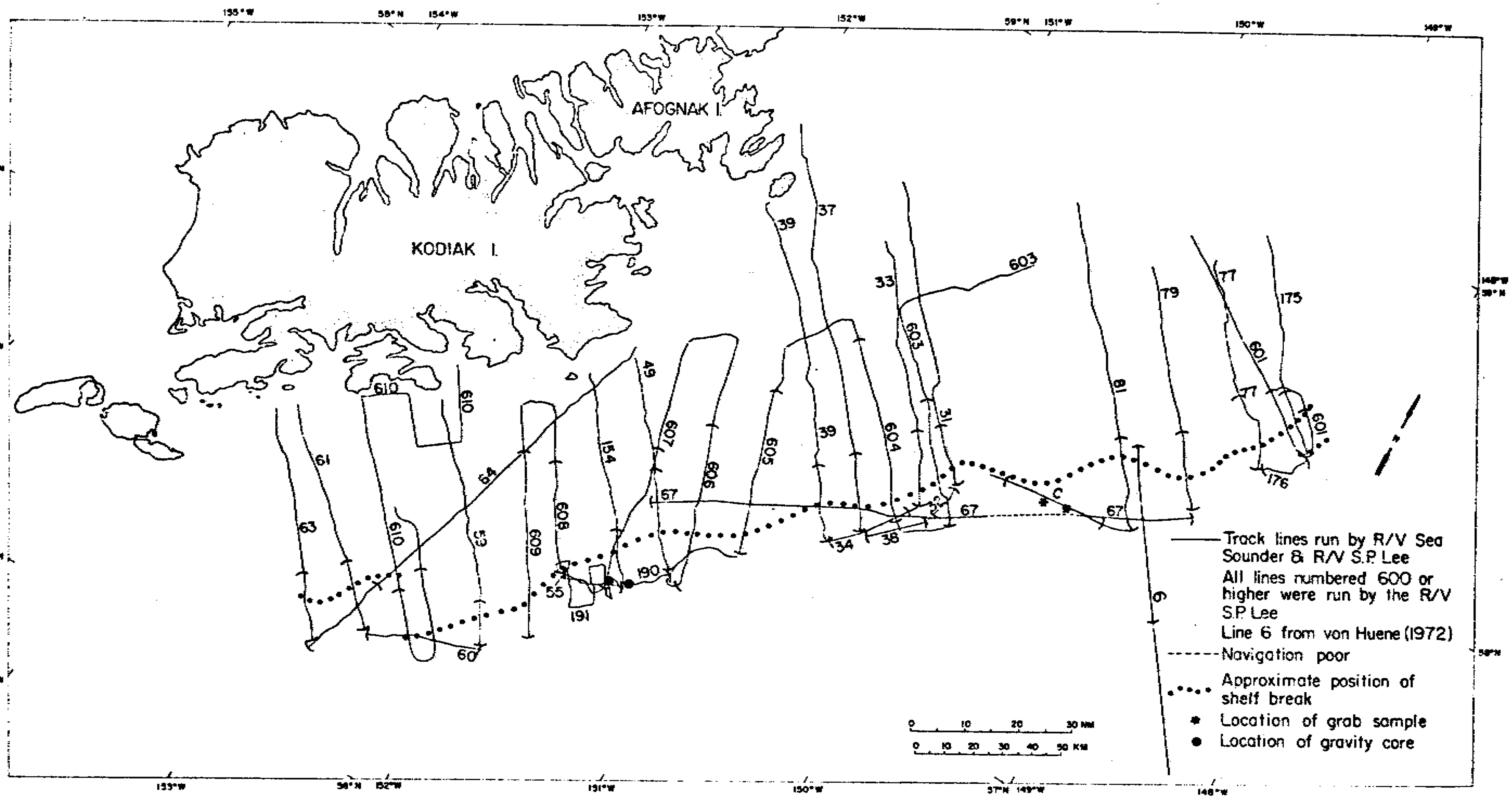
AFOGNAK I.
KODIAK I.
Track lines run by R/V Sea Sounder & R/V S.P. Lee
All lines numbered 600 or higher were run by the R/V S.P. Lee
Line 6 from von Huene (1972)
Navigation poor
Approximate position of shelf break
Location of grab sample
Location of gravity core
0 10 20 30 NM
0 10 20 30 40 50 KM

FIGURE 2

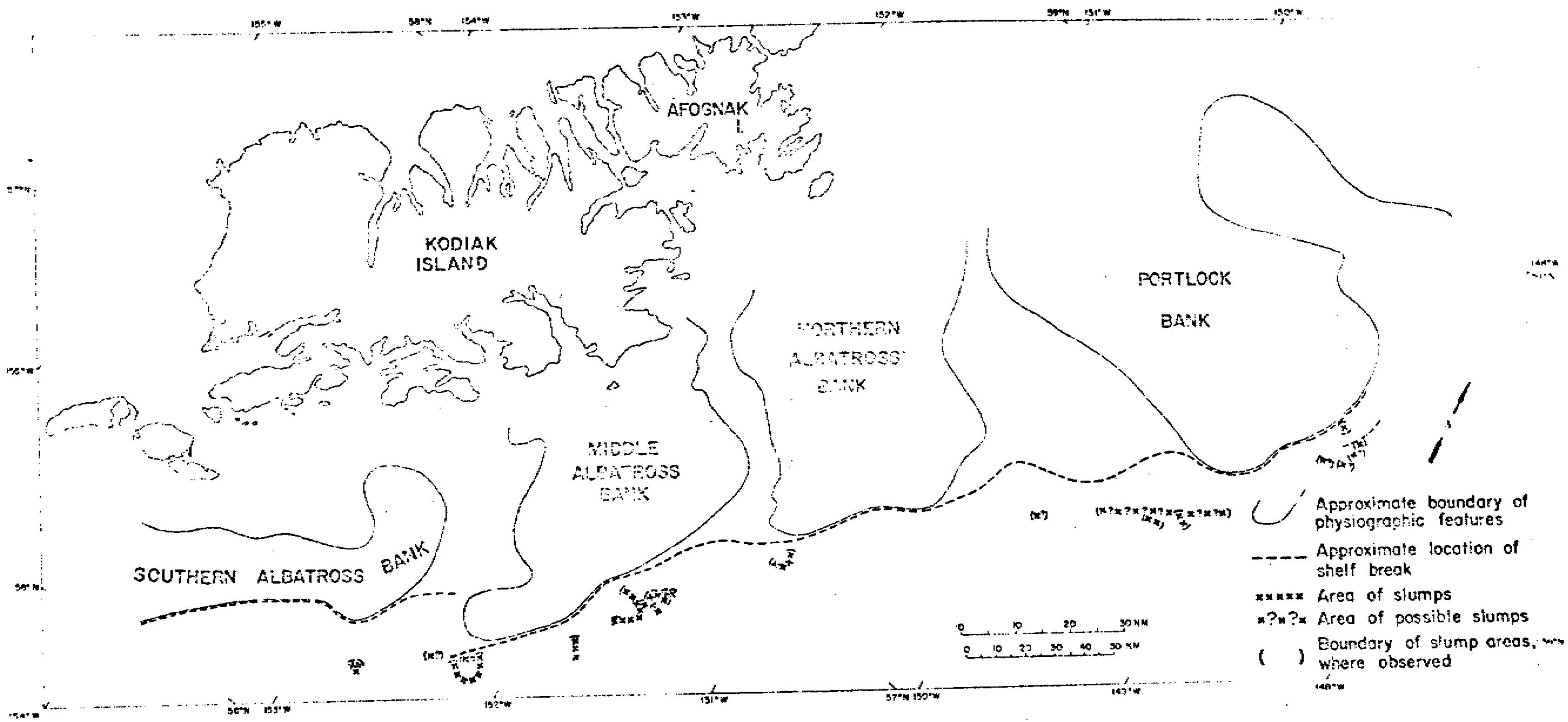
AFOGNAK I.
KODIAK ISLAND
PORTLOCK BANK
NORTHERN ALBATROSS BANK
MIDDLE ALBATROSS BANK
SOUTHERN ALBATROSS BANK
Approximate boundary of physiographic features
Approximate location of shelf break
xxxxx Area of slumps
x?x?x Area of possible slumps
( ) Boundary of slump areas, where observed

FIGURE 3

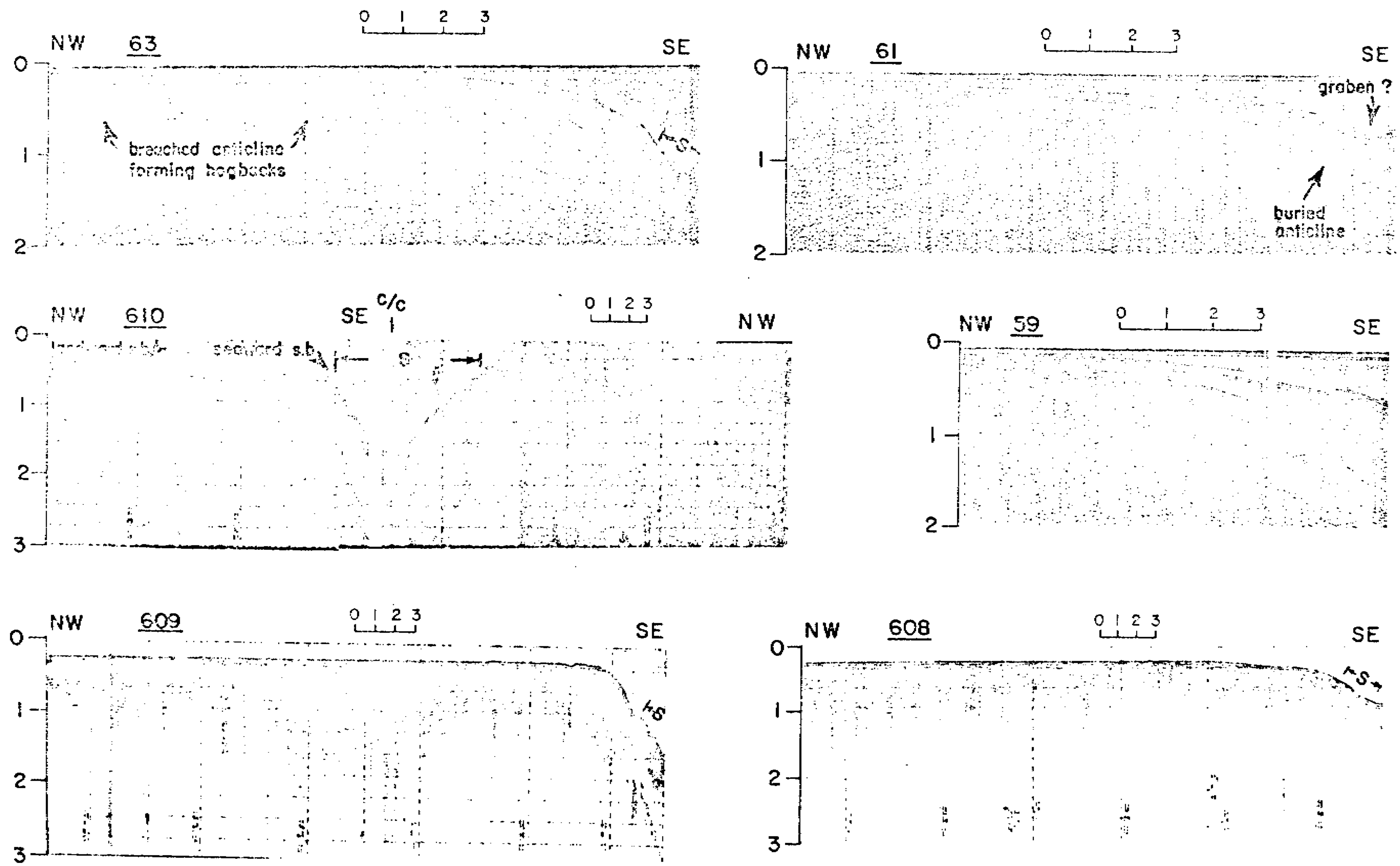

FIGURE 4 (1 OF 2)

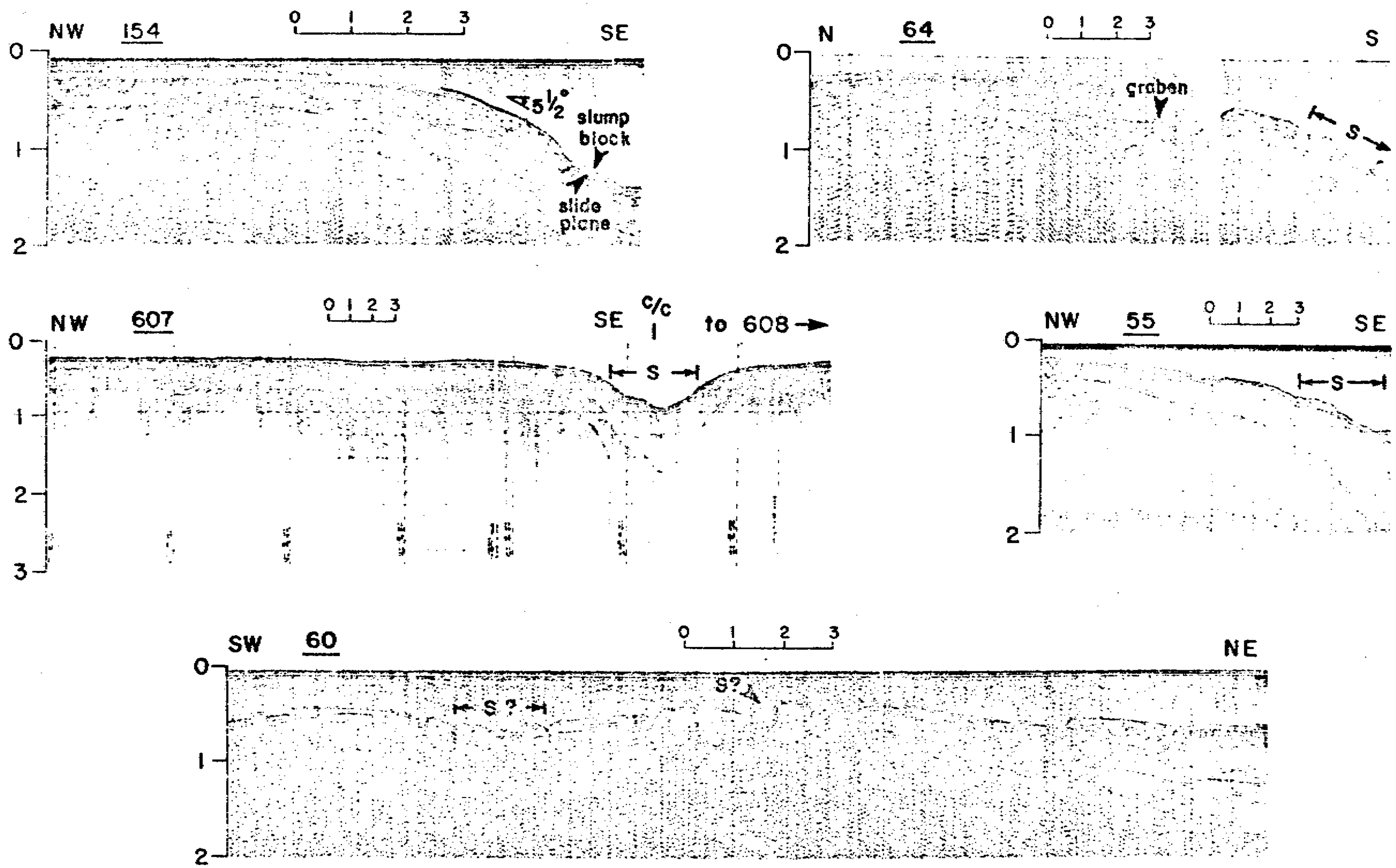

FIGURE 4 (2 OF 2)

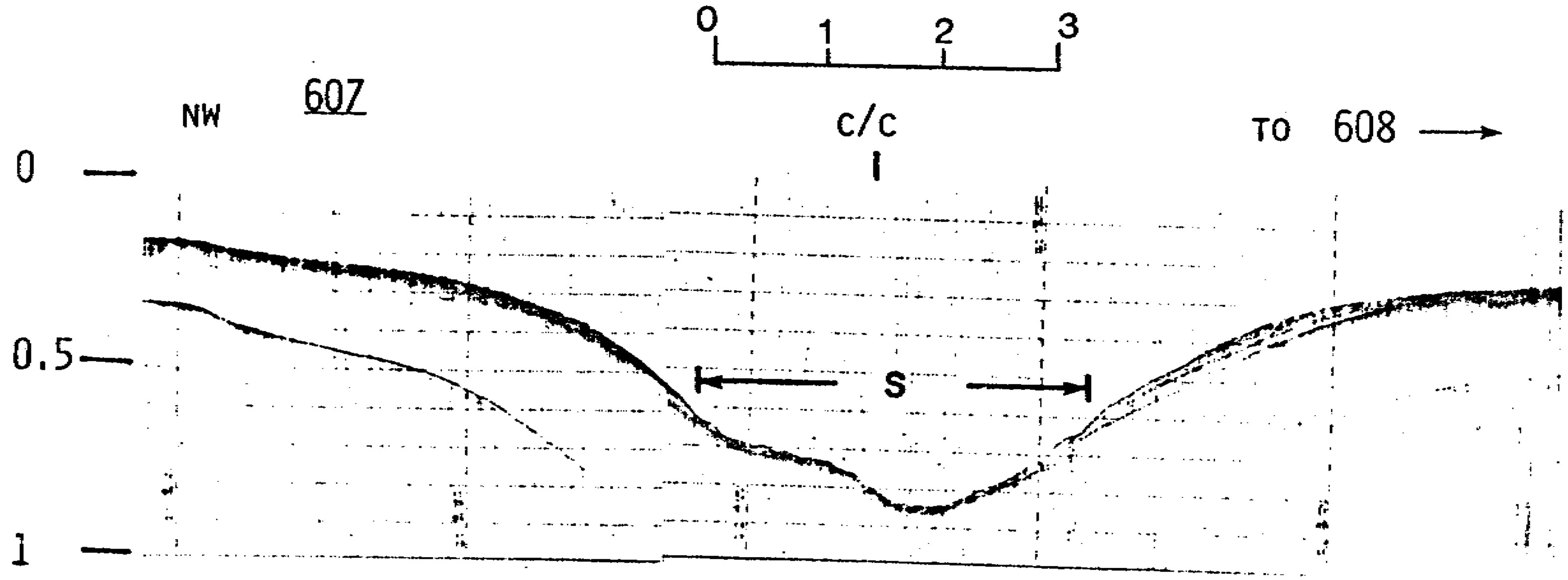

FIGURE 5

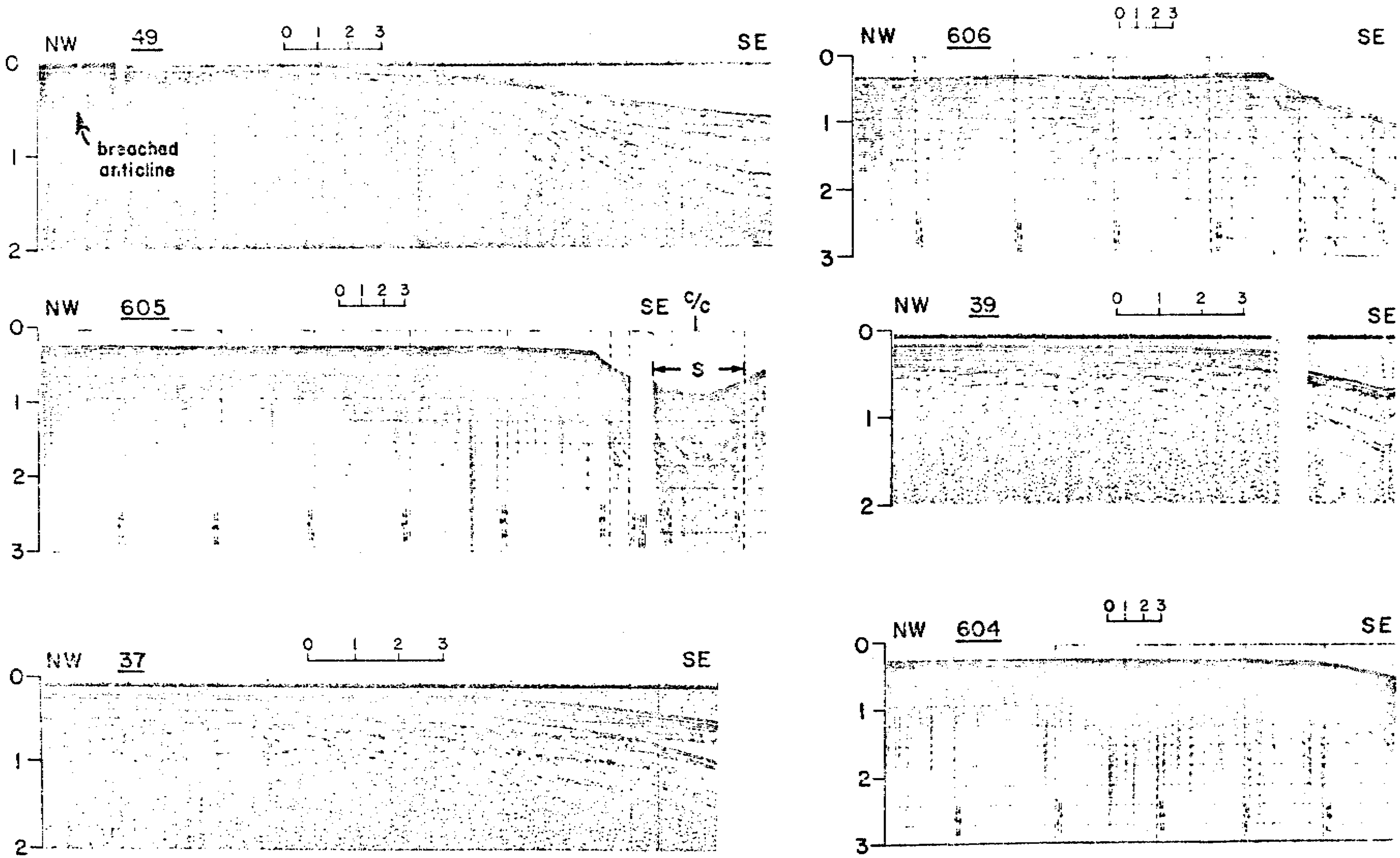

FIGURE 6 (1 OF 3)

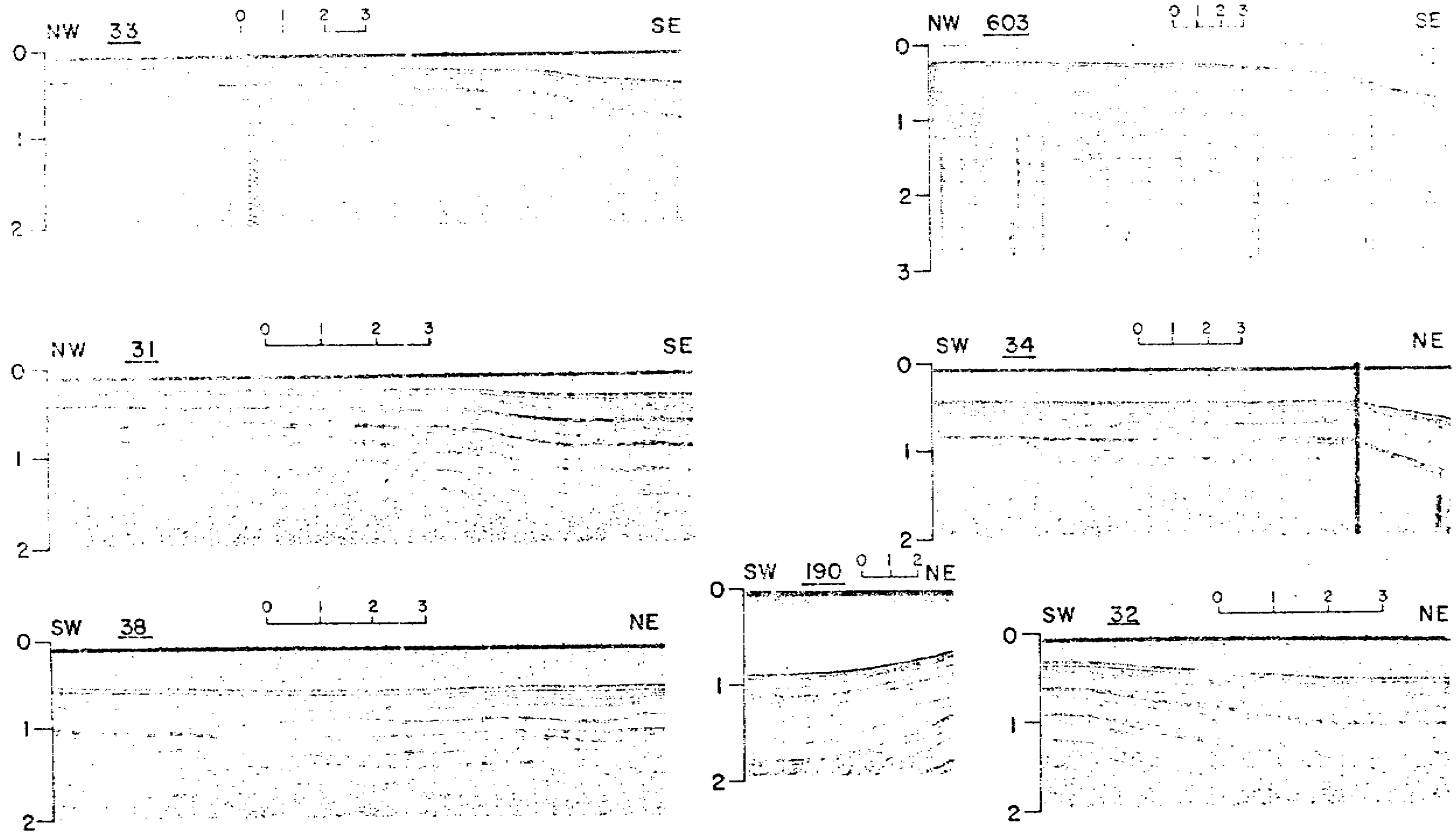

FIGURE 6 (2 OF 2)

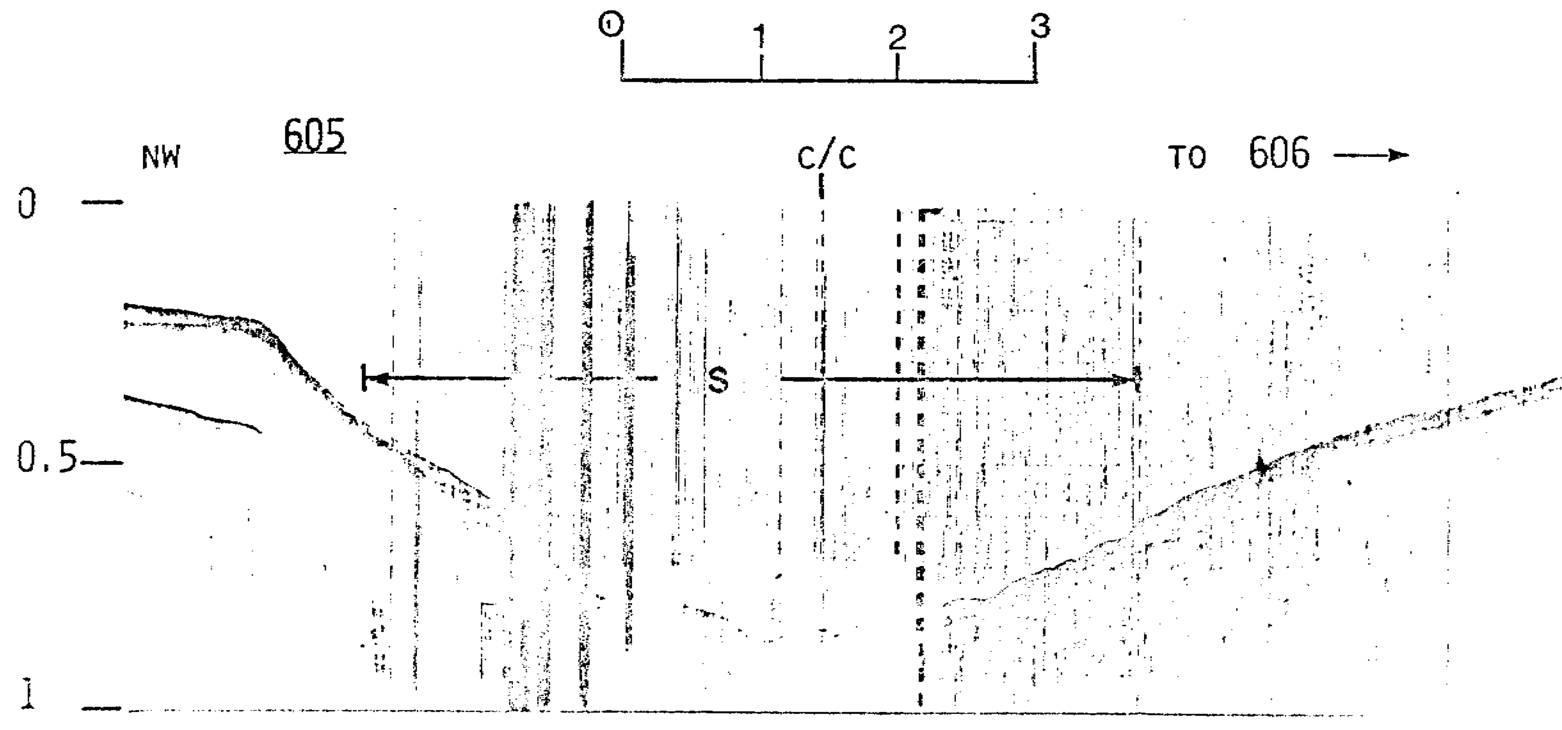

FIGURE 7

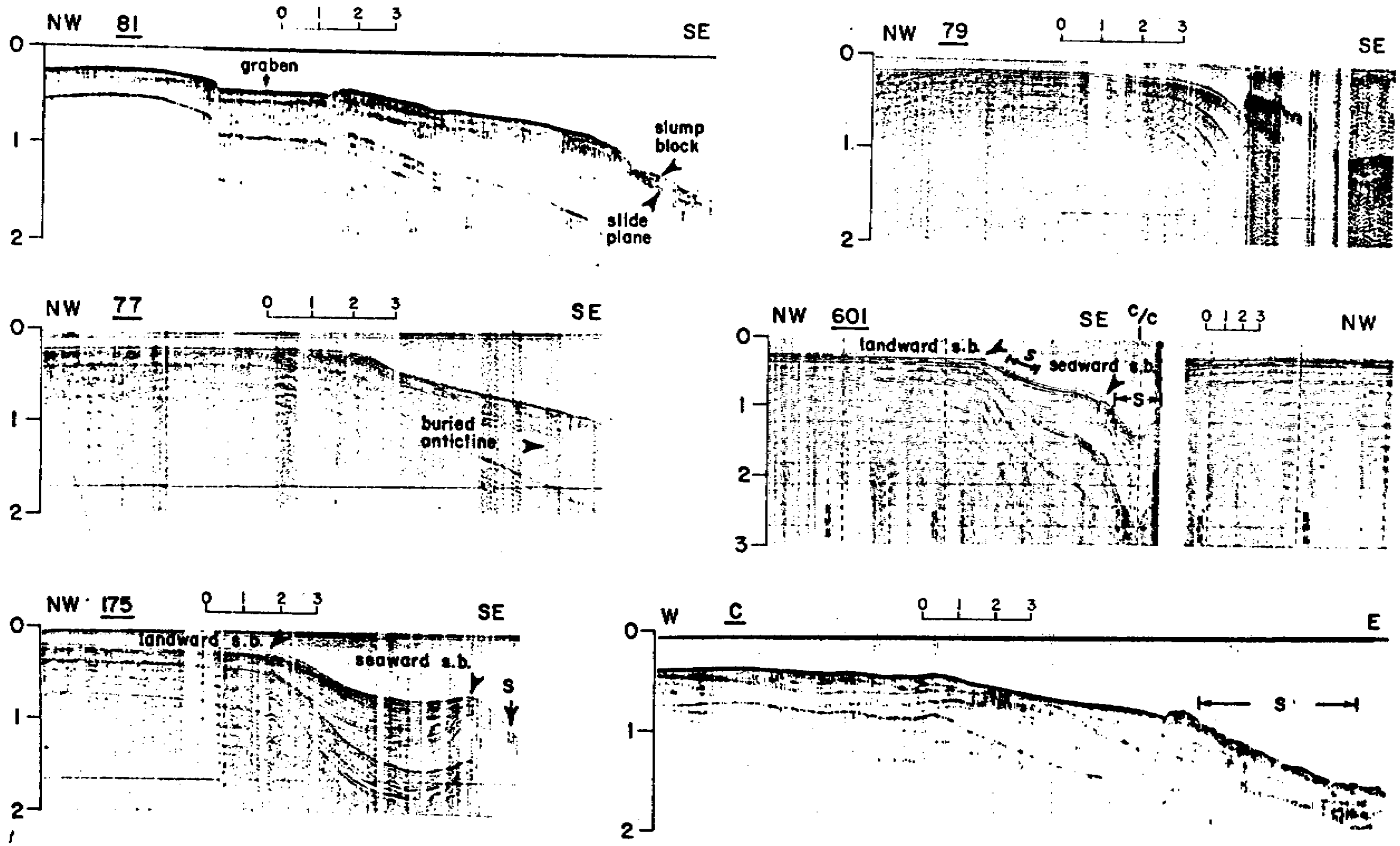

FIGURE 8 (1 OF 2)

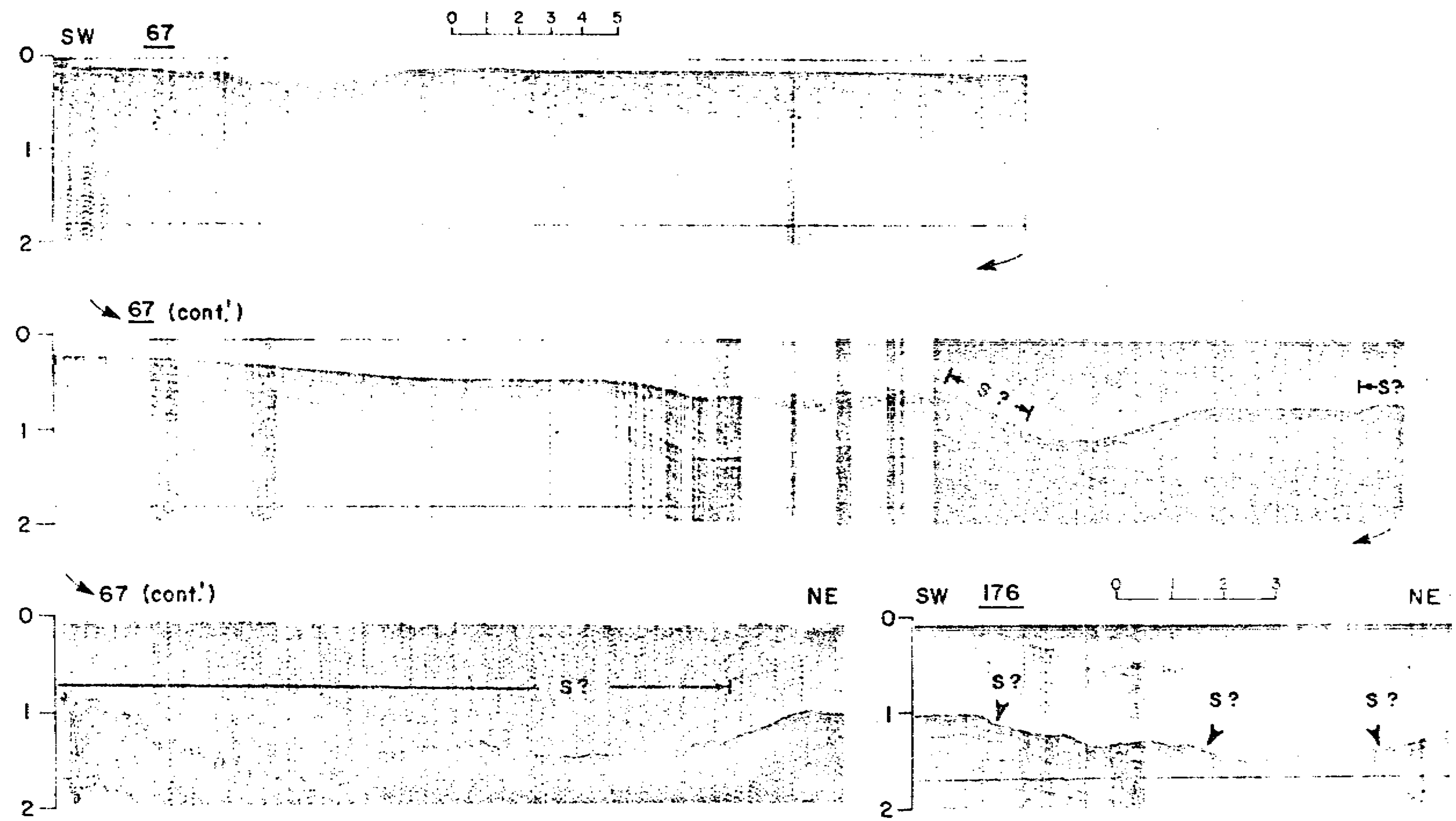

FIGURE 8 (2 OF 2)

625

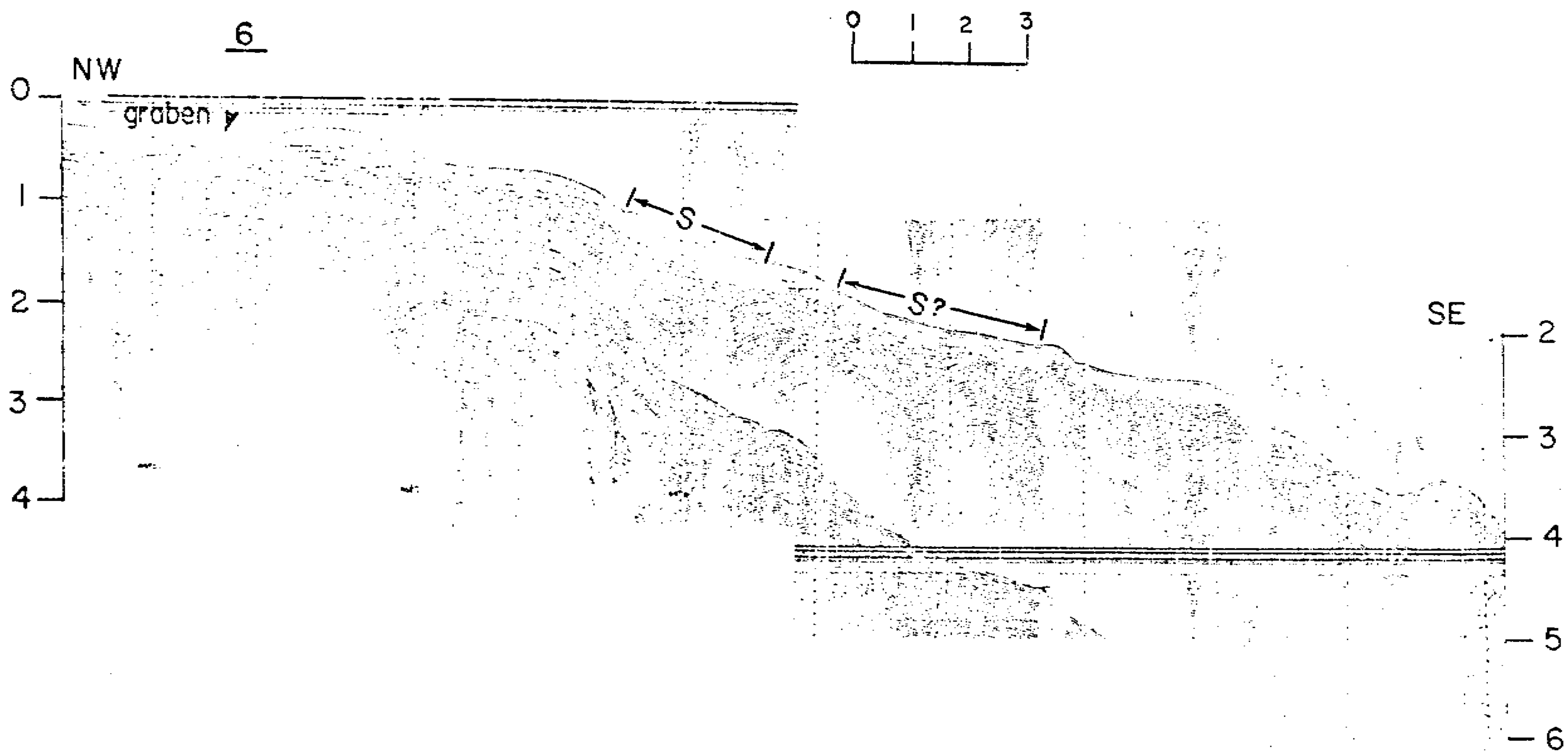

FIGURE 9

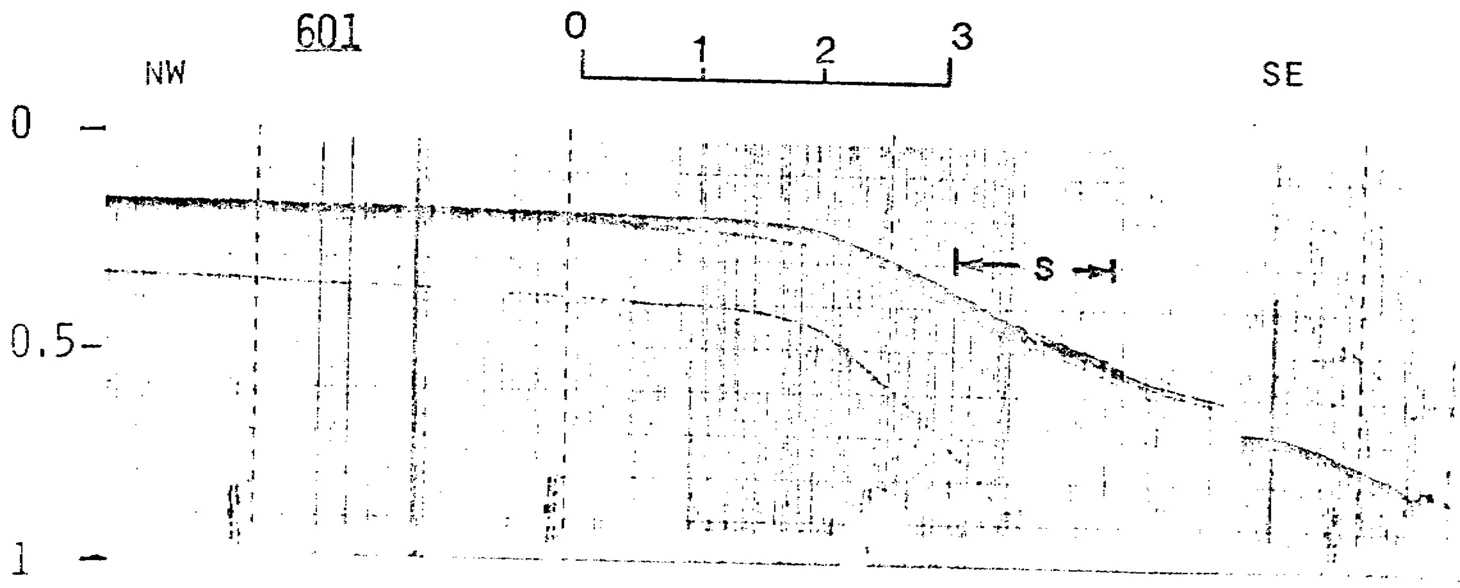

FIGURE 10

ANNUAL REPORT

Contract:
Research Unit: No. 352
Reporting Period: April 1, 1976-March 31, 1977

SEISMICITY OF THE BEAUFORT SEA, BERING SEA AND GULF OF ALASKA

Herbert Meyers
Solid Earth Data Services Division D62
National Geophysical and Solar-Terrestrial
Data Center
EDS/NOAA
Boulder, Colorado

March 31, 1977

ANNUAL REPORT

SEISMICITY OF THE GULF OF ALASKA, BERING SEA AND BEAUFORT SEA (RESEARCH UNIT NO. 352).

I. Summary. The Alaskan region is one of the most seismic regions in the world. The location and design of drilling platforms, pipelines, storage and support facilities will have to take this factor into consideration. The objective of Research Unit 352 is to compile a historical file of earthquake data and present it in a fasion which would permit independent assessment of the seismic risk for various localities in Alaska.

II. Introduction.

a. Scope of Study. Although the OCSEAP baseline study program covers specific geographic areas in Alaska, the entire Alaskan region is included in this seismicity study. This expanded coverage of seismicity is necessary since earthquakes from outside the specific area of interest can cause effects within the area of interest.

b. Specific Objectives. The study will result in a series of reports which summarize the occurrence and effects of earthquakes and tsunamis in Alaska. The reports will contain numerous tables and plots which can be used to determine potential hazards due to earthquakes.

c. Relevance. The environmental risks due to earthquakes in some regions of Alaska is great. In addition, the financial investment in platforms and supporting facilities will be substantial. All such equipment and facilities should be located and designed to withstand earthquakes and tsunamis for economic factors as well as environmental factors.

III. Current State of Knowledge. A large number of reports and papers have been written on the seismicity of Alaska since the great earthquake of 1964. However, prior to this OCSEAP study there was no document available which could be considered to be a fairly definitive report on the seismic history of the Alaskan region.

IV. Study Area. 48^{o}-75 N, 165^{o}E-125^{o}W

V. Sources, Methods and Rationale of Data Collection. The NOAA file has been the major source of the epicenter and intensity data used in the study. Supplemental information from other sources has been added to the special file created for Alaska. Data have been cross-checked and examined for reasonability. There are approximately 10,000 tape records in the Alaska epicenter file, and 4,000 tape records in the earthquake intensity file for Alaska.

VI. Results. Three publications have been produced to date:

1. A Historical Summary of Earthquake Epicenters in and Near Alaska, April 1976, NOAA Technical Memorandum EDS, NGSDC-1.

* 2. Catalog of Tsunamis in Alaska, Revised 1976, March 1976, Report SE-1.

* 3. An Analysis of Earthquake Intensities and Recurrence Rates in and Near Alaska, October 1976, NOAA Technical Memorandum EDS NGSDC-3

A copy of the first publication was included with the April 1976 annual report. Copies of the second and third publication are attached to this annual report. The availability of the three reports have been widely advertised and to date more than 600 copies of each of the publications have been distributed in response to specific requests.

VII. Discussion. None

VIII. Conclusions. In general, the formats of the reports enable the reader to draw his own conclusions on matters relating to the seismicity of any specific region of interest in Alaska.

IX. Summary of Fourth Quarter Operations. The agreed upon work under Research Unit No. 352 was completed in the third quarter, hence no activity occurred in the fourth quarter.

Attachments

* These two reports were attached to annual report, but due to availability on request from the author they are not reproduced here. (Ed.)

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