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Tectonics of the Yakutat block, an allochthonous terrane in the northern Gulf of Alaska

by

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TABLE OF CONTENTS

FIGURES AND TABLES

ABSTRACT

Marine geophysical and geological data delineate the late Cenozoic structure and tectonic history of the northern Gulf of Alaska continental margin, and indicate that part of the margin, the Yakutat block, is an allochthonous terrane that has moved with the Pacific plate for at least the last 5 m.y. The block is currently colliding with and subducting beneath southern Alaska.

The Yakutat block is bounded onshore by the Fairweather Fault and the Chugach-Saint Elias fault system, and offshore by the Queen Charlotte fault system, by Kayak Island and its offshore structural extension, and by the Transition fault at the base of the continental slope from Cross Sound to Kayak Island. Magnetic and structural data indicate that the block is subducting at Kayak Island, and continues west of Kayak Island to at least the Kenai Peninsula in the lower, subducted plate. A recently recognized Benioff zone, the Wrangell Benioff zone, also indicates the block is subducting beneath the Chugach and Saint Elias mountains.

Basement rocks of the block consist of Paleocene(?) and early Eocene, probable oceanic basalt west of a basement high, the Dangerous River zone, and a Mesozoic flysch and melange sequence to the east. The oceanic basement is overlain by up to 5 km of Paleogene strata that onlap and are truncated along the Dangerous River zone and at the continental slope. The Dangerous River zone is probably a paleoslope that marks the Paleogene basin edge. The thick Paleogene basin of the block indicates that it was adjacent to a large source area, probably a continental margin, during the Paleogene. The Paleogene strata, and basement rocks east of the Dangerous River zone are in turn overlain by up by 5 km of late Miocene and younger glaciomarine strata.

Offshore strata of the Yakutat block are deformed by uplift of a structural high underlying Fairweather Ground, and by numerous broad anticlines and synclines between Icy Bay and Kayak Island. Otherwise, the block is characterized by regional subsidence. The fold and thrust belt within the Yakutat block reflects the seaward propagation of thrust faults during Pliocene and Quaternary time within the sedimentary sequence covering the block. This deformation is occurring in the region of maximum convergence between the Yakutat block and southern Alaska.

The Transition fault is a major tectonic boundary that has been inactive during Pliocene and Quaternary time. Strata of that age are undeformed over the fault, and Pliocene and younger fans at the base of the slope have not been offset from their probable source areas. There is no connection between the Transition fault and the Queen Charlotte fault of the adjacent transform margin. Therefore, the Yakutat block has moved with the Pacific plate for at least the last 5 m.y.

Prior to Pliocene time, the Transition fault was an active tectonic boundary along which Oligocene oceanic basement was juxtaposed against Mesozoic and Paleogene rocks of the Yakutat block, and which truncated the Paleogene basin of the block. Tectonism caused no major deformation or accretion along the margin, and did not disrupt or subduct a thick pre-Pliocene sedimentary wedge at the base of the slope.

The Yakutat block collision with southern Alaska provides examples of tectonic processes that can occur during microplate collision and accretion. These include: the subduction of thick, low density crust of the block, with only a narrow zone of deformation marking the subduction zone; a possible correlation of mountain building with collision of continental crust; extreme end members of accretion and subduction within a short distance along the collision zone; and a possible latest Pleistocene to Holocene shift in the subduction zone outboard of the Yakutat block.

The identification of the Yakutat block as an allochthonous terrane indicates that North America-Pacific plate motion has been accomodated by a combination of crustal shortening and subduction of at least 300 km of ocean plate or Yakutat block terrane beneath southern Alaska. Major faults or subduction/collision sutures must be present onshore along which subduction has occurred. Microfaunal assemblages and tectonic models suggest that the Yakutat block may have moved with the Pacific plate for most of the late Cenozoic.

INTRODUCTION

In the northern Gulf of Alaska, the Pacific-North America plate boundary changes from transform motion along the Queen Charlotte and Fairweather faults to convergent motion at the Aleutian Trench. Also, a major orogeny has uplifted the high (to 6098 m) Chugach and Saint Elias mountains that rim the northern Gulf of Alaska margin. A recently recognized tectonostratigraphic terrane, the Yakutat block (Fig. 1), is a central element in both of these tectonic events. The block is currently moving with the Pacific plate and colliding with southern Alaska, and the northern margin of the block forms the current Pacific-North America plate boundary. Knowledge of the structure, geology, and tectonic history of the Yakutat block is therefore important for determining both the Cenozoic evolution of southern Alaska, and how Pacific-North plate motion has been accomodated within the transform-to-convergent margin transition.

The Yakutat block is in part defined by major faults of southern Alaska. The present Pacific-North America plate boundary lies along the Queen Charlotte-Fairweather and the Chugach-Saint Elias thrust fault systems (Fig. 1) as demonstrated by abundant seismicity on these fault systems (Tarr and Martin, 1912; Sykes, 1971; Thatcher and Plafker, 1977; McCann and others, 1980; Davies and House, 1979; Lahr and others, 1979, 1980; Lahr and Plafker, 1980; Perez and Jacob, 1980) and by measured Holocene offsets and rates on the Fairweather Fault (Plafker and others, 1977, 1978b). The segment of the continental margin seaward of these faults, termed the Yakutat block by Rogers (1977), is currently moving with the Pacific plate (Plafker and others, 1978b; Perez and Jacob, 1980; Lahr and Plafker, 1980). However, currently recognized offset on these faults, and on other major strike-slip faults of southern Alaska including the Denali, Totschunda, and Duke River faults (Fig. 1), is only about 10 km in post-Miocene time (Reed and Lanphere, 1974; Plafker and others, 1977a, 1978b; Lanphere, 1978). This offset is only a small part of the approximately 300 km of Pliocene and Quaternary Pacific-North America convergence required by plate tectonic models (Minster and Jordan, 1978; Chase, 1978; Engebretson, 1982).

Has this convergence been accomodated offshore, possibly by transform

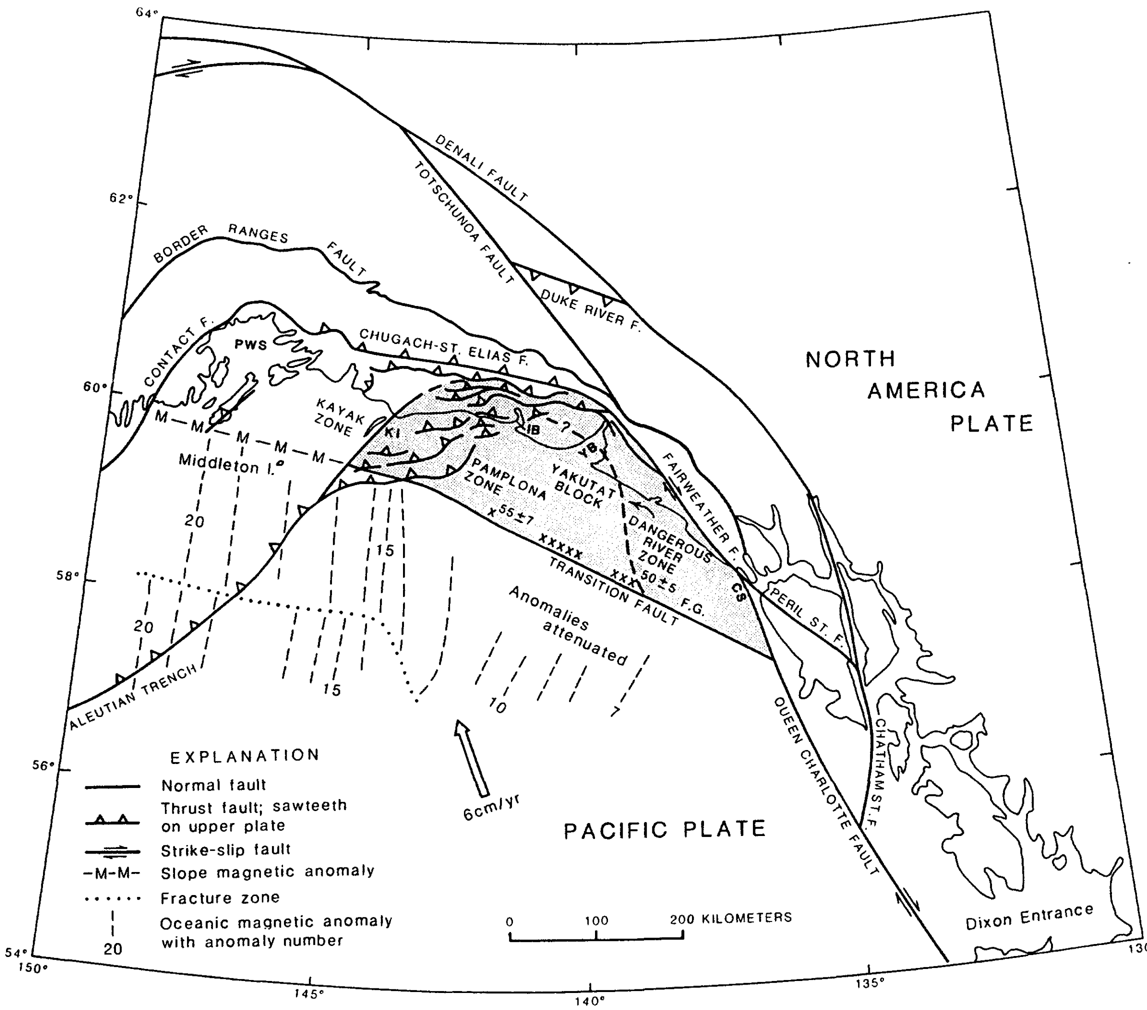


Figure 1. Tectonic setting of northern Gulf of Alaska showing magnetic anomalies and major structural features. Stippled area shows extent of Yakutat block, Slope magnetic anomaly shows south edge of subducted part of block. Small x's indicate where basalt has been dredged from the continental slope; ages from Plafker et al. (1980). Large arrow indicates current Pacific-North America relative convergence vector (Minster and Jordan, 1978). CS-Cross Sound; FG-Fairweather Ground; IB-Icy Bay; KI-Kayak Island; PWS-Prince William Sound; YB-Yakutat Bay.

faulting or oblique subduction along the Transition fault at the base of the continental slope? Offshore studies have found little evidence that such motion has occurred (Bruns, 1979; 1982, 1983a, 1983b; Von Huene and others, 1979; Bruns and Schwab, 1983). These studies and others (Schwab and others, 1980; Keller and others, 1983, 1984) have instead proposed that the Yakutat block is an allochthonous terrane that has moved with the Pacific plate for much of the late Cenozoic. These studies have differed greatly on the definition of the offshore Yakutat block boundaries, the degree to which the block is coupled to the Pacific plate, and the length of time that the block has moved with the Pacific plate.

Marine geophysical and geological data presented in this paper are used to delineate the offshore boundaries, structure, and tectonics of the Yakutat block and the adjacent continental margin segments, and to provide constraints on the motion history of the block. Interpretations of these data show that the Yakutat block is bounded offshore by the extension of the Fairweather Fault into the Queen Charlotte fault system, by Kayak Island and its submarine structural extension, the Kayak zone, and by the Transition fault at the base of the continental slope (Fig. 1). These data also indicate that the Transition fault has been an inactive tectonic feature for at least the last 5 m.y. (Pliocene and Quaternary time). Therefore, the Yakutat block is an allochthonous terrane that has moved with the Pacific plate for that time. At least 300 km of Pliocene and Quaternary Pacific-North America convergence has been accomodated by a combination of crustal shortening in the Chugach-Saint Elias range, and by subduction of oceanic crust or Yakutat block terrane beneath southern Alaska.

The goals of this paper are three-fold: first, to describe the structure, geology, and geologic history of the northern Gulf of Alaska continental margin in order to define the Yakutat block; second, to delineate the Pliocene and Quaternary movement history of the Yakutat block; and third, to establish constraints on the pre-Pliocene geologic and tectonic history of the block. In this paper, most consideration is given to the Pliocene and Quaternary tectonics of the block, since the marine geophysical data primarily provide control on the structural development of the block during that time. I also compare the pre-Pliocene constraints with two speculative plate tectonic models that have been proposed for the Cenozoic origin and movement history of the Yakutat block.

REGIONAL SETTING

The present tectonic regime in the northern Gulf of Alaska involves three types of plate boundaries (Fig. 1; Atwater, 1970; Richter and Matson, 1971; Gawthrop and others, 1973; Rogers, 1977; Plafker and others, 1978b; Von Huene and others, 1979; Bruns, 1979; Perez and Jacob, 1980): (1) a transform margin extending from Dixon Entrance to about Cross Sound; (2) a convergent margin extending from about Kayak Island southwest along the Aleutian Trench, and (3) a transition margin between the two, from Cross Sound to Kayak Island.

The modern plate boundaries are defined moderately well, and isolate the Yakutat block from southern Alaska. The current transform margin is defined by historical large earthquakes, offshore geophysical data, and onshore geology as lying along the Queen Charlotte fault and the onshore Fairweather Fault (Tobin and Sykes, 1968; Page, 1973; Kanimori, 1977; Von Huene and others, 1979; Plafker and others, 1978b; Lahr and Plafker, 1980; Carlson and others, 1979, 1981, and in press). Plafker and others (1978b) showed that the Fairweather Fault has taken up the major portion of Pacific-North America motion for at least the last 1000 years. Geomorphic evidence from offset stream drainages shows a total of 5.5 km of offset along the fault, and this motion could have occurred within the last 100,000 years. The offshore extension of the Fairweather fault has been traced across the continental slope and upper shelf along southeast Alaska on the basis of offsets of the seafloor and disruption of seismic reflectors on marine seismic reflection data (Von Huene and others, 1979; Carlson and others, 1979, 1981, in press; Bruns, 1981).

The current convergent margin can be similarily well defined along the Alaskan Peninsula-Kodiak Island regions. Along the western margin, the 1964 Great Alaska earthquake and a well defined Benioff zone indicate relative convergence and subduction of the Pacific plate beneath the North America plate along the Aleutians and the Alaska Peninsula about as far north as Kayak Island (Plafker, 1969; Lahr, 1975; Davies and House, 1979; Perez and Jacob, 1980). The topographic expression of the Aleutian Trench (Atwood and others, 1981) and the associated, well defined Aleutian Benioff zone (Lahr, 1975; Lahr and Plafker, 1980; Perez and Jacob, 1980) die out near Kayak Island.

The current connection between the transform and convergent plate boundaries lies along the Chugach-Saint Elias thrust fault system (Lahr and Plafker, 1980; Perez and Jacob, 1980) and crosses the continental shelf and slope along Kayak Island and its offshore extension (Bruns, 1979, 1983b; Bruns and Schwab, 1983; Lahr and Plafker, 1980). The north end of the Fairweather fault merges with the Chugach-Saint Elias fault near Yakutat Bay, and the fault extends westward to about Kayak island where it joins the Ragged Mountain and Wingham Island faults (Fig. 1).

The Chugach-Saint Elias fault is a fundamental boundary separating mainly Mesozoic and lower Tertiary metasediments, metavolcanics, crystalline rocks, and younger intrusives on the north from mostly middle and upper Cenozoic sedimentary rocks on the south. The younger strata are thrust relatively against and beneath the older, more competant rocks north of the fault, resulting in numerous, seismically active thrust and reverse faults between Icy Bay and Kayak Island, and on Kayak Island (Stoneley, 1967; Plafker, 1967, 1971, 1974, Winkler and Plafker, 1981a).

The transition boundary is also associated with a recently recognized Benioff zone, the Wrangell Benioff zone, that is nearly horizontal north of the Chugach-Saint Elias fault and reaches a depth of at least 85 km beneath the mainly Pleistocene Wrangell volcanic field of southern Alaska. The Wrangell Benioff zone has not been previously identified, because it is characterized by an order of magnitude less seismicity than is seen in the Aleutian Benioff zone to the west (Stephens and others, 1983, 1984).

An understanding of how late Cenozoic Pacific-North America plate motion has been accomodated in the northern Gulf of Alaska, and of the evolution of the modern plate boundaries is in part dependant on delineating the tectonic history of the Yakutat block. The Wrangell Benioff zone and the Wrangell volcanic field could be due to subduction of the Pacific plate beneath the Yakutat block along the continental margin. Alternatively, these features could arise from subduction of the northern part of the Yakutat block, or of oceanic crust ahead of the Yakutat block, along the Chugach-Saint Elias fault as the block advances northward with the Pacific plate.

Known offset on the Fairweather fault favors the first premise. Plafker and others (1978b) find only about 5.5 km of offset along the Fairweather fault based on geomorphic evidence of offset stream drainages. They assume that the mountains into which these drainages have been incised have been in place since about middle Miocene time, and therefore that the total post-middle Miocene offset along the fault is 5.5 km. Known offset on other major fault systems of southern Alaska, such as the Denali and Totschunda faults is also small, less than about 10 km (Reed and Lanphere, 1974; Plafker and others, 1977a, 1978b; Lanphere, 1978). Therefore, Plafker and others (1978b) suggest that most of late Cenozoic Pacific-North America plate motion has been accomodated along the Transition fault at the base of the continental slope between Cross Sound and Kayak Island. In this case, the Yakutat block would be underthrust by the Pacific plate.

An alternate premise presented in this study is that the Yakutat block is an allochthonous terrane that is moving with the Pacific plate, colliding with, and subducting beneath southern Alaska. In the next several sections, I utilize an extensive set of marine geophysical and geological data to define the boundaries, structure, and tectonic history of the Yakutat block, and compare the block with the adjacent transform and convergent margins.

DATA

This study is based on interpretation of about 7000 km of multichannel seismic reflection data collected by the U. S. Geological Survey since 1974 (Fig. 2). The multichannel data include 24- and 48-fold data acquired in 1975 from the Geophysical Services Inc. vessel M/V Cecil H. Green under contract to the U.S. Geological Survey (Bruns and Bayer, 1977), and 24-fold data acquired in 1977 and 1978 from the U. S. Geological Survey research vessel R/V S. P. Lee.

The seismic system on the M/V Green consisted of a tuned array of 22 airguns with a total capacity of 19.6 liters (1200 cu. in.), a 2400 m, 48-group streamer, and DSF IV digital recording instruments. These data were processed by Petty-Ray Geophysical Division of Geosource Inc., Houston, Texas (Bruns and Bayer, 1977). The seismic system on the R/V Lee consisted of a tuned array of 5 airguns with a capacity of 21.7 liters (1326 cu. in.), a 2400 m, 24-group streamer, and GUS 4300 digital recording instruments. These data were processed by the U.S. Geological Survey in Menlo Park, California. In all surveys, navigation was by means of an integrated satellite, Loran C, and doppler sonar navigation system.

Data coverage from Dixon Entrance to Icy Bay is reconnaissance only, with line spacings of about 25 to 50 km (Fig. 2). Line spacing west of Icy Bay is around 10 km. Single channel seismic data (von Huene and others, 1975) provide structural information in areas of complex structure west of Icy Bay, and between some of the widely spaced multichannel lines to the east.

The interpretation of structure and geologic history from the multichannel seismic data is based on mapping of seismic horizons throughout

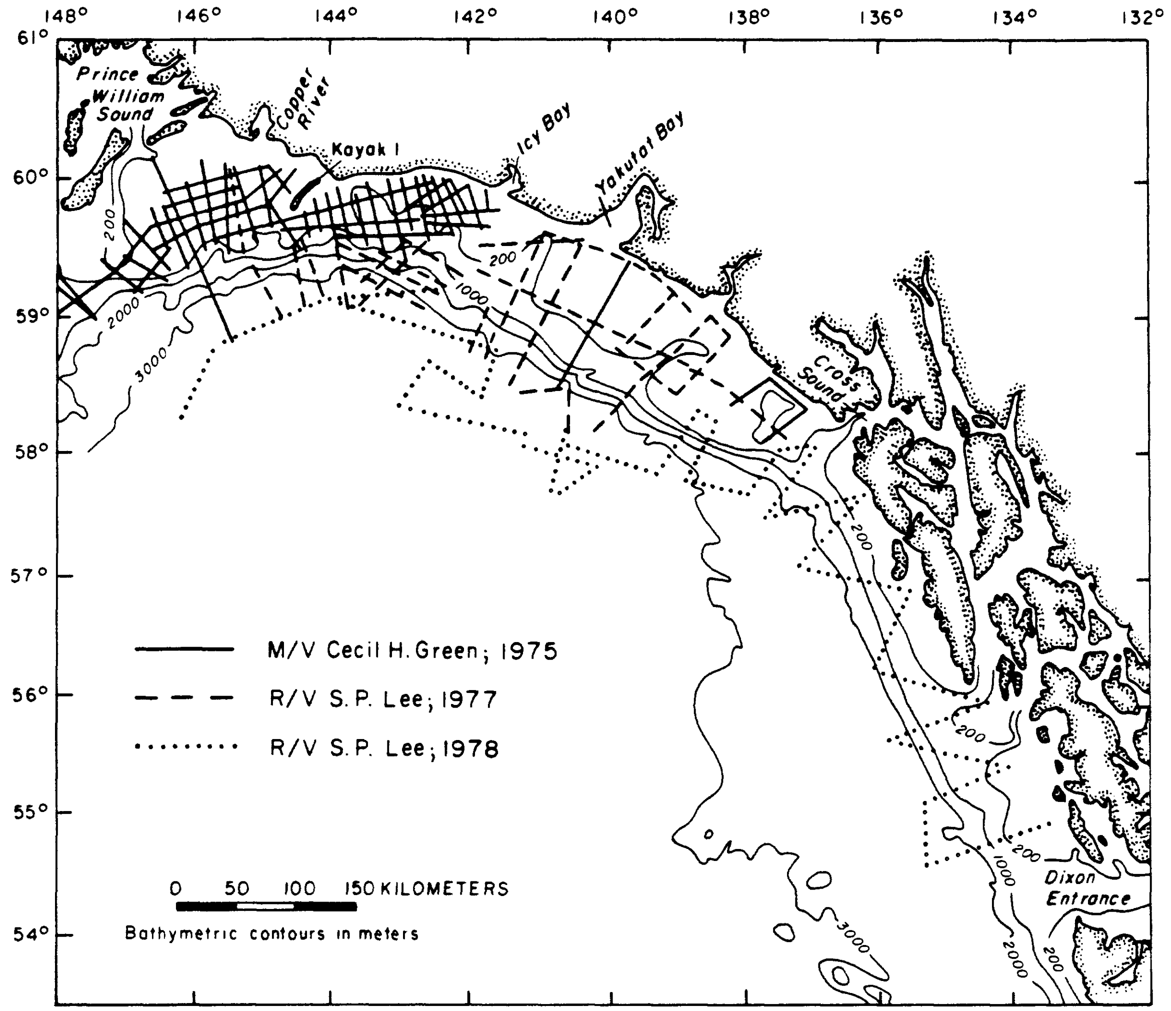


Figure 2. Tracklines of multichannel seismic data in the northern Gulf of Alaska.

the data grid. A curve giving time-to-depth conversion for sedimentary strata on the seismic data is derived from refraction data and stacking velocities obtained during processing of the multichannel seismic reflection data. The time-to-depth conversion is approximately given by the curve $z = 0.7t + 0.3t^2 - 0.02t^3$, where z is the depth in kilometers and t is the two-way travel time in seconds from the water-bottom. Interpretation methods, derivation, and error limits of the depth conversion function are discussed in Bruns (1979, 1982, 1983b) and Bruns and Schwab (1983).

Bathymetric, gravity, and magnetic data were acquired during these and other cruises; these data were processed by the U.S. Geological Survey in Menlo Park, California and are presented in Schwab and Bruns (1979), Schwab and others, 1980), Burkhard and others (1980a, b), Atwood and others (1981), and Bruns and others (1981a, b). Three dredging cruises in 1977, 1978, and 1979 obtained rock samples from the continental slope; geologic data and interpretations from the dredged rocks are presented by Plafker and others (1978c, 1979c, and 1980), Rau (1979, 1981), and Keller and others (1983, 1984)

TRANSFORM MARGIN--THE SOUTHEAST ALASKA SEGMENT

If the Yakutat block has moved with the Pacific plate during Pliocene and Quaternary time, then the structure and tectonics of southeast Alaska are important for two major reasons. First, where are faults along which this motion could be accomodated? If only limited motion has occurred on the currently active Queen Charlotte fault, as suggested by recognized motion on the connecting Fairweather Fault, then there should be other areas, either landward or seaward of the Queen Charlotte fault, along which motion can be accomodated. Second, is there any connection between the active Queen Charlotte fault and the Transition fault that could indicate Pliocene and Quaternary motion along the Transition fault? If such a connection exists, then there should be deformation in the vicinity of Cross Sound and Yakobi Valley related to the almost 45° change in fault trends. Alternatively, a fault at the base of the continental slope could bypass this area and join with the Transition fault west of Yakobi Valley.

Geology

The islands of southeast Alaska are underlain by a diverse assembledge of Mesozoic and Paleozoic rocks that comprise parts or all of at least nine fault bounded tectonostratigraphic terranes (Berg and others, 1978). Cenozoic tectonic activity in the region includes Cenozoic intrusion, thermal metamorphism, local deposition of volcanic and sedimentary rocks, and faulting which has redistributed the Mesozoic and Paleozoic terranes along major fault zones such as the Chatham Strait fault (Berg, 1979).

The offshore geology of the southeast Alaska continental margin is largely unknown, and can be inferred only from limited geophysical data (Bruns and Plafker, 1982). Seismic reflection data shows acoustic basement near the seafloor over much of the continental shelf; rocks forming the acoustic basement are likely to be the continuation of the Paleozoic and Mesozoic rocks of the nearby islands. On seismic reflection records, a sedimentary section up to 2 km thick, of probable late Cenozoic age, locally overlies acoustic basement in the middle to outer shelf regions (von Huene and others, 1979; T.R. Bruns, unpublished data).

The southeast Alaska continental margin is a tectonically truncated margin. The Mesozoic and Paleozoic rocks that are present on the islands and beneath the continental shelf can extend no further seaward than the base of the continental slope, since oceanic crust of about Miocene age underlies the adjacent continental rise (Naugler and Wageman, 1973). Thus, the Queen Charlotte fault marks the edge of crystalline continental crust and forms a fundamental tectonic boundary along southeast Alaska.

The Queen Charlotte fault

The Queen Charlotte fault off southeast Alaska has been mapped by von Huene and others (1979) and Carlson and others (1979, 1981, in press) on the basis of offset reflectors and seafloor scarps in areas where detailed bathymetry and single-channel seismic-reflection data are available. The seismic data show evidence for two fault traces about 10 km apart between Cross Sound on the north to Chatham Strait on the south (Fig. 3). Between Chatham Strait and Cross Sound, the eastern fault trace is located on the shelf; this trace cuts across the shelf beneath the Yakobi Valley and trends into the onshore Fairweather Fault. The western trace is located along or near the shelf break between Chatham Strait and Cross Sound, and trends across the shelf into a fault, the Icy Point-Lituya Bay fault, that lies just offshore of the coastline between Icy Point and Lituya Bay (Plafker, 1967; von Huene and others, 1979; Carlson and others, 1979, 1981, in press; Bruns, 1983b).

Of the two traces, the western trace may be the more active. The western fault trace is the best defined and shows the most evidence for Holocene displacement, as indicated by seafloor scarps and disruption of well defined seismic reflectors. The eastern trace is more discontinuous and sinuous. The seismic reflection data thus suggest that the western trace is relatively more active than the eastern trace, although the eastern trace is the one that trends into the presently active onshore Fairweather Fault (Carlson and others, 1979, 1981, in press).

Near Chatham Strait, the two fault traces merge, and the remaining trace, as mapped on single channel records (von Huene and others, 1979) and on widely spaced multichannel seismic lines, trends along the upper slope from Chatham Strait to Dixon Entrance (Fig. 3; Bruns, 1981; Bruns and others, 1981; Carlson and others, 1981; Bruns and Plafker, 1982).

This complex fault system is now accomodating the relative motion between the Pacific and North America plates, based on observed seismicity along the fault (Page, 1969, 1975), on 5 to 6 cm/yr of Holocene offset on the connecting Fairweather fault (Plafker and others, 1978b), and on the structure observed along the fault (Von Huene and others, 1979; Carlson and others, 1979, 1981, in press; Bruns, 1981).

The amount and rate of displacement along these fault traces and the age of rocks cut by the faults are unknown. However, there are several indications of late Pleistocene and Holocene motion. Yakobi Valley is a glacially carved seavalley seaward of Cross Sound and the Queen Charlotte fault. The glacier carving the valley flowed through Cross Sound and across the Queen Charlotte fault traces (Fig. 3; Carlson and others, 1982). Detailed bathymetry of Yakobi Valley shows displacement of about 300 to 400 m of the

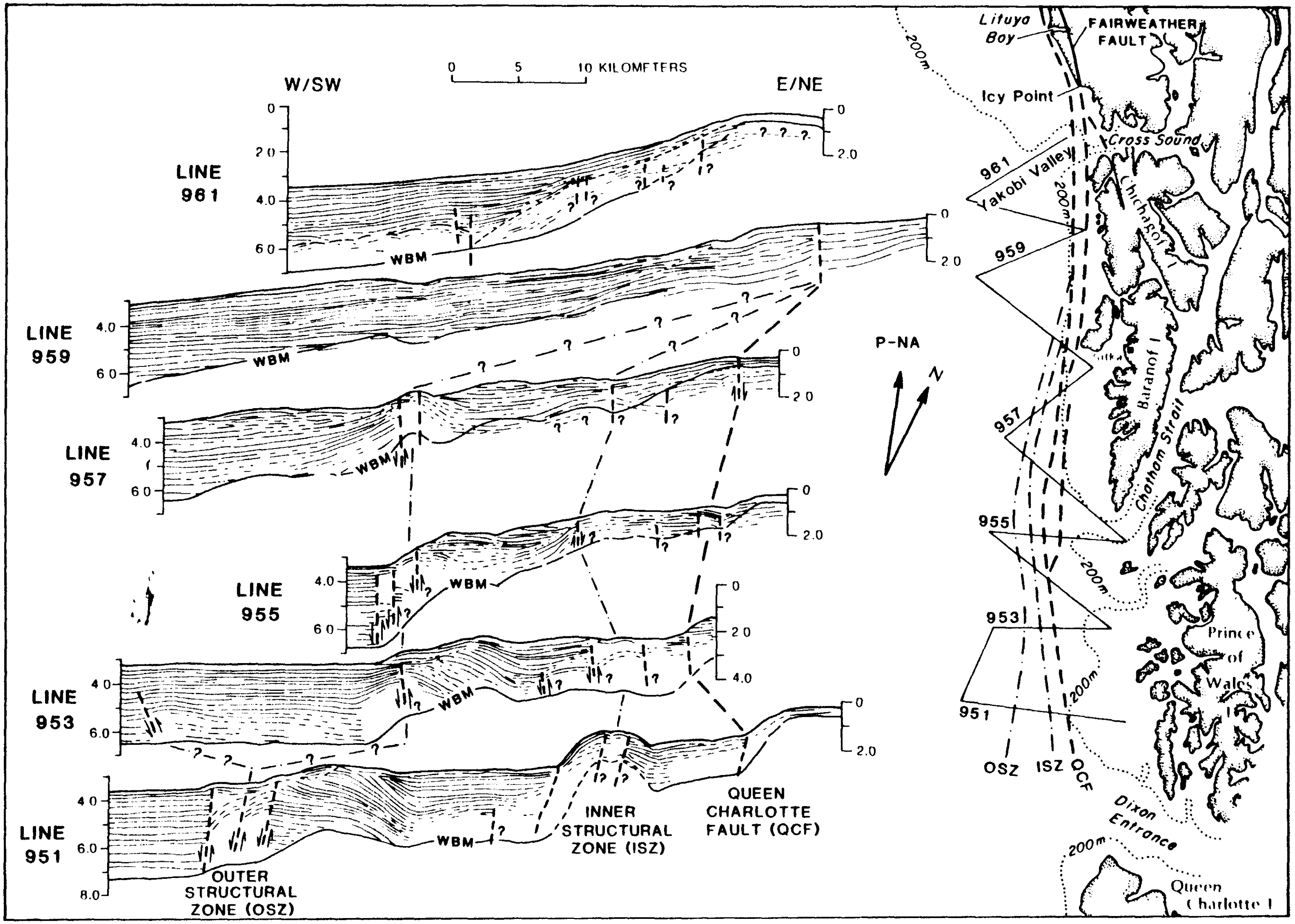


Figure 3. Line drawings of seismic profiles across the southeast Alaska continental margin, and generalized location of structural trends. Trends shown are the Queen Charlotte fault traces (QCF, Carlson and others, 1981, and in press), an outer structural zone (OSZ), and an inner structural zone (ISZ). Vertical scale on seismic lines is two-way time in seconds. WBM-water bottom multiple. Pacific-North America (P-NA) relative convergence direction (arrow) from Minster and Jordan (1978).

southeast wall of the valley along the fault traces. This offset probably reflects Holocene displacement along the fault that has occurred since retreat of the glacier that carved the valley (Von Huene and others, 1979; Carlson and others, 1979, 1981, 1982, in press; Atwood and others, 1981). Atwood and others (1981) and Carlson and others (1982) note that the boxlike shape of Yakobi Valley may result from a combination of glacial erosion and displacement along the Queen Charlotte fault, with the northwest wall of the glacial valley systematically offset to the northwest.

Atwood and others (1981) also note a valley-like depression on the continental shelf between Cross Sound and Lituya Bay that is similar in form to Yakobi Valley. They suggest that this depression could be a northwestwardly offset, ancestral Yakobi Valley.

If the morphology of both this depression and Yakobi Valley is fault controlled, offset could be about 20 km for Yakobi Valley, and about 70 km for the depression, largely during late Quaternary time (Carlson and others, in press). At present, known post-late Miocene displacement on the connecting, onshore Fairweather Fault is about 5.5 km (Plafker and others, 1978b). This observation raises the possibility that most of Pliocene and Quaternary motion along the Queen Charlotte fault has been taken up on the western mapped trace and its probable northern extension along the Icy Point-Lituya Bay fault. The Icy Point-Lituya Bay fault could be a major transform fault.

Faulting landward of the Queen Charlotte fault

Landward of the Queen Charlotte fault, late Cenozoic plate motion could have been accomodated along several faults. Southeast Alaska contains numerous faults with a complicated, poorly known movement history. At least two of these faults, the Chatham Strait and Peril Strait faults (Fig. 3), have histories of post-Cretaceous movement. Right-lateral offset on the Chatham Strait fault is about 150 km during post middle-Cretaceous and pre-Holocene time, and about 100 km of this offset may have occurred during post-Oligocene time, based on offset of an Oligocene volcanic sequence (Hudson and others, 1982). The Peril Strait fault has about 11 km of right-lateral separation since the late Cretaceous (Plafker and others, 1976). These faults or fault systems could therefore accomodate part, but only a small part, of Cenozoic Pacific-North America plate motion.

Faulting seaward of the Queen Charlotte fault

Seaward of the Queen Charlotte fault, the age and structure of sedimentary strata show that no major transform faulting has occurred during at least Pliocene and younger time. Seismic reflection data (Fig. 3) show a sedimentary section at least 3 to 5 km thick beneath the continental slope and at the base of the slope. Gravity modeling and refraction data indicate this section could be as much as 10 km thick (von Huene and others, 1979). This sedimentary section is of late Cenozoic age, largely Pliocene and younger, based on the Miocene age of adjacent oceanic magnetic anomalies (Naugler and Wageman, 1973) and on a correlation of seismic reflectors on multichannel seismic data to Deep Sea Drilling Project (DSDP) hole 178 (Von Huene and others, 1979; Bruns, 1983b; and T.R. Bruns, unpublished data).

Deformation of these strata is probably due to wrench tectonics along the

Queen Charlotte fault (Bruns, 1981; Bruns and others, 1981). From Dixon Entrance to Chatham Strait, these strata are deformed into broad folds, lying roughly in two zones, with eastward dipping thrust faults on the seaward side (Fig. 3; also see Snavely and others, 1981). The western folds are young features, affecting even the youngest sedimentary strata, and are likely Quaternary features. The eastern folds are in part covered by up to 0.5 km of undeformed strata, are therefore older than the western folds, and are perhaps Pliocene or early Pleistocene in age. Limited bathymetric data (Chase and others, 1970; Seeman and Tiffin, 1980) suggests that, within each structural zone, individual structures form an en-echelon pattern; such a pattern is typical of deformation in a strike-slip tectonic setting (Harding and Lowell, 1979), and primarily reflects wrench tectonics resulting from motion along the Queen Charlotte fault (Bruns, 1981; Bruns and others, 1981; Snavely and others, 1981).

The degree of deformation in each of the structural zones decreases to the north. Between Chatham Strait and Sitka, only minor deformation of the slope section is seen on the seismic records (Fig. 3; line 957), and between Sitka and Cross Sound, strata seaward of the Queen Charlotte fault trace are undeformed (Fig. 3, line 959). Thus, north of Sitka, there is no evidence seaward of the shelf break for any transform fault. Faulting could be present in the very lowermost part of the section where the structure is obscured by the water-bottom multiple. If faulting is present, it occurred prior to Pliocene time, based on the probable age of the undeformed strata.

Tectonic implications

The southeast Alaska margin shows no deformation in the vicinity of Yakobi Valley that might be associated with a Pliocene or Quaternary connection between the Transition fault and the Queen Charlotte fault. There is also no evidence for a throughgoing Pliocene or Quaternary strike-slip fault along the slope or at the base of the slope that could connect with the Transition fault west of Yakobi Valley, thus providing a seaward bypass to the 45° bend at Yakobi Valley. Pliocene and Quaternary offset between the Pacific plate and southeast Alaska must be taken up largely on the mapped Queen Charlotte fault traces, or on faults landward.

Much of this motion must have occurred on the Queen Charlotte fault. Known offset on the Chatham Strait and Peril Strait faults indicates that these faults can accomodate only part of Pliocene and Quaternary offset, about 100 km and 11 km maximum respectively, during post-Oligocene time. This offset is still much less than the 300 km required by plate tectonic models for Pliocene and Quaternary time. The remainder of this motion must be accomodated either on unknown faults or on the Queen Charlotte fault system.

However, the Queen Charlotte fault also marks the edge of the crystalline continental crust. Gravity models and refraction data (Von Huene and others, 1979) across the margin indicate the slope seaward of the Queen Charlotte fault is underlain by a sedimentary sequence up to 10 km thick. The nearest correlative age rocks to those truncated at the margin are in southern Alaska, and possibly in the Yakutat block. Therefore, the truncation of the continental crust and of the Chatham Strait fault indicates that substantial, rather than limited, offset must have occurred along the Queen Charlotte fault.

The fault lying near the shoreline from Icy Point to Lituya Bay might have taken up at least part, and perhaps much of this motion. Definitive data are lacking to prove this suggestion. However, at Icy Point, the Queen Charlotte fault system connects with both the onshore Fairweather fault and the Icy Point-Lituya Bay fault. Either greater late Cenozoic motion has occurred along the Fairweather fault than is so far recognized, or motion must be accomodated along the Icy Point-Lituya Bay fault. This fault could be both a major late Cenozoic, but currently inactive, transform fault, and a major tectonic boundary within the Yakutat block.

TRANSITION MARGIN-THE YAKUTAT BLOCK

This section describes structural interpretations of geologic and geophysical data from the Yakutat block that establish the offshore boundaries of the block and define constraints on tectonic processes that have affected the block during the Cenozoic. If late Cenozoic plate convergence has been accomodated offshore within or along the Yakutat block, then there should be observable effects in the structure and geologic history of the block.

The tectonic history of the continental margin presented here indicates oblique subduction or transform faulting has not occurred on the Transition fault during Pliocene and Quaternary time. Instead, the Yakutat block has moved with the Pacific plate for at least that time and has been colliding with and subducting beneath southern Alaska. The structure of the block also shows that deformation related to the collision of the block with southern Alaska primarily happens along the northwestern margin of the block where the maximum rate of convergence between the Yakutat block and southern Alaska occurs.

The structure of the Yakutat block (Fig. 4) divides it into two segments, the Yakutat and Yakataga segments, that are characterized by markedly differing structural styles (Bruns, 1983b; Bruns and Schwab, 1983). The Yakutat segment includes that part of the margin seaward of the Fairweather-Queen Charlotte fault from about Cross Sound to Icy Bay. This segment has undergone little deformation during the late Cenozoic, and is characterized primarily by regional subsidence. The Yakataga segment is the margin segment between Icy Bay and Kayak Island, and is characterized by broad folds and associated thrust faults that trend northeast across the shelf and slope. These folds were termed the Pamplona zone by Plafker and others (1978b).

In this section I first summarize the geology and onshore structure, then discuss the structure of the Yakutat and Yakataga segments as shown by multichannel seismic reflection data. Finally, I present magnetic and gravity data and models to further delineate the extent of the block and the character of the Transition fault which forms the southern boundary of the block.

Onshore geology and structure

Rocks of Paleozoic through Cenozoic age underlie southern Alaska and form fault-bounded tectonostratigraphic terranes (Fig. 5; Jones and others, 1977, 1981; Coney and others, 1980). North of the Yakutat block, the upper Paleozoic and lower Mesozoic Wrangellia terrane is separated from upper Cretaceous flysch and melange of the Chugach terrane along the Border Ranges fault. The Chugach terrane is a Cretaceous accretionary wedge that is present

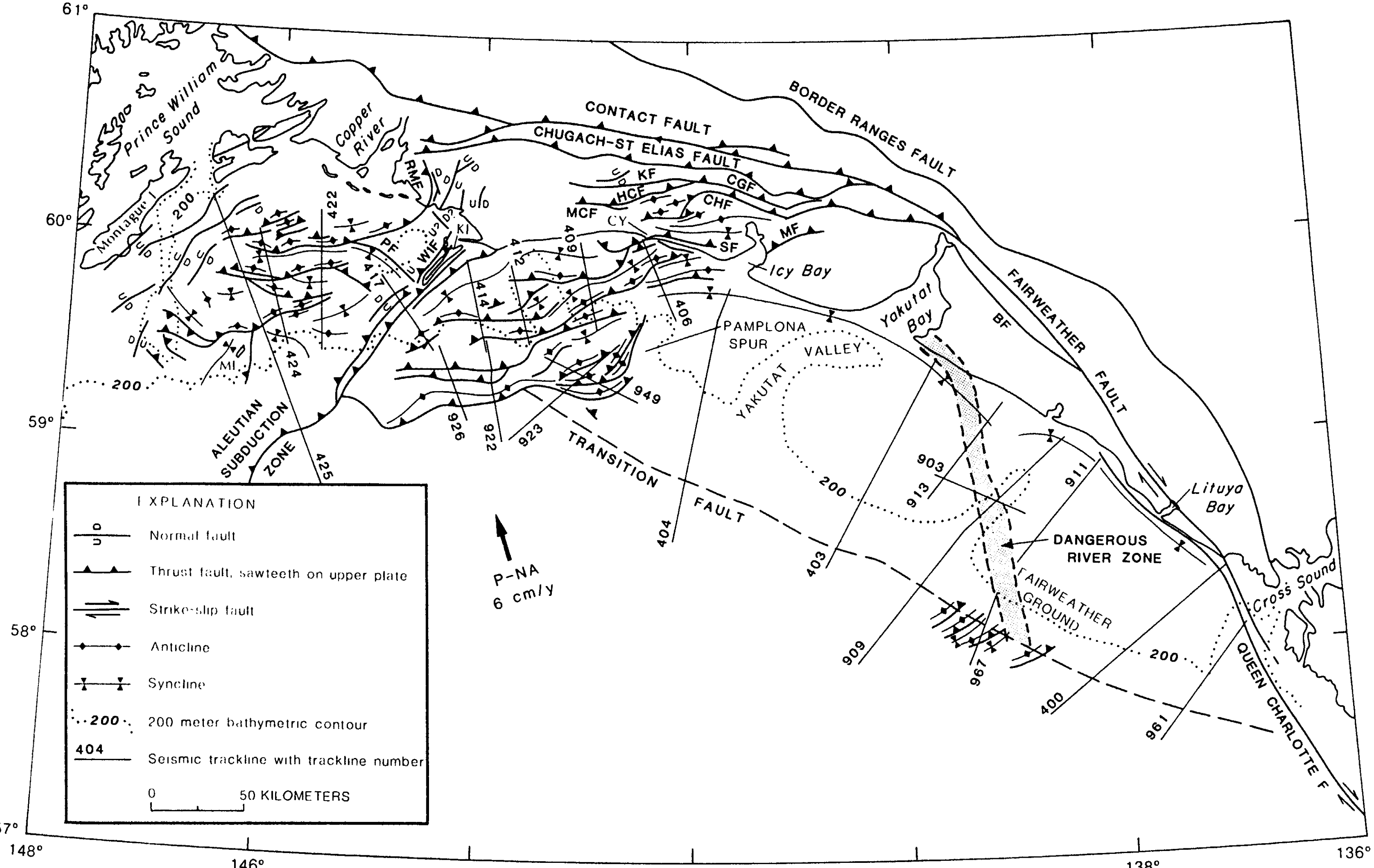
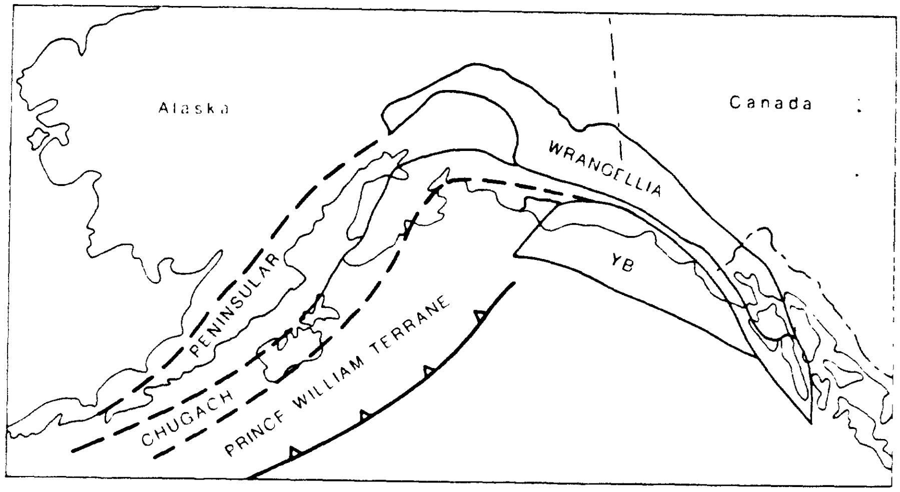


Figure 4. Structural features of the northern Gulf of Alaska continental margin; for details and structure contours, see Figures 8, 9, 15, 17, and 29. Seismic sections corresponding to tracklines are shown in Figures 11-14, 18-21, and 30-32. Large arrow shows direction of Pacific plate-North America convergence. CY-Cape Yakataga; KI-Kayak Island; MI-Middleton Island; BF-Boundary Fault; CGF-Coal Glacier Fault; CHF-Chaix Hills Fault; HCF-Hope Creek Fault; IPF-Icy Point-Lituya Bay Fault; KF-Kosakuts Fault; MCF-Miller Creek Fault; MF-Malaspina Fault; PF-Pinnacle Fault; RMF-Ragged Mountain Fault; SF-Sullivan Fault; WIF-Wingham Island Fault.



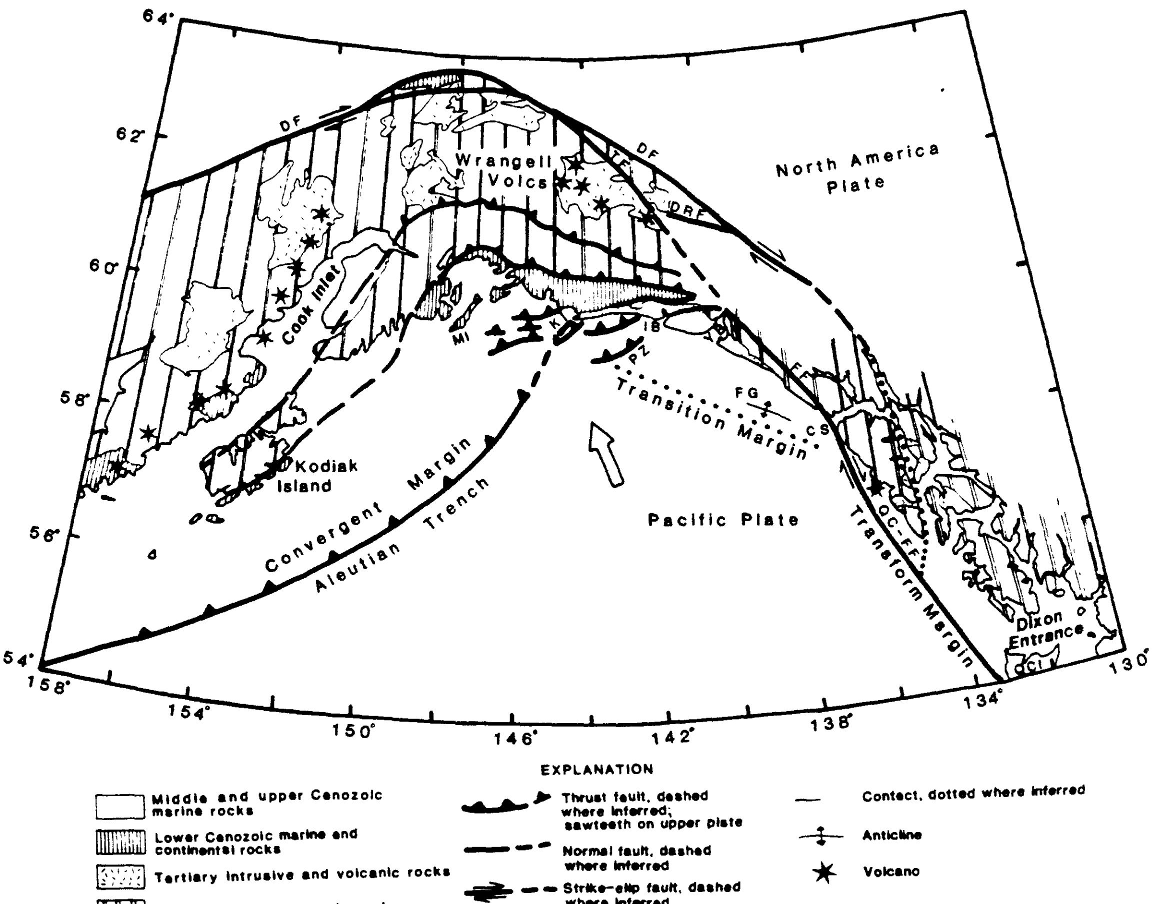


Figure 5. Top: Terrane boundaries adjacent to the northern Gulf of Alaska; after Coney and others (1980) and Jones and others (1981). YB-Yakutat block. Bottom: Generalized onshore geology in the northern Gulf of Alaska showing distribution of Paleozoic, Mesozoic and Cenozoic rocks. Geology after Beikman (1980). Pacific-North America relative convergence vector (large arrow) from Minster and Jordan (1978). CS-Cross Sound; DF-Denali fault; DRF-Duke River fault; FF-Fairweather fault; FG-Fairweather Ground; IB-Icy Bay; KI-Kayak Island; PZ-Pamplona zone; QC-FF-Queen Charlotte-Fairweather fault system; TF-Totschunda fault; YB-Yakutat Bay; Wrangell Volcs-Wrangell volcanoes and volcanic field.

in an arcuate belt throughout the Gulf of Alaska (Plafker and others, 1977; Plafker and Campbell, 1979; Nilsen and Zuffa, 1982). In the area from Icy Bay to Prince William Sound, the Chugach terrane is juxtaposed against Paleocene and Eocene(?) Orca Group rocks of the Prince William terrane along the Contact fault system (Winkler and Plafker, 1975, 1981a; Plafker and others, 1977). Finally, the Orca Group rocks of the Prince William terrane, and the Chugach terrane west of about Icy Bay are in turn juxtaposed against Mesozoic and Cenozoic rocks of the Yakutat block along the Chugach-Saint Elias and Fairweather fault systems. Thus, each of the major fault systems is a fundamental tectonic boundary separating rocks of different ages and tectonic environments.

Geology

The geology and structure of the onshore rocks bordering the northern Gulf of Alaska is described by Miller (1951, 1957, 1967a, b, c, d, e, 1971, 1975), Miller and others (1959), Plafker and Miller (1957), Stoneley (1967), Plafker (1967, 1971, 1974), Plafker and Addicott (1976), Rau and others (1977), Addicott and others (1978), and Winkler and Plafker (1981a). The following summary is taken from these reports.

Much of the onshore area is covered by glaciers and Quaternary alluvial, lacustrine, and beach deposits, particularly between Lituya Bay and Yakutat Bay, and in the areas of the Malaspina and Bering glaciers. The subsurface geology in these covered areas is known only from exploratory wells, and is reported in Rau and others (1977).

Pre-Cenozoic rocks of the Yakutat block outcrop adjacent to the Fairweather and Chugach-Saint Elias faults from Cross Sound to midway between Yakutat Bay and Icy Bay (Figs. 4 and 5). These rocks consist of Mesozoic flysch and melange of the Yakutat Group. The Yakutat Group rocks are also present beneath much of the onshore area between Lituya Bay and Yakutat Bay, as they were sampled in several coreholes and wells (Rau and others, 1977). The Yakutat Group is highly deformed and typically forms fault-bounded slices. The deformed and faulted sequence is cut by early Eocene granitic plutons, and in part overlain with marked unconformity by Eocene shallow marine and continental strata (Plafker and others, 1977; Nilsen and others, in press). Zuffa and others (1980) and Winkler and Plafker (1981b) found that sandstones from the Yakutat Group have a very different source area from coeval sandstones of the Chugach terrane. Winkler and Plafker (1981b) further suggest that the Yakutat Group may have undergone substantial tectonic transport with respect to the adjacent Chugach terrane rocks.

Cenozoic sedimentary rocks outcrop in an up to 10 km wide band along the shoreline near Lituya Bay and have been sampled in exploratory wells near Yakutat Bay and beneath the adjacent coastal plain (Figs. 4 and 5). These strata also underlie an up to 70 km wide area of the coastal mountains and foothills from about Yakutat Bay to the Ragged Mountain fault. West of the Ragged Mountain fault, lower Cenozoic rocks of the Orca Group (discussed later) underlie Prince William Sound and the Copper River area. East of the Ragged Mountain Fault, the Cenozoic rocks consist of Eocene and younger continental and shelf facies strata of the Gulf of Alaska Tertiary Province (Miller and others, 1959; Stoneley, 1967; Plafker, 1967, 1971). These rocks are broadly divisible into three subdivisions corresponding to changes in the depositional environment and tectonics of the basin. These subdivisions are:

(1) A middle or late Eocene through early Oligocene clastic sequence includes shallow to deep marine rocks of the Stillwater Formation, which grade upward into continental and shallow marine rocks of the Kulthieth Formation. The Kulthieth Formation is overlain by shallow marine rocks of the Tokun Formation. The Kulthieth and Tokun formations were deposited as thick, interfingering lagoon, barrier beach, and delta complexes in relatively warm seas. The maximum thickness of the Stillwater, Kulthieth, and Tokun formations is about 1500 m, 2700 m, and 1000 m respectively.

(2) Middle Oligocene through Miocene age rocks include the Topsy Formation and Cenotaph Volcanics near Lituya Bay and the Poul Creek Formation west of Yakutat Bay. The Cenotaph Volcanics and the Topsy Formation are an up to 750 m thick sequence of interfingering continental and marine volcanic and sedimentary rocks. The Poul Creek Formation includes up to 1860 m of shallow to deep water marine strata that are composed of predominately shaley sediment, in part organic rich, characteristically glauconitic, and intercalated with basaltic tuff, breccia, and pillow lavas.

(3) A late Miocene and younger sequence up to 5 km thick comprises the marine Yakataga Formation. The formation consists of interbedded siltstone, mudstone, and sandstone, which predominate in the lower part of the section, and till-like diamictite, which becomes the dominant rock type in the upper part of the formation. Conglomerate is present throughout the formation. Clasts, probably dropstones, are present in all lithologies. These clasts have been dominantly derived from the bordering Chugach and Saint Elias mountains, and include a few percent with preserved glacial striations.

The dropstones and diamictite are interpreted to represent glaciomarine sedimentation and proximity to tidewater glaciers and ice rafting (Plafker and Addicott, 1976). The deposition of the formation coincides with a marked drop in species diversity of molluscan fauna, and the replacement of temperate water fauna by cold water, high latitude species. The Yakataga Formation deposition thus corresponds to a marked cooling of the marine environment, and the onset of glaciation in the adjacent mountains.

The Yakataga Formation provides important constraints on the tectonics of the Yakutat block. First, the Yakataga Formation overlies the older rocks seaward of the Yakutat Group from Lituya Bay to Icy Bay, and seaward of the Hope Creek-Coal Glacier fault (Fig. 4) west of Icy Bay. The formation thus links onshore and offshore strata at the beginning of Yakataga time. Second, deposition of the formation records initiation of a major late Cenozoic orogeny that has uplifted the high Chugach and Saint Elias ranges. Third, the Yakataga Formation requires that the Yakutat block be adjacent to these rising mountains. If the Yakutat block is an allochthonous terrane, than the initial Yakataga Formation deposition records the arrival and collision time of the block with southern Alaska.

The age of the lowermost part of the Yakataga formation, at its contact with the Poul Creek Formation, is therefore extremely important in dating the timing of major tectonic events of southern Alaska. Plafker and Addicott (1976) find that the oldest part of the section, on Kayak Island, is of early Miocene age, and on the mainland, the base of the section is of about middle

Miocene age. Their age assignments are primarily based on identification and correlation of abundant molluscan fauna and sparse benthic foraminifera from the Yakataga Formation with fauna of Washington and Oregon.

Recent work on foraminiferal biostratigraphy of the upper Poul Creek and lower Yakataga Formation on the mainland indicates, however, that the Poul Creek/Yakataga Formation contact may be late Miocene (Lagoe, 1983; Armentrout, 1983; Armentrout and others, 1978) instead of middle Miocene as suggested by the molluscan biostratigraphy. The Poul Creek Formation at Yakataga Reef (Cape Yakataga, Fig. 4) consists of Oligocene and early Miocene strata, conformably overlain by late Miocene strata. The Poul Creek/Yakataga Formation contact, also conformable, lies within the late Miocene foraminiferal zone, and this zone extends upsection only about 100 m before reaching the Miocene/Pliocene boundary. Thus, at Cape Yakataga, only the lowermost 100 m of the Yakataga Formation is of late Miocene age, and the formation is dominantly of Pliocene and Quaternary age. Studies of other mainland sections indicate similar results for the Poul Creek/Yakataga Formation contact (Armentrout and others, 1978; Areay, 1978; Lagoe, 1978, 1983), although greater thicknesses of the Yakataga formation may be of late Miocene age, as for example in the Kulthieth Mountains (Plafker and Addicott, 1976).

A major control on the age of the lowermost Yakataga Formation is the first occurrance of Neogloboquadrina Pachyderma (sinistrally coiled) just below the Poul Creek/Yakataga Formation contact. This species indicates an age no older than late Miocene, since this species first occurs at about 8 m.y. (G. Keller, personnel communication, 1983). Further, the morphology of N. pachyderma suggests a latest Miocene or early Pliocene age, since the sampled species is a well developed form indicating an age of about 5.5 m.y. (Lagoe, 1983; G. Keller, personnel communication, 1983). In addition, Armentrout (1983) and Armentrout and others (1978) have obtained minimum K-Ar age dates of 5.6 ± 0.5 m.y. and 6.4 ± 0.4 m.y. on glauconites from the upper Poul Creek Formation at Yakataga Reef, in agreement with the plantonic foraminiferal age. Lagoe (1983) and Armentrout (1983) conclude that the base of the Yakataga Formation is about 6 m.y. old. Thus, the beginning of uplift of the Chugach-Saint Elias mountains, and the collision of the Yakutat block with southern Alaska began in late Miocene time, about 6 m.y. ago.

Reanalysis of the Kayak Island Yakataga Formation section, dated by Plafker and Addicott (1976) as early Miocene, has not been done. Plafker and Addicott (1976) note that Rau (in Plafker, 1974) found foraminifera typical of early or middle Miocene stages (Saucesian and Relizian) of Washington. These stages are age correlative to molluscan stages (Pillarian and Newportan) of Washington which are apparently of late Miocene age in the Gulf of Alaska (compare studies of Ariey, 1978; Lagoe, 1978, 1983; Armentrout, 1983, and Armentrout and others, 1978). Thus, if the molluscan and benthic foraminiferal biostratigraphy is indeed younger in the Gulf of Alaska than at more southerly latitudes, the lower Miocene age of Plafker and Addicott (1976) for Kayak Island needs to be reevaluated.

Lagoe (1983) notes that the disagreement of age assignments for foraminifera and mollusks arises from the often endemic nature of the faunas and the attempt to correlate them with biostratigraphic standards established at the more southerly and different biogeographic provinces of Washington and

Oregon. The molluscan and benthic foraminiferal stages are apparently time transgressive, and are younger in the northern Gulf of Alaska than in Oregon and Washington. A detailed study of molluscan and benthic foraminiferal ages compared to more widely ranging forms such as planktonic foraminifera is badly needed to establish a northern Gulf of Alaska biostratigraphy that is independent of Washington and Oregon biostratigraphy, and to better delineate the age of the Yakataga Formation.

Structure

The overall trend of structures in the Cenozoic rocks is subparallel to the trend of the bordering Fairweather and Chugach-Saint fault systems, and the related bounding Ragged Mountain and Wingham Island faults (Fig. 4). The structural trend is easterly east of Kayak Island and changes to a northeasterly trend in the area adjacent to Kayak Island and the Ragged Mountain Fault. The structure is characterized by moderately to intensely compressed folds and displacement along northward dipping thrust faults. The intensity of folding and the magnitude of displacement along faults increases from south to north. The observed structures consistently show uplift and overthrusting of older, landward formations over younger, seaward formations. The onshore structure is described in Miller and others (1959), Miller (1957, 1961, 1971), Plafker and Miller (1957), Stoneley (1967), and Plafker (1967, 1971).

The Tertiary section in the area of Lituya Bay is deformed into a broad syncline between the Mesozoic Yakutat Group rocks to near the shoreline, and a strongly assymetrical anticline at or near the shoreline (Miller, 1961; Plafker, 1967, 1971; Stoneley, 1967).

From Yakutat Bay to Kayak Island, the structure of the Cenozoic strata includes east-west trending synclines and thrust-faulted anticlines (Fig. 4). The principle faults in this area, the Kosakuts, Hope Creek, and Miller Creek faults, separate belts of differing structural styles, and expose increasingly older and more deformed rocks at the surface towards the Chugach-Saint Elias fault. In the coastal belt, the structure is characterized by broad synclines and narrow, tightly compressed assymetrical, thrust-faulted anticlines. To the north, folds are of smaller, but more nearly equal amplitude, and become more intensely folded and faulted (Miller, 1957; Miller and others, 1959; Plafker, 1967; Stoneley, 1967).

In the area of Kayak Island and the Ragged Mountain fault (Fig. 4), structural trends are more northerly to northeasterly. Folds are typically of small amplitude, tightly compressed, and assymmetric or overturned (Winkler and Plafker, 1981).

The amount of displacement on major onshore faults, and the amount of shortening due to structural deformation indicate a significantly greater degree of deformation onshore than offshore. Displacement on the Kosakuts fault (Fig. 4) is estimated only as "several thousand feet", and on the Hope Creek fault as about 6 km (Miller, 1951). Displacement on the Miller Creek fault is estimated at 2 to 3 km north of Cape Yakataga (Miller, 1967, 1971), and as not less than about 5 km on its continuation into the Chaix Hills fault (Plafker and Miller, 1957). These estimates are in marked contrast to offshore maximum vertical offsets of about 1.5 km, and more commonly 0.5 to 1 km (next section). Stoneley (1967) estimates onshore structural shortening as at least 16 km in 40 to 50 km, or about 30 to 40 percent; Lathram and others (1974) estimate about 25 percent shortening.

The onshore strata have been strongly uplifted and deformed during the late Cenozoic (Miller, 1957; Plafker and Miller, 1957; Plafker, 1967, 1971; Stoneley, 1967). Deformation continues to the present, as shown by seismicity (Perez and Jacob, 1980; Lahr and Plafker, 1980), by uplifted beach terraces at Lituya Bay and between Icy Bay and Kayak Island (Hudson and others, 1976; Plafker and Rubin, 1978; Plafker and others, 1982b), and by measured uplift along the Fairweather fault during the 1958 Lituya Bay earthquake (Toucher, 1960; Kanamori, 1977), around Yakutat Bay during a series of earthquakes in 1899 (Tarr and Martin, 1912), and on Kayak and Middleton Islands during the 1964 Alaska earthquake (Plafker, 1969; Plafker and Rubin, 1978). The onshore Yakataga formation exhibits numerous unconformities within the Pliocene and younger section, also indicating active uplift of the basin during deposition.

Offshore geology

Rocks of Mesozoic through Quaternary age that outcrop on the continental slope of the Yakutat segment have recently been sampled by dredging (Table 1 and Fig. 6; adapted from Plafker and others, 1980). These rocks provide data on the geology, stratigraphy, and depositional environment of the offshore part of the Yakutat block, and give age control for mapped seismic horizons of the shelf and slope.

These rocks can be generalized as follows (Plafker and others, 1980):

(1) Unit A, an undated sequence consisting of mildly metamorphosed (zeolite facies) metasandstone and argillite is found on the continental slope off Fairweather Ground, and probably underlies much of Fairweather Ground and the continental shelf to the north. This sequence probably contains intrusive rocks, since Fairweather Ground is associated with a high magnetic anomaly (Naugler and Wageman, 1973; Taylor and O'Neill, 1977; Schwab and others, 1980). The dredged rocks are lithologically similar to the onshore Yakutat Group, a Mesozoic flysch and melange sequence (Plafker, 1967, 1971; Plafker and others, 1977; Winkler and Plafker, 1981).

(2) Units B-F comprise a Paleogene sequence of volcanic and sedimentary rocks found along parts of the continental slope from Fairweather Ground to Pamplona Ridge. This sequence consists of Unit B, an inferred late Paleocene(?) or early Eocene(?) unit of sandstone, conglomerate, and shale; Unit C, Paleocene(?) and early Eocene tholeiitic basalt flows and pyroclastic rocks; Unit D, early to middle Eocene sandstone, conglomerate, siltstone, and shale; Unit E, late Eocene and early Oligocene(?) shale, tuffaceous shale, siltstone, and sandstone; and Unit F, upper Oligocene silty shale.

The Paleocene(?) rocks (Unit B) were sampled only in the vicinity of Yakutat valley (Fig. 6); the thickness and extent of these rocks is unknown.

Paleocene(?) and early Eocene tholeiitic basalt (Unit C) was sampled between Fairweather Ground and Yakutat Valley (Fig. 6). Where dredged, the basalt sequence has a thickness of at least 1300 m; the total thickness of the sequence is not known. The basalts yielded ages of 55±7 and 50±5 m.y. B.P. at

Table 1. Stratigraphic summary of rocks dredged from the continental slope of the Yakutat segment, Northern Gulf of Alaska (from Plafker and others, 1980)

Unit	Age	Lithology and Comments	Estimated Maximum Thickness (m) Where Dredged
A	Late Cretaceous	Hard graywacke, argillite, and possible intrusive rocks.	unknown
B	Late Paleocene (?) to early Eocene (?)	Calcareous feldspatholithic sandstone and conglomerate interbedded with hard carbonaceous and organic-rich shale or siltstone. Also includes subordinate amygdaloidal basaltic flow and pyroclastic rocks and diabase dike (?) rocks.	900
C	Early Eocene	Dominantly basaltic flow and pyroclastic rocks with subordinate associated clastic marine sedimentary rocks. Most basalts are amygdaloidal; Plagioclase phenocrysts are common, and serpentinized olivine phynocrysts are locally present. Textures range from glassy to diabasic.	1300
D	Early and middle Eocene	Interbedded feldspatholithic sandstone, siltstone, organic rich shale, calcareous and concretionary shale, tuffaceous shale, minor pebbly mudstone, tuff, volcaniclastic and bioclastic sandstone, and basalt. Unit contains a diverse and abundant microbiota including coccoliths, foraminifers, siliceous microfossils, polynomorphs, and organisms characteristic of shallow-water tropical carbonate reefs, such as algea, coral, bryozoans, and echinoids.	2100
E	Early Eocene to late Eocene, and possible early Oligocene.	Organic rich shale, calcareous shale, tuffaceous shale, micaceous siltstone, and feldspatholithic calcite-matrix sandstone. Shale is commonly laminated and organic rich. Sequence contains a rich biota of microfossils, including coccoliths, foraminifers, and palynomorphs.	800
F	Late Oligocene	Silty shale with abundant mica and a rich diatom and silicoflagellate assembledge. In contrast to underlying strata, calcareous microfossils are absent and shale is relatively low in organic carbon content. Correlative in age with the onshore marine Poul Creek Formation, but lacks the characteristic Poul Creek glauconite, mafic aquagene tuff and flow rocks, and foraminifers.	300
G	Miocene and younger	Marine mudstone, siltstone, sandstone, conglomerate, and conglomeratic sandy mudstone or diamictite. Ice rafted dropstones common. Correlative with the Yakataga Formation. See Plafker and Addicott (1976) for detailed study.	2000

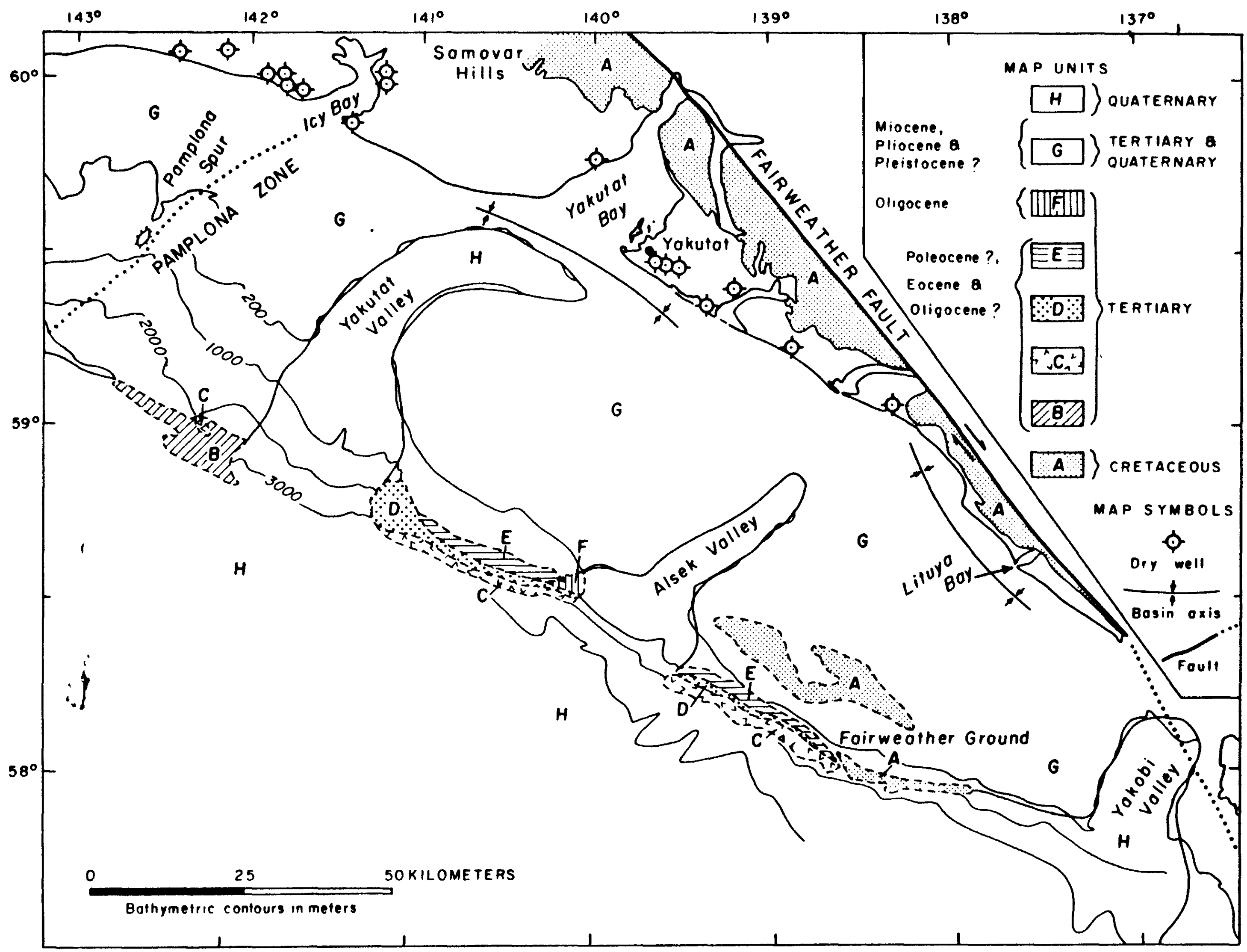


Figure 6. Generalized geologic map showing bedrock outcrop distribution of dredge samples, the outcrop area of pre-Tertiary rocks onshore, areas of thicker unconsolidated deposits, major structural features, and onshore wells. Units G and H not distinguished by pattern; contact is at continental slope except in shelf valleys. See text and Table 1 for description of map units. From Plafker and others (1980).

locations south of Icy Bay and adjacent to Fairweather Ground respectively (Fig. 1). The basalts exhibit textures and primary mineralogy commonly found in ocean-floor basalts. The geochemistry of the basalts indicates that they are a chemically diverse assemblage of tholeiites, most similar to basalts from seamounts on and near midoceanic ridges (Davis and Plafker, 1984).

The basalts are likely the source body for a linear magnetic anomaly, the Slope anomaly, that extends along the continental slope from Fairweather Ground to Kayak Island, and continues across the shelf west of Kayak Island to the Kenai Peninsula (Naugler and Wageman, 1973; Taylor and O'Neill, 1978; Schwab and Bruns, 1979; Schwab and others, 1980). The basalts have some of the highest magnetic susceptibilities measured in the Gulf of Alaska, averaging about .003, with a high of .0055. The magnetic data will be discussed in detail in a later section.

The Eocene and Oligocene sedimentary strata overlying the basalt have a combined thickness of about 3200 m at the continental slope. Units D and E were sampled from Fairweather Ground to Yakutat Valley. Unit F was sampled only along the upper slope near the west side of Alsek Valley, and is about 300 m thick where dredged.

The Paleogene sedimentary strata are terrigeneous. Some of the dredged sandstones are lithofeldspathic with quartz and feldspar each comprising about 40% of framework grains, and rock fragments comprising about 20%. The rock fragments are dominantly plutonic and metamorphic, and suggest deposition from a plutonic and metamorphic source terrain. Also, compositional and textural data from these sandstones indicate rapid deposition from a nearby source area, probably a continental margin (Plafker and others, 1980).

The entire Paleogene sequence dredged on the slope differs markedly in lithology from coeval rocks either exposed or penetrated in exploratory wells onshore (Plafker and others, 1980). In addition, early and middle Eocene foraminiferal assembledges have not been recorded from onshore outcrops or subsurface wells in the northern Gulf of Alaska, except for a well at Middleton Island (Rau, 1979, 1981). Thus, at least part of the offshore Paleogene section is not represented in onshore sedimentary strata. Therefore, no correlations have been made with the onshore sections.

Benthic foraminifora indicate deposition of the Paleogene strata in increasingly shallower water (Rau, 1979, 1981; Plafker and others, 1980; Keller and others, 1983, 1984). Early to middle Eocene fauna indicate deposition occurred in lower middle bathyal or deeper depths (1500 m or greater), with transport of outer shelf and upper slope fauna into the basin during early Eocene time. Late Eocene and Oligocene fauna indicate deposition in middle bathyal depths, with gradual shallowing.

The Paleogene sedimentary sequence contains a microfauna that indicates significant northward transport. Microfauna from the dredge samples are similar to microfauna of California, Oregon, and Washington (Plafker and others, 1980; Rau, 1979, 1981). Keller and others (1984) find that early Eocene microfauna are similar to assemblages currently found at about $30^\circ \pm 5^\circ$ N. in California, while middle Eocene and upper Eocene to Oligocene fauna are similar to assemblages at about $40^\circ \pm 5^\circ$ N. in California, and $45^\circ \pm 5^\circ$ in Oregon and Washington respectively. These correlations require at least 30°

of northward motion of the Yakutat block since the early Eocene.

Geophysical data (next section) show that the Paleogene rocks are present beneath the Yakataga segment, but the Paleogene rocks have not been extensively sampled as on the Yakutat segment. Paleogene age rocks were sampled at one location on Khitrov Ridge during the dredge cruises (Plafker and others, 1979). Paleogene rocks are also reported from the bottoms of five exploratory wells drilled in the Yakataga segment (Herrera, 1978; Jones, 1979).

(3) Unit G, a middle Miocene(?) and younger clastic sedimentary sequence equivalent to the onshore Yakatage Formation, overlies all the older units. At the slope, these strata are up to 2000 m thick. These rocks were not extensively sampled during the dredge cruises, but are extensively exposed in outcrop and wells onshore (Plafker, 1971; Plafker and Addicott, 1977). Some of the offshore exploratory wells penetrated up to 4 km of these rocks without reaching the base of the section or sampling rocks older than Pliocene (Lattanzi, 1981).

A detailed study of a well drilled by Exxon Company, U.S.A. southeast of Kayak Island (Exxon OCS-Y 0080; Lattanzi, 1981) shows the geology in the well is similar that exposed on the mainland. In the offshore well, the oldest unit penetrated, between 2582-4117 m, is of late Miocene to early Pliocene age, and is lithologically equivalent to the onshore Poul Creek Formation. These strata are overlain by Yakataga Formation equivalents. Thus, the offshore strata at the bottom of the well are equivalent to the upper Miocene Poul Creek and Yakataga Formation section exposed at Cape Yakataga (Areay, 1978; Lagoe, 1978, 1983; Armentrout and others, 1978; Armentrout, 1983). Both onshore and offshore units are overlain by thick, cool-water, glaciomarine strata of the Yakataga Formation.

At present, the continuity of pre-Yakataga Formation rocks onshore and offshore has not been established. Significant differences in lithology have so far precluded correlation of the dredged rocks with coeval onshore rocks (Plafker and others, 1980). The dredged rocks also include basalts and early and middle Eocene rocks, for which no onshore equivalents have been recognized. Most likely, the offshore Paleogene rocks are deep water facies of the onshore, mainly shallow marine and non-marine rocks. Alternatively, and less likely, the Paleogene rocks onshore and offshore could be fault bounded and unrelated, and the Yakutat block itself comprise a composite terrane. Better delineation of the geologic history of the pre-Yakataga Formation part of the block is dependant on a better correlation of onshore and offshore lithologies, and on better delineation of faults that could affect these older strata.

Seismic horizons

The structure of the offshore part of the Yakutat block is determined by correlation and mapping of selected seismic horizons throughout the multichannel seismic reflection grid. These horizons then delineate the structure, and the timing and pattern of structural development of the continental margin. The seismic horizons were used to construct the structure and isopach maps presented here, and are shown on the seismic lines.

Six seismic horizons, designated from youngest to oldest as A through F, are mapped in various areas of the shelf, and three, designated as A1 through A3, are mapped at the base of the slope (Fig. 7; Bruns 1979, 1982, 1983b; Bruns and Schwab, 1983). Each of these horizons is at least locally, and in part regionally, mapped on an unconformity; where the unconformities are not present, mapping is on seismic reflectors correlative with the unconformity. Thus, each of the seismic horizons is, or approximates, a time boundary.

Horizons A, B, and C are mapped on the Yakataga shelf (Bruns and Schwab, 1983). Structure contours on horizon C, the deepest horizon correlated throughout the Yakataga shelf seismic grid, are presented in this paper. The age of strata at horizon C is difficult to determine, since faunal data do not provide accurate age differentiation in Pliocene and Quaternary strata (Rau and others, 1977; Lattanzi, 1981). Based on correlations to onshore and offshore wells, Bruns and Schwab (1983) estimated strata at horizon C could be as old as about middle Pliocene; however, these strata could be as young as earliest Pleistocene, based on correlation into four offshore wells drilled by Exxon Co., U.S.A. (Lattanzi, 1981). Horizons A and B are of about middle Pleistocene and early Pleistocene age respectively; structure maps for these horizons are shown in Bruns and Schwab (1983).

Horizons D, E, and F are mapped throughout the seismic data from the Yakutat shelf and slope, and horizon D is discontinuously seen in seismic data from the Yakataga slope.

Correlation of these horizons to rocks dredged from the continental slope (Plafker and others, 1980) and to onshore wells (Rau and others, 1977) gives age control on the horizons; this correlation is summarized below, and discussed in detail in Bruns (1982, 1983b).

Horizon D is mapped at the base of strata correlative with the onshore Yakataga Formation. Horizon D may mark a major hiatus that occurred during middle Miocene time (Bruns, 1983b). Onshore well data (Rau and others, 1977) suggest that much of the Yakataga Formation adjacent to the shelf is Pliocene and Quaternary age, and, near Yakutat Bay, the formation directly overlies Eocene and older strata. Also, detailed studies at Cape Yakataga (Armentrout, 1983; Lagoe, 1983) and in an offshore well (Lattanzi, 1981) indicate that the base of the Yakataga Formation is of late Miocene age, and that middle Miocene strata are thin or absent. Thus, the age offshore of strata above horizon D is likely late Miocene and younger.

Horizon E is mapped on an unconformity that is locally present between horizons F and D south of Yakutat Bay. Correlation of this horizon with the dredge data from the slope indicates that the unconformity is between rocks of early to middle Oligocene (Unit E of Plafker and others, 1980) and late Oligocene age (Unit F). The horizon cannot be seismically correlated throughout the shelf.

Horizon F is acoustic basement on the seismic reflection data. Between Yakutat and Icy Bays, the horizon is too deeply buried to be seen in the reflection data except beneath the outer shelf and slope. In this area, the approximate position of the horizon is defined by a 7 km/s layer in refraction data of Bayer and others (1978). Horizon F corresponds to the top of the Paleocene(?) and Eocene basalt (Unit C of Plafker and others, 1980) from about

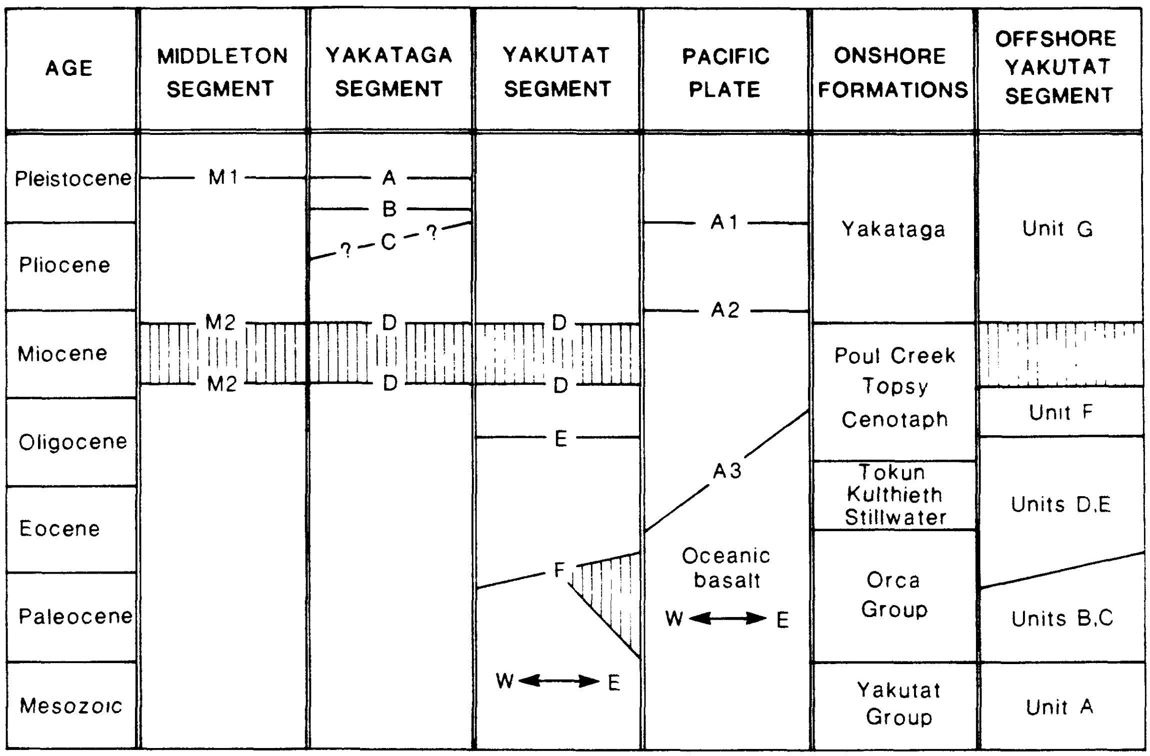


Figure 7. Generalized age and geologic correlation of seismic horizons, from Bruns (1983), Bruns and Schwab (1983), and this report. Horizons mapped on the Middleton, Yakataga, and Yakutat segments and on the adjacent Pacific plate are shown in first four columns to right of age column; west to east variation indicated for Yakutat segment and Pacific plate. Fifth column shows highly generalized age ranges for onshore formations. The thickness and distribution of these formations, and unconformities within and between units are not noted but are complex; see Stoneley (1967), Plafker (1967, 1971), and Winkler and Plafker (1981a) for detailed stratigraphic correlations, distribution, and description of onshore units. Sixth column shows geologic units defined by Plafker and others (1980) from dredge data from the Yakutat segment continental slope; see Figure 6, Table 1, and text.

Alsek Valley to Icy Bay, and to the top of probable Mesozoic flysch and melange (Unit A of Plafker and others, 1980) from Cross Sound to the Alsek Valley (Bruns, 1982, 1983b). Horizon F therefore shows the minimum thickness of sedimentary strata of the shelf and slope. Strata between horizons F and D are largely of Paleogene age, based on correlations to the dredge data, and could include rocks of lower Miocene age as seen onshore.

Horizons D and F cannot be correlated throughout seismic data on the Yakataga segment shelf as the horizons are obscured beneath the thick late Miocene and younger strata (post-horizon D strata) of the shelf. However, horizon D is discontinuously seen on slope segments of the seismic lines.

At the base of the slope, three seismic horizons are correlated through a set of single and multichannel seismic reflection lines to Deep Sea Drilling Project Site 178 near Kodiak Island. The horizons are A1, base Pleistocene; A2, base Pliocene; and A3, top oceanic basalt. Horizon A3 ranges in age from about middle Eocene on the west (anomaly 20, 46 Ma) to late Oligocene on the east (anomaly 7, 25 Ma; Schwab and others, 1980). The age correlation of horizons A1 and A2 is less certain than the correlation of the shelf horizons because of the distance between the Yakutat segment and the only point of age control at site 178. The age correlation is in good agreement with a similar correlation by Von Huene and others (1979).

In the following sections, the seismic horizons are used to delineate both time and strata sequences; for example, the time between any two horizons, like the F and D horizons, will be "F-D time".

Yakutat segment structure

If significant Pacific-North America convergence has been accomodated by subduction of the Pacific plate beneath the Yakutat block, then the structure of the Yakutat segment should reflect this convergence with accretion along the south margin of the segment and with major deformation of the shelf or slope rocks. Instead, interpretation of multichannel seismic reflection data shows little compressional deformation of the segment, and further shows that the Transition fault bounding the south side of the segment has been an inactive tectonic feature for at least Pliocene and Quaternary time. The structure of the segment also establishes important constraints for the pre-Pliocene tectonic history of the Yakutat block. In this section, I describe the structure of the shelf, slope, and adjacent abyssal plain, then examine the structure of the Transition fault at the base of the continental slope.

Shelf and slope structure

The structure of the Yakutat segment is characterized by four major features (Figs. 4, 8-10; Bruns, 1983b): (1) a large structural high at the shelf edge between Yakobi and Alsek Valleys that is centered on Fairweather Ground; (2) the Dangerous River zone, extending from the western edge of Fairweather Ground towards the mouth of the Dangerous River, along which acoustic basement shallows abruptly by about 2 km from west to east, (3) the Icy Point-Lituya Bay extension of the Queen Charlotte fault system, and (4) two subbasins separated by the Dangerous River zone.

Fairweather Ground high. Dredge data indicate that the Fairweather Ground high is cored by rocks of early Tertiary and probable Mesozoic age

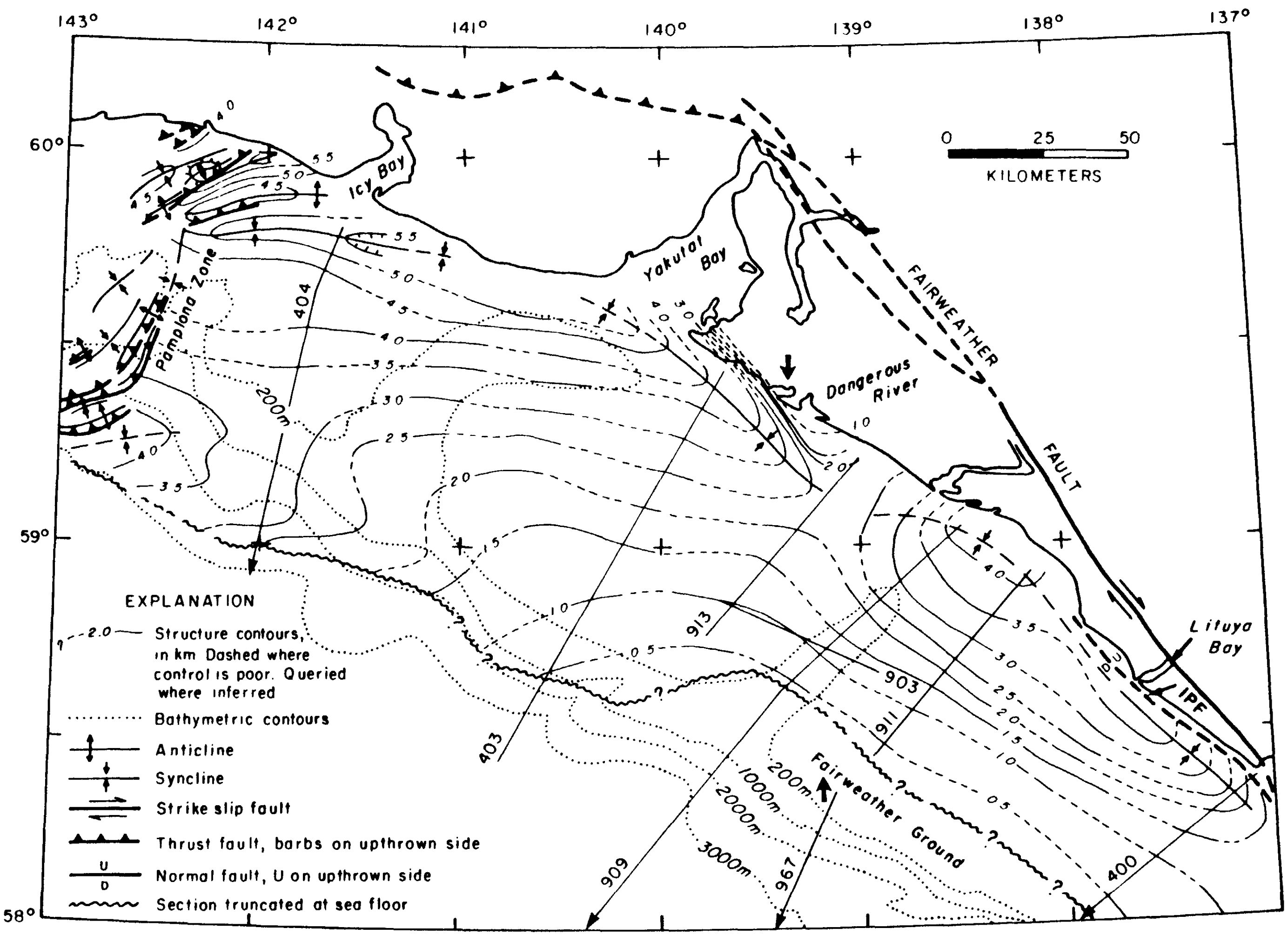


Figure 8. Structure contours on a seismic horizon (horizon D) at approximately the base of late Miocene and younger strata. Arrows indicate location and trend of Dangerous River zone discussed in text. IPF-Icy Point-Lituya Bay fault. Contour interval = 0.5 km. Numbered lines show location of seismic lines shown in Figs. 11-14. From Bruns (1983).

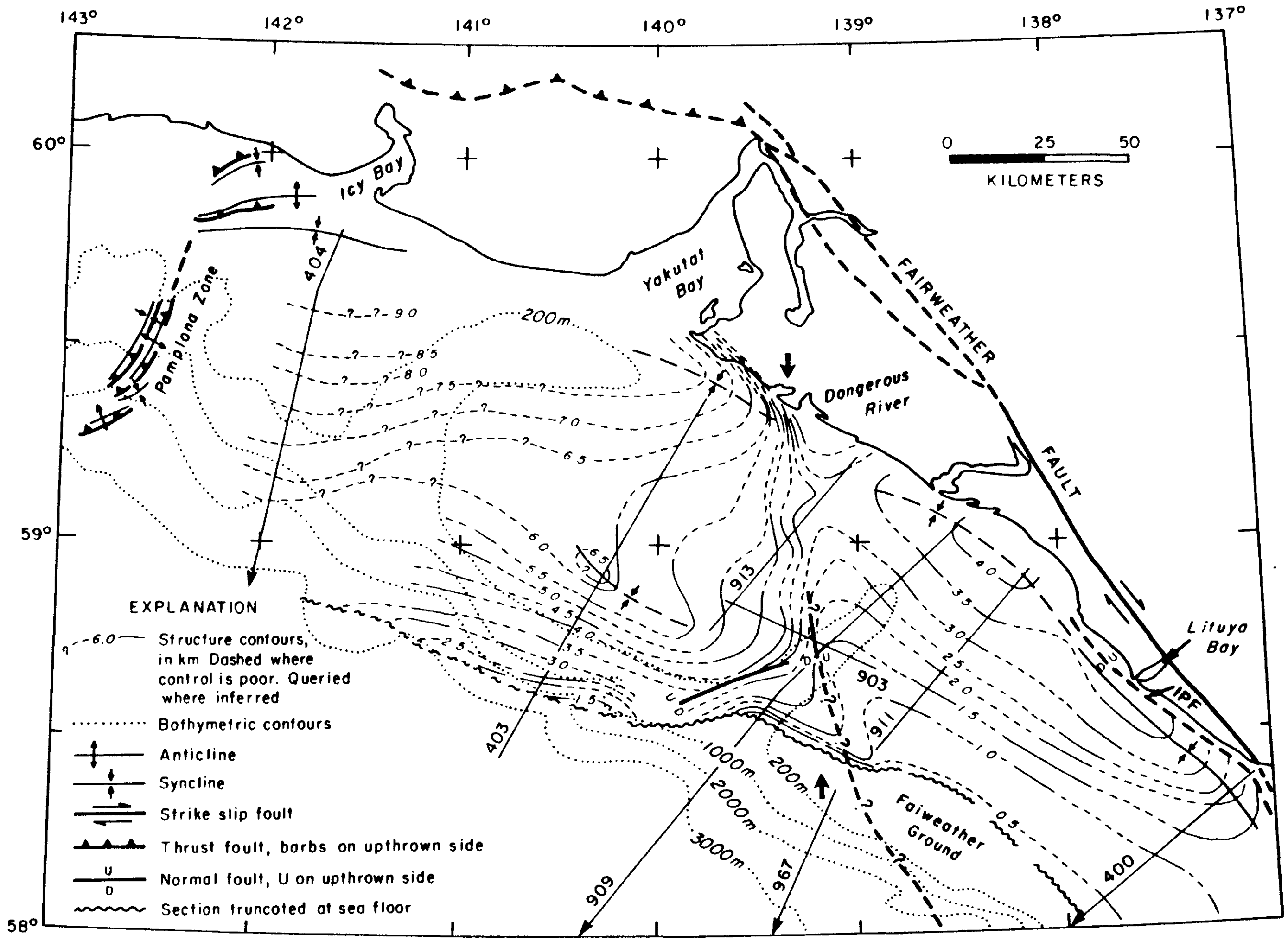


Figure 9. Structure contours on a seismic horizon (horizon F) at approximately the base of the Paleogene sedimentary strata. Contour interval = 0.5 km. Other explanations as in Fig. 8. From Bruns (1983).

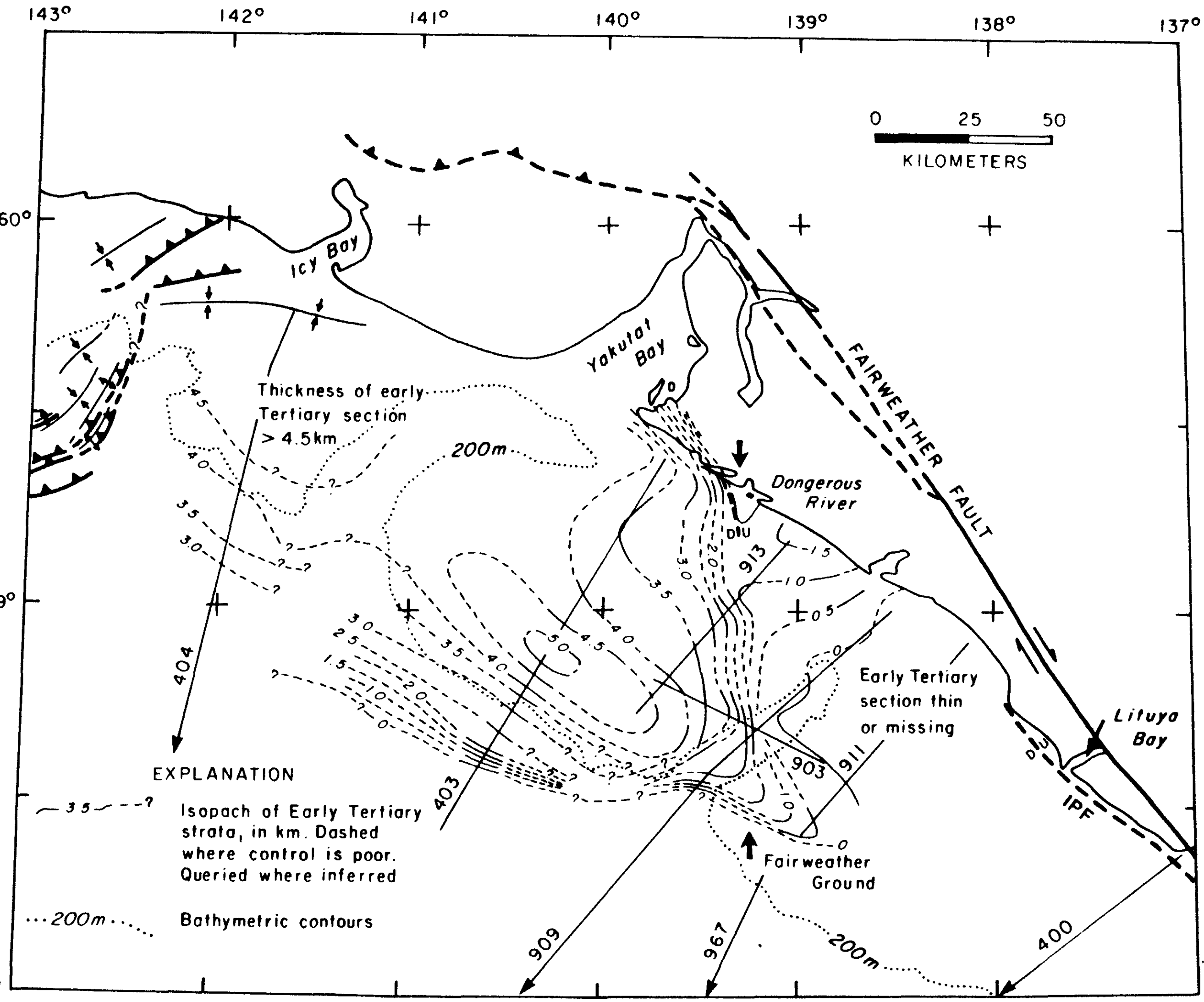


Figure 10. Isopach map of Paleogene sedimentary strata (strata between horizons F and D). Contour interval = 0.5 km. Other explanations as in Fig. 8. From Bruns (1983).

(Plafker and others, 1980; Bruns, 1983b). Neogene and Quaternary strata onlap the high and dip toward the coast into the eastern subbasin of the Yakutat shelf (Fig. 8). These strata are uplifted and truncated at the sea floor along much of the high (lines 400, 911, and 909, Figs. 12, 13). Most of this uplift occurred during the late Cenozoic, probably during Pliocene and Quaternary time. Seismic reflectors in the lower part of the section (between horizon D and U, lines 909 and 911, Figs. 12, 13) show little thinning onto the high, while reflectors in the upper part of the section thin onto the high (above horizon U). Based on flattening of these horizons to remove the effects of uplift, late Cenozoic (post-horizon D) uplift of Fairweather Ground has been at least 2 km in the vicinity of Alsek Valley, and around 1 km south of Lituya Bay (Bruns, 1983b).

Dangerous River zone. The Dangerous River zone is an area where the acoustic basement on the seismic data becomes markedly shallower, with structural relief on the acoustic basement of 2 km or more (Fig. 9). The thick Paleogene rocks present west of the Dangerous River zone (F-D strata) are truncated along the zone (Fig. 10), primarily by onlap against the acoustic basement (horizon F; see lines 903 and 913, Fig. 11 and line 909, Fig. 13). Faulting occurs at the base of the section, and part of the section is truncated by the overlying late Miocene and younger strata (post-horizon D strata).

The southern extension of the Dangerous River zone trends into an area on the continental slope, where, on the basis of dredge data (Plafker and others, 1980), Paleogene strata are juxtaposed against Mesozoic rocks (Fig. 6). The northwest extension of the zone is inferred to pass beneath three exploratory wells near Yakutat where a thick Paleogene section is cut out by truncation or faulting (Rau and others, 1977). West of these wells, the position of the zone is unknown.

The Dangerous River zone marks a major change in the basement rocks of the Yakutat block. East of the zone, basement rocks both onshore and offshore consist of possible Mesozoic flysch and melange (Unit A of Plafker and others, 1980, offshore, and the Yakutat Group onshore). West of the zone, refraction velocities (Bayer and others, 1978; Von Huene and others, 1979), magnetic data (Schwab and others, 1980), and magnetic models (presented later) indicate that the Eocene basalt sampled at the continental slope is continuous beneath the shelf. The onlap of the Paleogene sedimentary sequence onto the acoustic basement indicates that the Dangerous River zone formed the edge of the Paleogene basin and is a paleo-slope formed prior to the deposition of these strata (Bruns, 1982, 1983b). The Dangerous River zone marks the transition from a probable Mesozoic continental margin accretionary sequence on the east to what could be an oceanic basalt sequence on the west.

Icy Point-Lituya Bay fault. The Icy Point-Lituya Bay fault, the extension of the western Queen Charlotte fault trace, bounds the east subbasin of the shelf along the shoreline (Figs. 8, 9). From Cross Sound to Cape Fairweather, marked uplift and folding of the basin strata occurs at or near the shoreline, where the Yakataga Formation crops out with almost vertical dip (Stoneley, 1967; Plafker, 1967; 1971). Offshore seismic data (line 400, Fig. 12) show flat-lying sediment within 3 km of the coast near Lituya Bay, suggesting the fault is associated with significant deformation and vertical displacement near the shoreline. The fault may extend to the west beneath the

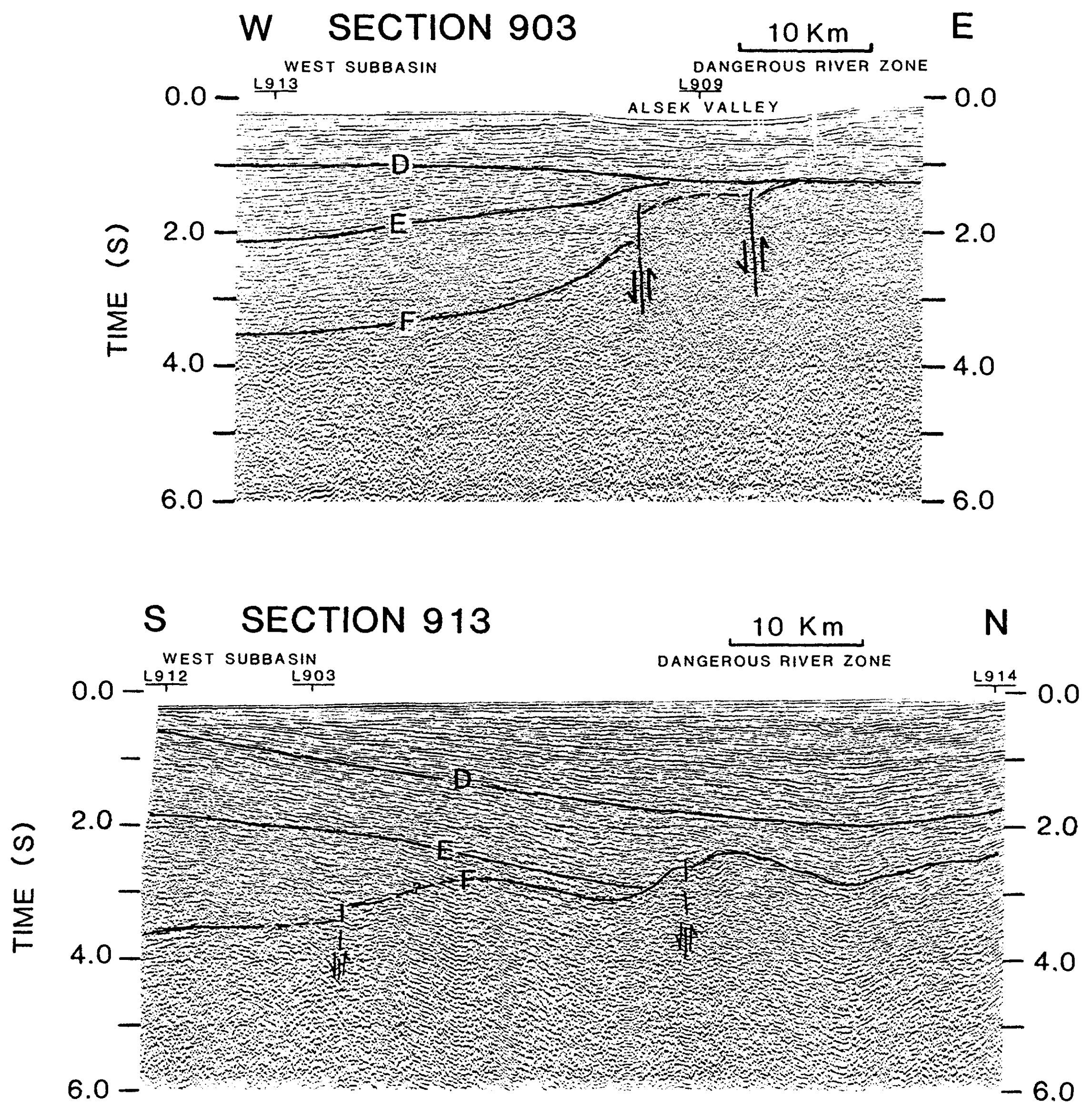


Figure 11. Interpreted seismic sections 903 and 913, Yakutat segment. Seismic horizons D and F correspond to mapped horizons of Figures 8 and 9 respectively. Locations of lines shown in Figures 8-10. V.E. 6.7:1 at the seafloor.

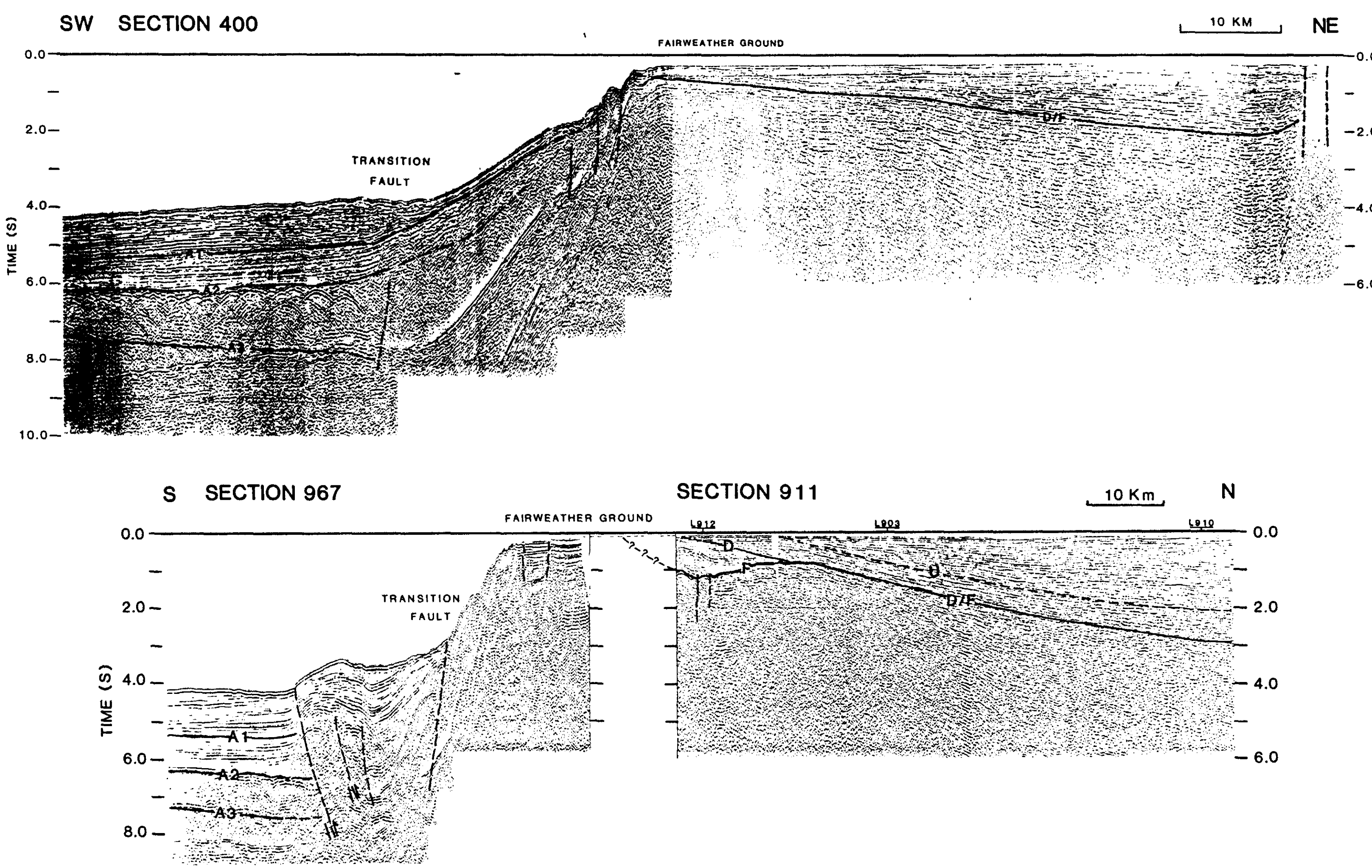


Figure 12. Interpreted seismic sections 400 and 967-911, Yakutat segment. Seismic horizons D and F correspond to mapped horizons of Figures 8 and 9 respectively; horizons A2 and A3 to mapped horizons in Figs. 15 and 16. Locations of lines shown in Figures 8-10. V.E. at the seafloor 5:1 for line 400 and 6.7:1 for line 967-911.

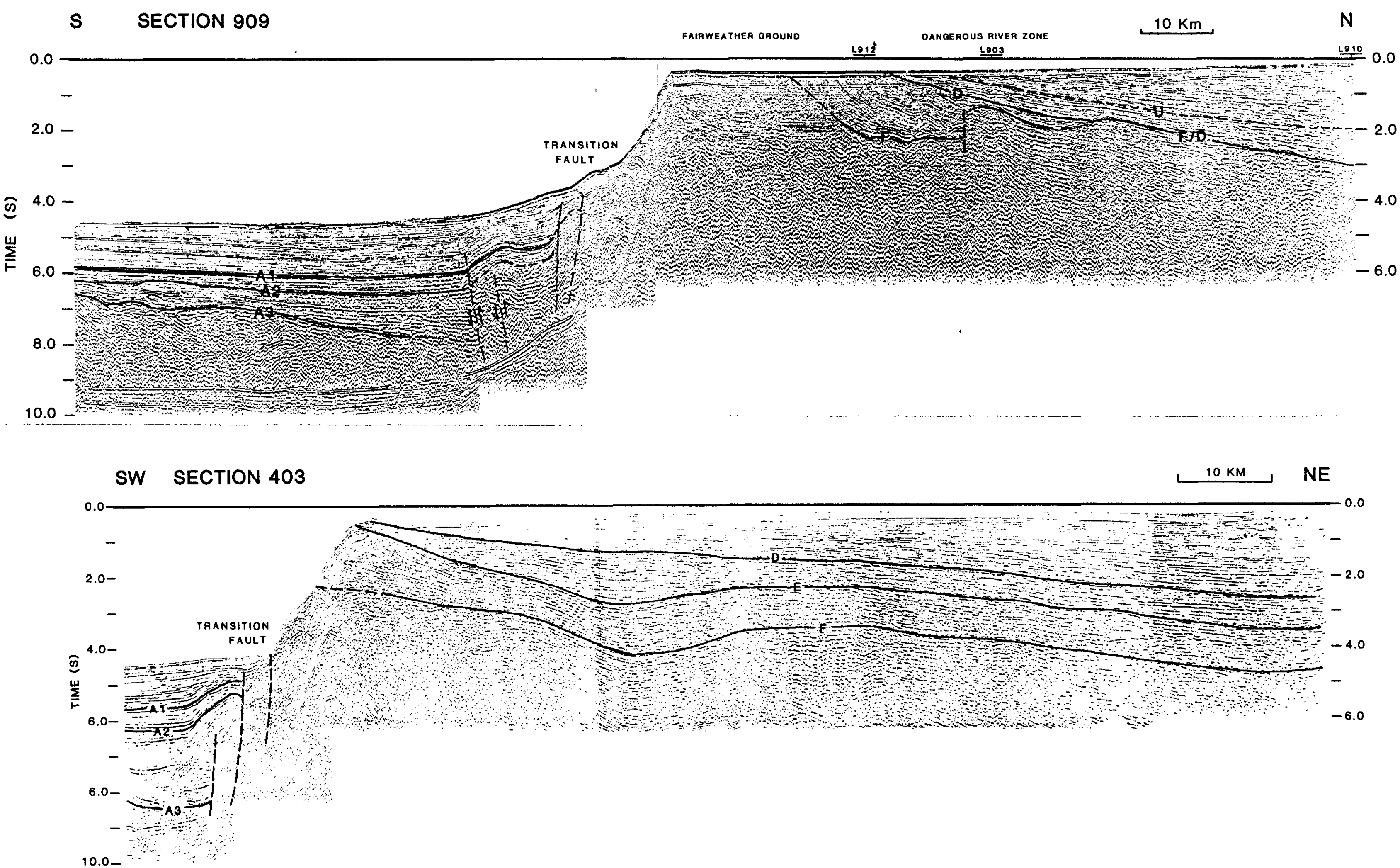


Figure 13. Interpreted seismic sections 909 and 403, Yakutat segment. Seismic horizons D and F correspond to mapped horizons of Figures 8 and 9 respectively, horizon E is a local unconformity of about middle Oligocene age, and horizons A2 and A3 correspond to mapped horizons in Figs 15 and 16. Locations of lines shown in Figures 8-10. V.E. at the seafloor 6.7:1 for line 909, and 5:1 for line 403.

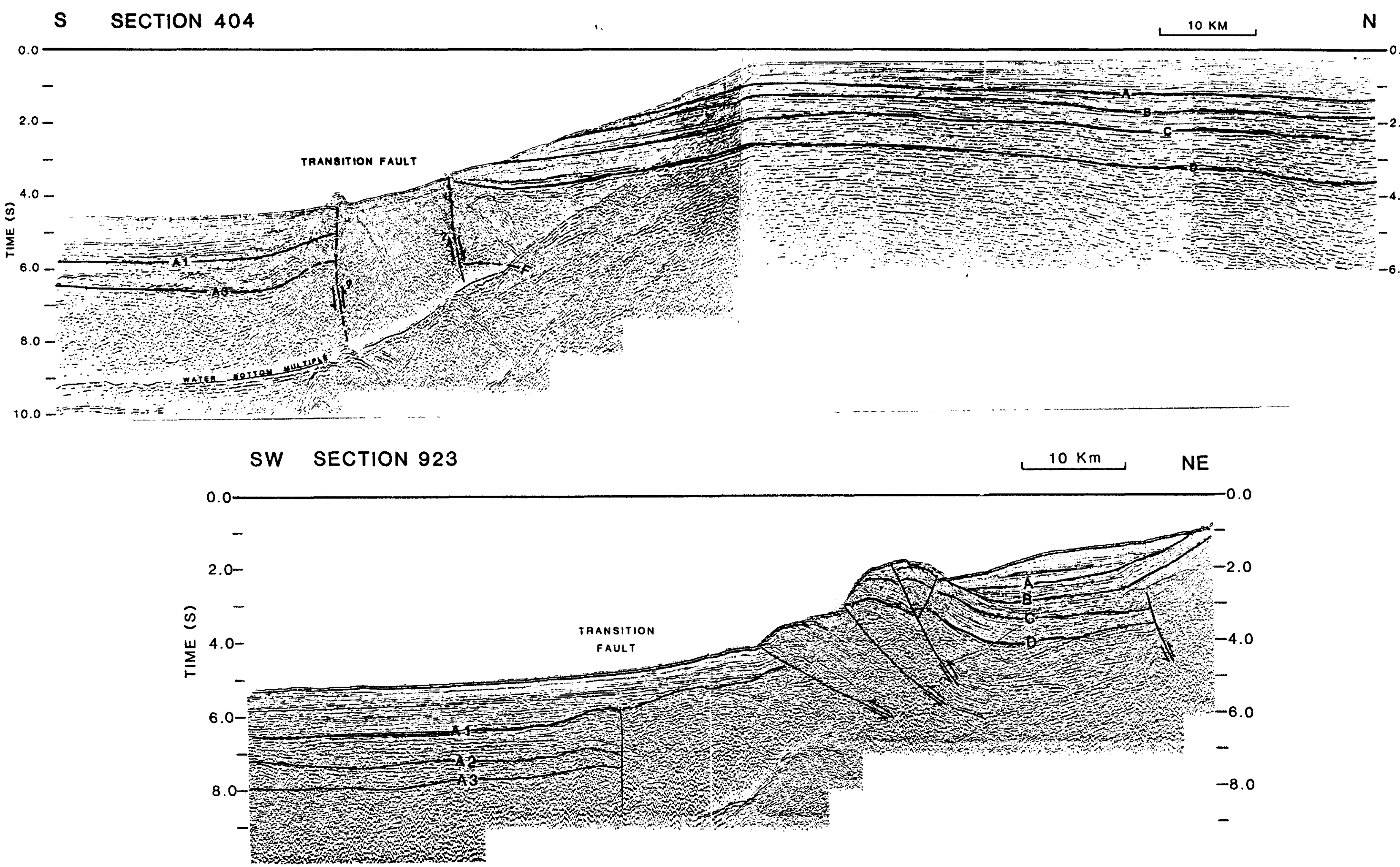


Figure 14. Interpreted seismic sections 404 and 923, Yakutat and Yakataga segments. Seismic horizons D and F correspond to mapped horizons of Figures 8 and 9 respectively; horizons A2 and A3 correspond to mapped horizons in Figs. 15 and 16. Location of line 404 shown in Figures 8-10 and 15-17; for line 923, see Figures 15-17. V.E. at the seafloor 5:1.

thick onshore alluvium, but no data are available to trace this extension. As discussed in the previous section, this fault could be a major strike-slip fault similar to the onshore Fairweather Fault, since it trends into the most active trace of the Queen Charlotte fault as mapped by Carlson and others (1979, 1981, and in press).

Basins. The Dangerous River zone separates the Yakutat shelf into two distinct subbasins. The eastern basin (Figs. 8, 9) is bounded by the shoreline, the Dangerous River zone, the Fairweather Ground high, and the offshore extension of the Fairweather fault system. Strata in this basin that are resolvable on the seismic data (D-seafloor strata on lines 400, 911, and 909, Figs. 12, 13) are of late Cenozoic age, and lower Tertiary strata are missing, thin, or form acoustic basement.

The late Cenozoic strata within the eastern basin show regional dip towards the basin axis, and are deformed only over and around the Fairweather Ground high, and along the Queen Charlotte-Fairweather fault system. The sedimentary section dips towards the coast, with a maximum thickness of around 4 km east of Dry Bay. The axis of the basin is near and parallels the coast.

The western subbasin lies between the Dangerous River zone and the compressional folds of the Yakataga segment. The structure and isopach maps (Figs. 8-10), show that the Tertiary sedimentary section thickens markedly west of the Dangerous River zone to greater than 9 km south of Icy Bay, primarily due to the presence of the thick Paleogene section (F-D strata on seismic lines in Figs. 11-14). South of Yakutat Bay, roughly midway between the shelf break and the coast, the Paleogene section has a maximum thickness greater than 5 km. In the western part of the subbasin, the thickness and extent of this section is not well defined, since seismic reflection and refraction data (Bayer and others, 1978; Bruns, 1982, 1983b) give only very general control on the position of the F horizon, but the section is at least 4.5 km thick. The thickest part of the Paleogene section, as seen in the isopach map (Fig. 10), trends northwest, and may define the early Tertiary basin axis. The section is truncated along the Dangerous River zone.

Local deformation occurred within the Paleogene strata prior to the late Cenozoic (prior to horizon D time), resulting in a prominant local unconformity (horizon E, line 403, Fig. 13). Otherwise, the Paleogene strata within the basin are undeformed. Both dredge data (Plafker and others, 1980) and seismic data (Bruns, 1982, 1983b) show that the Paleogene section is truncated at the continental slope over most of the length of the Yakutat segment. These strata outcrop at the slope primarily along and west of the Fairweather Ground high, suggesting that late Cenozoic uplift of the margin along the high is the primary reason the Paleogene strata are now exposed at the continental slope.

The structure map on horizon D (Fig. 8) shows that the depositional axis of the late Cenozoic strata (D-seafloor strata) in the west subbasin trends east to west, and lies near the coast. The section increases rather uniformly in thickness from the shelf edge to the basin axis, with a thickness greater than 5.5 km in the deepest part of the basin. These strata and the depositional axis of the late Cenozoic basin are continuous across the Dangerous River zone into the east subbasin, with faulting and folding seen nearshore only along the northern extent of the zone. Strata above horizon D show regional subsidence towards the basin axis, but are otherwise relatively undeformed.

The structure of the Yakutat shelf and slope shows little evidence for late Cenozoic oblique convergence across the margin. There is no evidence of large scale uplift, folding, and faulting of the shelf or slope as is typically, but not always, seen on other convergent margins of the world. The Paleogene strata are truncated at the continental slope, and there is no evidence for an accretionary wedge. Paleogene deformation of the basin west of the Dangerous River zone was very localized, consisting of low relief folding. East of the Dangerous River zone, deformation is limited to uplift of Fairweather Ground, primarily during about Pliocene and younger time, and by deformation along the trend of the Fairweather-Queen Charlotte fault system. Otherwise, the shelf is characterized by regional subsidence.

Base-of-slope structure

Three major structural features are present at the base of the slope and on the adjacent abyssal plain (Figs. 15-16). (1) A thick, relatively undeformed sedimentary sequence overlies oceanic basalt and forms a sedimentary trough or basin at the base of the slope. (2) Two sediment fans are present on the abyssal plain off the Alsek and Yakutat Valleys. (3) The Transition fault lies along the base of the slope, and forms a major structural boundary between the Yakutat block and the Pacific plate.

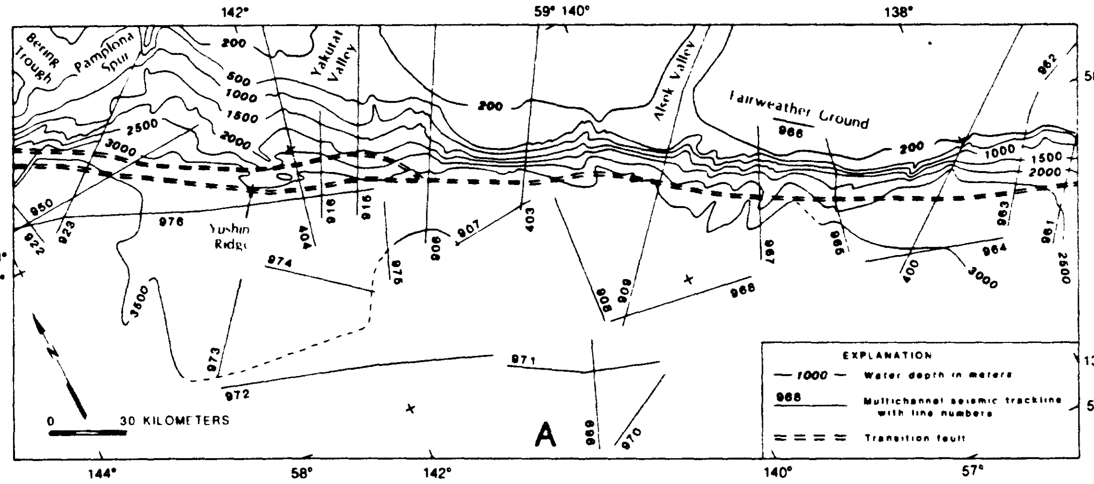
Sedimentary basin. An elongate basin at the base of the slope from Yakobi Valley to Yushin Ridge contains over 6 km of sedimentary strata (Fig. 15). The basin strata are thickest at or near the base of the slope, and thin seaward to about 2 to 2.5 km thick, 60 km from the base of the slope. To the west, the strata thin rapidly to about 2.5 km in the vicinity of Yushin Ridge. West of Yushin Ridge, and adjacent to the folds of the Yakataga segment, the strata thicken to about 3.5 km.

About half of the section is of pre-Pliocene age (A3-A2 strata) based on the age correlation of horizon A2, and mapping of the A2 horizon through the seismic grid. The age of the underlying basalt is about middle to late Oligocene, based on the age of adjacent oceanic anomalies (anomalies 7-13, Naugler and Wageman, 1973; 25-32 m.y., LaBrecque and others, 1977).

Isopach maps of both the pre-Pliocene strata (A3-A2 strata) and of the Pliocene and younger strata (A2-seafloor strata) in the sedimentary trough show that the trough has formed a subsiding basin throughout Neogene and Quaternary time (Fig. 16). The axis of the pre-Pliocene strata is adjacent to the base of the slope, while the axis of the Pliocene and younger strata is offset seaward by about 10 to 15 km.

Deformation of the basin strata occurs only adjacent to the Fairweather Ground high. Elsewhere along the margin, particularly in the vicinity of Yakobi Valley at the east end of the margin, and from Yakutat Valley to the west, seismic data show no evidence for deformation of the abyssal strata (line 400, Fig. 12; lines 404 and 923, Fig. 14).

The seismic data show two ages of deformation (Bruns, 1983b). The oldest



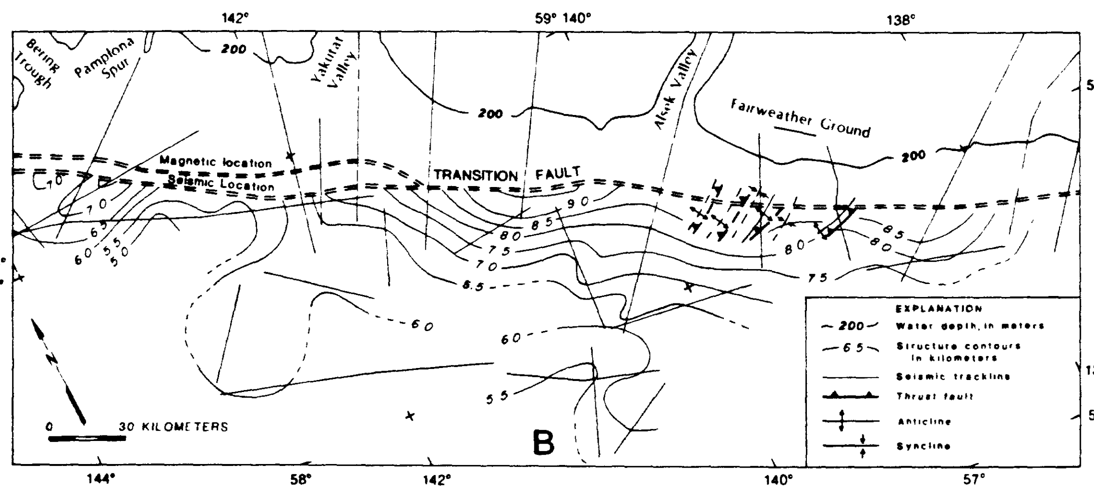


Figure 15. A. Bathymetry (from Atwood and others, 1981) and multichannel seismic tracklines across the outer shelf and slope of the Yakutat block and adjacent Pacific plate. Location of Transition fault is determined from seismic data and magnetic models as discussed in text. B. Structure contours to top of oceanic basalt adjacent to the Transition fault. Bathymetry and identification of seismic tracklines shown in Fig. 15a.

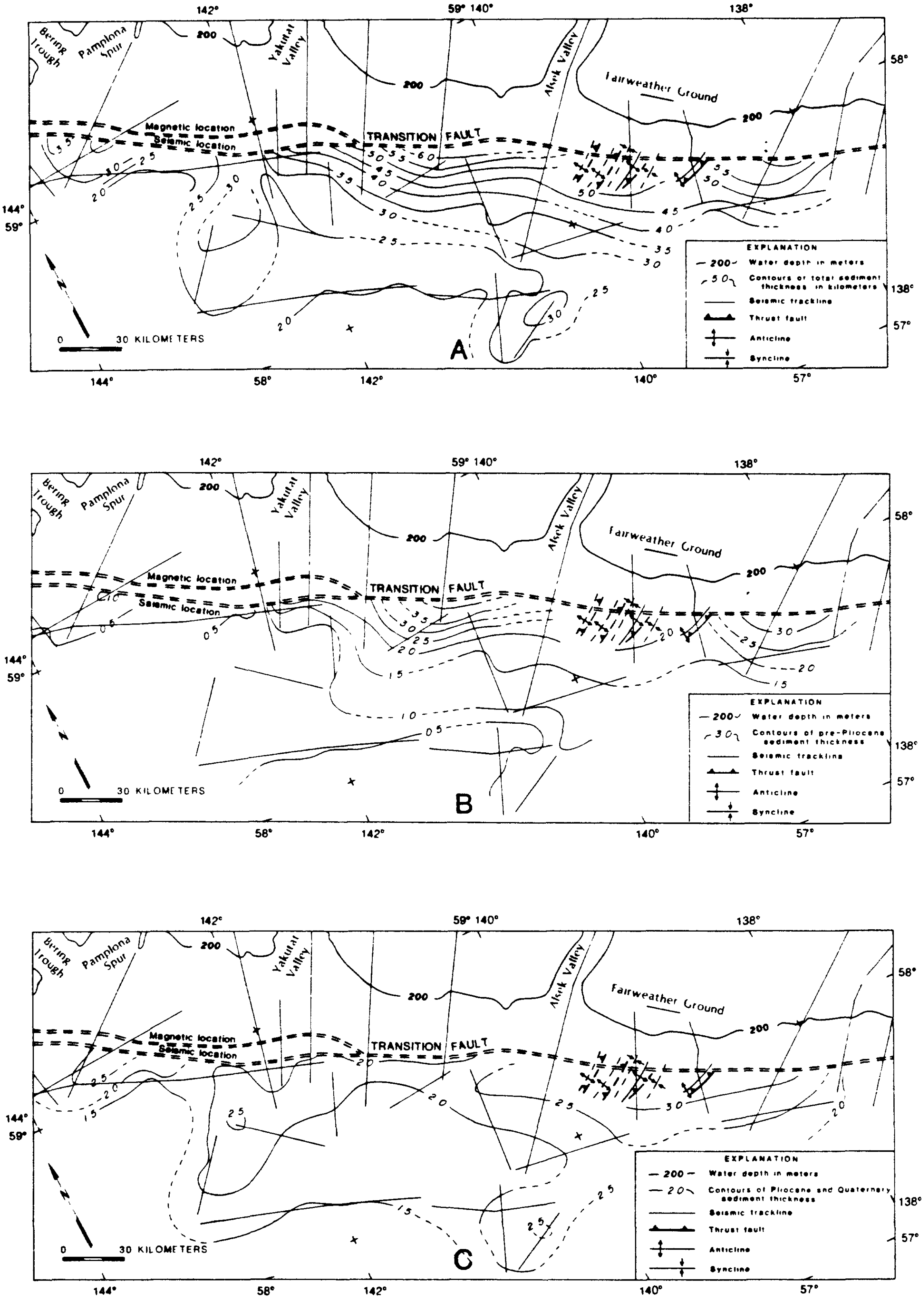


Figure 16. A. Isopach map of total sediment thickness above oceanic basalt adjacent to the Transition fault (A3-Seafloor strata). B. Isopach map of pre-Pliocene strata (A3-A2 strata). C. Isopach map of Pliocene and Quaternary strata (A2-Seafloor strata). Bathymetry and identification of seismic tracklines shown in Figure 15a.

structures show the greatest deformation in Pliocene and older strata, with decreasing deformation in the overlying strata. Only minor deformation is present in the upper part of the Pleistocene section (line 909 and 403, Fig. 13). This deformation is of about the same age and magnitude as has occurred on the adjacent the Fairweather Ground high. These structures are likely caused by the late Cenozoic uplift of the high (Bruns, 1983b).

The youngest structures show major Quaternary growth. Bathymetric data (Atwood and others, 1981) show four subparallel ridges at the base of Fairweather Ground that are 15 to 30 km long (Fig. 15a, inferred structural axis are shown). Seismic lines across these ridges (for example, line 967, Fig. 12), although highly oblique to the bathymetric axis of the structures, show that young, Pleistocene and Holocene age anticlines underlie the ridges. The bathymetric ridges associated with the anticlines trend about N. 60° E. to N. 70° E., almost perpendicular to the N. 15° W. relative convergence vector for the Pacific and North America plates (Minster and Jordan, 1978). The geometry suggests that the structures developed in response to this convergence (Atwood and others, 1981; Bruns, 1983b).

<u>Sedimentary fans.</u> Two Pliocene and Quaternary age sedimentary fans are present at the base of the slope off the Alsek and Yakutat Valleys, as seen in both the bathymetric data and the total sediment thickness map (Fig. 15).

The eastern fan, south of Alsek Valley shows a Pliocene and Quaternary sediment lobe about 2.5 km thick around 80 to 90 km from the base of the slope. The form of the fan, and tracing of a channel associated with this fan suggests a source in the vicinity of Yakobi Valley, rather that the closer Alsek Valley, but too few seismic lines are available at present to confirm this suggested source. Sediment originating from the Alsek Valley may be trapped within the subsiding trough at the base of the slope.

The bathymetric apex of the western fan off the Yakutat Valley appears to be offset to the west from the mouth of the valley, and trends into a Paleocene(?) bedrock high (Plafker and others, 1980) at Yushin Ridge. The apparent offset of the apex of the fan from the mouth of the valley and against a bedrock high suggests faulting. However, the isopach map of Pliocene and younger strata (Fig. 16b) shows a fan around 2 to 2.5 km thick extending outward from the mouth of the Yakutat Valley. The pre-Pliocene isopach map (Fig. 16a) shows a thickness of between 0.5 to about 0.9 km, but shows no distinct fan shape. The thickness of these older strata is mainly effected by the marked thinning of the westward edge of the sediment wedge. Thus, this fan is primarily a Pliocene and younger feature, with a probable source from the Yakutat Valley or predecessor sea valleys in about the same area. The position of the fan suggests that there has been little if any offset along the Transition fault during Pliocene and younger time.

<u>The Transition fault.</u>

The Transition fault (Figs. 1, 4, 15, 16) is a major structural boundary between the Yakutat block and the Pacific plate. The fault juxtaposes Mesozoic, Paleocene, and Eocene rocks of the Yakutat block against Oligocene oceanic basalt of the Pacific plate. Structural features along the Transition fault are therefore critical in determining how and when this juxtaposition occurred, and the movement history of the fault. These structural features constrain the Yakutat block to move with the Pacific plate for at least Pliocene and Quaternary time.

Description of the Transition fault from seismic reflection data. On the multichannel seismic data, the seaward limit of the Transition fault is defined by the termination of seismic reflectors from the oceanic basalt and overlying pre-Pliocene strata.

In the vicinity of Yakobi Valley, seismic reflectors in the pre-Pliocene sedimentary strata and from the Oligocene oceanic basalt terminate at or near the base of the slope. The overlying Pliocene and younger strata are undeformed and unfaulted, and onlap the Cretaceous and Paleogene rocks of the continental slope (see especially lines 961, Fig. 3 and 400, Fig. 12). Along the Fairweather Ground high, the Transition fault probably lies at the base of the slope, landward of the Quaternary folds (see line 967, Fig. 12).

Between the Alsek and Yakutat valleys, the Transition fault lies in a 3 to 5 km wide zone at the base of the slope (lines 909 and 403, Fig. 13). From about Yakutat Valley to the initial structures of the Pamplona zone at Khitrov Ridge, the location of the Transition fault is at the south side of a 10 to 15 km wide zone at the base of the slope where no seismic reflectors are resolvable (line 404, Fig. 14). Seaward of the mouth of the Yakutat Valley, this zone of disruption is covered by about 0.7 to 1 km of undeformed and unfaulted strata of probable late Quaternary age that had a source in the Yakutat Valley. The rocks in the disrupted zone are of probable Paleogene age, based on rocks dredged from Yushin Ridge at the seaward side of the disrupted zone (Plafker and others, 1980).

West of Yushin Ridge, the Transition fault is covered by unfaulted strata of at least Pleistocene, and perhaps Pliocene, age that prograde down the continental slope (line 923, Fig. 14). These strata are also surrounding and burying the western end of Yushin Ridge (Bruns and Schwab, 1983). The Transition fault trends into the northern end of Khitrov Ridge, a major bathymetric and structural high that forms the youngest and most seaward structure of the Yakataga segment fold belt. The westward extension of the Transition fault trends into and underlies a steep scarp on the continental slope landward of Khitrov Basin.

The Transition fault, as thus defined, is a major tectonic boundary that separates rocks of very different ages. The rocks outcropping at the continental slope include probable Mesozoic rocks at Fairweather Ground, Eocene basalts and Eocene and Oligocene sedimentary strata from Fairweather Ground to Yakutat Valley, and Paleocene(?) rocks at Yushin Ridge (Plafker and others, 1980). Adjacent to these rocks are Pacific plate crust of Oligocene and younger age.

The Transition fault also truncates the Paleogene basin at the continental slope. The extent and thickness of the Paleogene strata of the shelf and slope, and the truncation of these strata at the slope, indicates that at one time these strata were much more extensive than at present, and that the seaward part of the Paleogene basin is missing. Therefore, during Cenozoic time, tectonism along the Transition fault has removed part of the Paleogene basin, and juxtaposed rocks of markedly different ages along the fault.

Pliocene and Quaternary tectonics of the Transition fault. The Transition fault has not been an active Pacific-North America transform or subduction boundary during at least Pliocene and Quaternary time, and the Yakutat segment of the margin has been moving with the Pacific plate. Evidence for this conclusion is six-fold.

First, thick undeformed Pliocene and younger strata overlie the Transition fault in several areas. Seaward of Yakobi Valley, this undeformed cover is about 1 to 2 km thick. In this area, there is no active connection during Pliocene and Quaternary time between the Transition fault and the Queen Charlotte-Fairweather fault. Seismic data in the Cross Sound transition show no deformation of Pliocene and Quaternary sediment over the Transition fault (line 400, Fig. 12) or on the southeast Alaska shelf on the trend of the Transition fault (line 961, Fig. 3; also Von Huene and others, 1979). Finally, at the western end of the Transition fault, west of Yushin Ridge, the Transition fault is also covered by unfaulted or only slightly deformed sediment of about Pliocene and younger age, as determined by seismic mapping (line 923, Fig. 14; Bruns and Schwab, 1983).

Second, there is no apparent offset of the major sedimentary fan seaward of Yakutat Valley from its probable source of Yakutat Valley.

Third, the Transition fault is primarily characterized by minor or no deformation of strata at the base of the slope, except seaward of the Fairweather Ground high. There is no accretionary wedge along the base of the slope.

Fourth, nowhere can seismic reflectors from the oceanic basalt be traced past the Transition fault and below the margin, as is typical of a subduction zone. There is no evidence from the seismic reflection data for thrusting of ocean plate rocks beneath the continental margin.

Fifth, the Pliocene and younger sediments at the base of the slope appear to have been deposited in place. A subduction process at the Transition fault would have quickly removed these strata, or at least resulted in an offset of the basin axis upward in the section.

Sixth, as noted by Von Huene and others (1979), the presence of the thick pre-Pliocene basin at the base of the slope suggests little net convergence between the Yakutat block and the Pacific plate during Pliocene and Quaternary time. Such thick, abyssal sequences are usually formed in close proximity to a continental margin as an abyssal fan, or in this case, perhaps as a filled trough or trench. Such proximity would imply an originally limited extent of the trough. Convergence between the Pacific plate and the Yakutat block then seems unlikely because such motion would quickly subduct the sedimentary trough. The trough along the Yakutat segment may be analogous to a trough along the Queen Charlotte transform margin which is unfilled along the Queen Charlotte Island segment (Chase and Tiffin, 1972), and filled along the Dixon Entrance to Cross Sound segment (Von Huene and others, 1979; Snavely and others, 1981).

Some Pliocene and Quaternary deformation has occurred locally along the Transition fault, primarily seaward of the Fairweather Ground high. This segment has been active during the late Cenozoic as a probable normal fault associated with the areally limited uplift of the high. The uplift of

Fairweather Ground may reflect Pliocene and Quaternary reactivation of this segment of the Transition fault as a result of minor compressive stress across the margin.

Pre-Pliocene tectonics of the Transition fault. The Transition fault must have been an active tectonic boundary prior to Pliocene time, since both the pre-Pliocene abyssal rocks and the Paleogene shelf rocks are truncated along the fault. When this truncation occurred is unclear. Juxtaposition of the oceanic rocks against the older continental shelf and slope rocks could have occurred in Miocene time, or could have occurred earlier if the truncation of the Paleogene basin was an ongoing process during Eocene or Oligocene time.

The tectonic process that caused the Transition fault is most likely transform faulting. Such a mechanism would explain some of the observed relations along the Transition fault, including the truncation of the Paleogene rocks of the shelf and slope, and the juxtaposition of the different age strata at the base of the slope.

Major subduction along the Transition fault prior to Pliocene time cannot be ruled out, but seems unlikely, for two main reasons. First, none of the usual features of a subduction margin are present. The Yakutat segment and adjacent abyssal basin have undergone only minor deformation and are characterized by regional subsidence during the Cenozoic. There is no tectonically accreted wedge along the margin, even though a thick pre-Pliocene section is present at the base of the slope. The pre-Pliocene strata on either side of the Transition fault appear to be in fault contact with the margin, and there is no evidence that these strata were deformed prior to Pliocene and Quaternary time.

Second, in failed subduction zones, the original morphology of a subduction zone is often preserved. This morphology can include a trench, often filled, and a complexely deformed accretionary wedge along the lower slope. Examples are the Palawan Trench (Hamilton, 1979), the eastern Luzon Trench (Lewis and Hayes, 1983), the Bering Sea margin (Cooper and others, 1981), and the central California margin (D. McCulloch, personal communication, 1984). If the Transition fault was a subduction zone prior to the Pliocene, subduction related features would then need to be removed by transform faulting after the subduction zone failure.

Since the geophysical and structural data do not provide a definative answer to the pre-Pliocene tectonics of the Transition fault, the answer will probably be derived from more direct evidence than the geophysical data, as, for example, paleomagnetic evidence or geologic correlations of the Yakutat block with other areas of the North America continental margin. The problem of subduction at the Transition fault will be discussed further in a later section.

Tectonic implications.

The structure of the Yakutat segment establishes several tectonic constraints. (1) The Yakutat segment margin, like the southeast Alaska margin, is a tectonically truncated margin, with truncation occurring at the Transition fault. Thus, the Transition fault is a major structural boundary between the segment and the Pacific plate. (2) The Transition fault has been an inactive tectonic feature for at least Pliocene and Quaternary time. Therefore, the Yakutat segment, and hence the Yakutat block, have been moving with the Pacific plate for at least that time. (3) The fault between Icy Point and Lituya Bay forms the only possible zone seaward of the onshore Fairweather fault along which major Pliocene and Quaternary plate motion could be accomodated. (4) The structure of the Yakutat segment shows no evidence for major compressional deformation across, or subduction beneath, the margin. Any motion along the Transition fault prior to Pliocene time was most likely transform motion, rather than convergent motion. (5) The Dangerous River zone marks a major break in basement rocks of the margin, with probable Mesozoic rocks east of the zone, and Eocene oceanic basement to the west. This juxtaposition took place prior to or during the initial stages of deposition of the shelf and slope Paleogene sedimentary sequence. (6) The thick Paleogene strata of the segment were deposited adjacent to a continent. The Dangerous River zone formed the basin edge, and both the Dangerous River zone and the basin axis trend northwest beneath the continental shelf.

Yakataga segment structure

In contrast to the relatively undeformed strata of the Yakutat segment, strata of the Yakataga segment are deformed by northeast trending, broad, open folds and associated thrust faults (Figs. 4 and 17). This deformation is part of a fold and thrust belt that extends from the end of the Fairweather Fault at the head of Yakutat Bay to the Aleutian trench subduction zone south of Kayak Island. Seismicity indicates that the onshore part of this belt is currently accomodating much of Pacific-North America plate motion (Perez and Jacob, 1980; Lahr and Plafker, 1980). What is less clear is how much motion has been accomodated along the offshore part of the belt. Thus, the structure of the Yakataga segment is an important element in determining the movement and tectonic history of the Yakutat block.

Offshore geology

The Cenozoic section of the Yakutat segment is also present beneath the Yakataga segment. The late Miocene and younger section (post-horizon D strata) increases significantly in thickness west of Icy Bay. Structural contours on horizon C (Fig. 17; from Bruns and Schwab, 1983) show a maximum depth to the horizon of about 3 km south of Icy Bay, but up to 5 km between Icy Bay and Kayak Island. This thick sedimentary section obscures seismic reflectors from beneath horizon C, and neither horizon D or seismic reflectors from below horizon D can be accurately mapped beneath the Yakataga segment.

However, other data show that the Paleogene strata of the Yakutat segment are continuous beneath the Yakataga segment. Strata of Paleogene age were sampled at the bottoms of at least five exploratory wells (Herrera, 1978; Jones, 1979), and were recovered in one dredge haul from the continental slope (Plafker and others, 1979). Seismic refraction and reflection data show that the thick Paleogene strata of the Yakutat segment are present adjacent to the easternmost folds of the Yakataga segment south of Icy Bay (see previous section; also Bayer and others, 1978; Bruns, 1983b). These rocks certainly continue beneath the fold belt of the Yakataga segment, and were sampled in the exploratory wells in the adjacent folds. Also, magnetic data (next

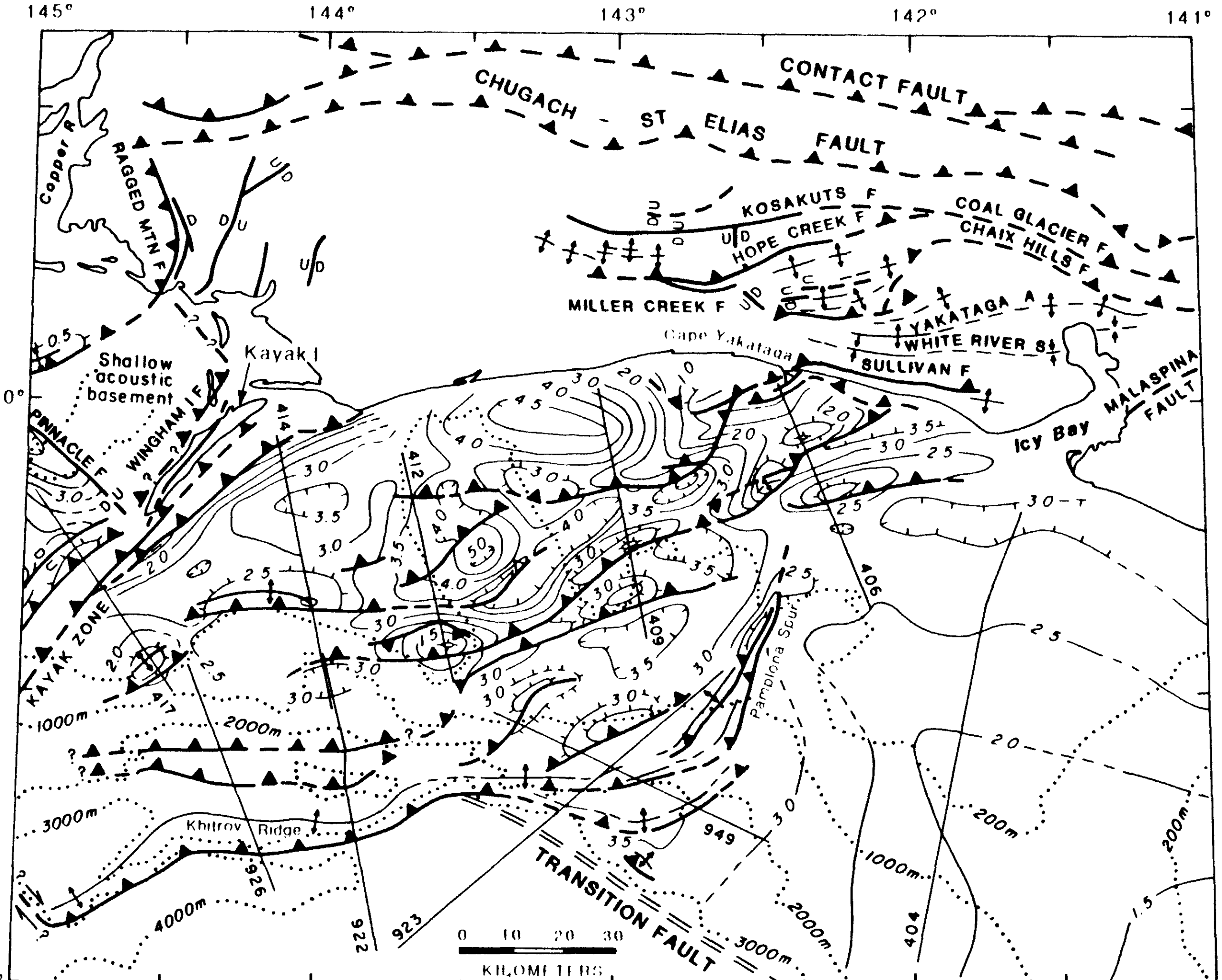


Figure 17. Yakataga segment structure contours in km and trends on seismic horizon C in about middle to late Pliocene strata, from Bruns and Schwab (1983). Contours west of Kayak Island are on seismic horizon M2 at base of late Miocene and younger section; see Figs. 7, 29 and text for further discussion. Numbered lines show location of seismic lines in Figs. 14 and 18-21. Onshore geology from Plafker (1967) and G. Plafker, unpublished data, 1977; bathymetry from Atwood and others (1981). Explanation as in Fig. 8.

section) show that the Slope anomaly, and therefore its associated source body, are continuous from the Yakutat segment through the Yakataga segment.

The Paleogene sedimentary section thins from east to west, from about 4 to 5 km thick south of Icy Bay to 1 to 2 km thick near Kayak Island. Magnetic modeling and refraction data near Kayak Island indicate a 5 to 7 km depth to the basalt source body of the Slope anomaly (next section). The Neogene and Quaternary strata in the area are at least 4 km thick in exploratory wells, and strata of Paleogene age were not reached. The seismic reflection data also indicate about 4 to 5 km of post-Paleogene strata are present (approximately the depth to horizon D; Figs. 18-21). Thus, the Paleogene section is only about 1 to 2 km thick in this area. This westward thinning is in marked contrast to the onshore Paleogene section, which thickens westward from about 1.5 km near Yakutat Bay to 6 to 7.5 km thick north of Kayak Island (Plafker, 1971)

Shelf structure.

The strata of the Yakataga shelf are deformed into numerous, discontinuous broad folds bounded on the seaward side by high-angle, landward dipping thrust faults (Figs. 17-21; Bruns and Schwab, 1983). The width of individual structures ranges from about 4 to 15 km, and closure is present along strike for distances of 15 to 40 km. Dips on the flanks of the anticlines are commonly less than 15°, but locally reach 30° or more. On the mapped seismic horizons, maximum vertical offset on the bounding thrust faults is as much as 1500 m, but is more commonly between 500 and 1000 m, significantly less than is seen on major faults of the adjacent onshore area. Vertical offset on these faults commonly dies out along strike, either terminating or showing only slight offset (less than about 100 m) in between major anticlines. Many of the structures show truncation of strata at the crest of the anticline either at the seafloor (line 406, Fig. 18) or in the subsurface (line 409, Fig. 18). The average trend of the Yakataga folds is about N. 65° E. (Bruns, 1979; Bruns and Schwab, 1983).

The shelf deformation occurred in Pliocene and younger time, and maybe largely during latest Pliocene or Pleistocene time (Bruns and Schwab, 1983). The earliest deformation observed in the seismic data occurs at about horizon C time, or about middle to late Pliocene time. Strata below horizon C are conformable, with no seismic evidence for major unconformities or structural growth below horizon C, or for truncation of strata at horizon C. Instead, post-horizon C strata onlap the horizon, and indicate the initial deformation of the Yakataga segment strata (lines 412 and 414, Figs. 19 and 20). Deformation of the segment has continued to the present, as indicated by uplift and truncation of even the youngest shelf strata at the seafloor (lines 406, 412, 414, Figs. 18-20).

Kayak Island and its offshore extension, the Kayak zone, form a major structural boundary to the shelf strata. Seismic reflectors are abruptly terminated at the Kayak zone (line 417, Fig. 21), and a seismic horizon west of Kayak Island, horizon M2 (discussed later) and approximately age-equivalent to horizon D, outcrops at the seafloor. On line 417, horizon D lies at a depth of 6 to 7 km. Therefore total vertical relief of equivalent age strata across the Kayak zone must be in excess of 6 to 7 km, significantly greater than anywhere on the Yakataga segment (Bruns and Schwab, 1983).

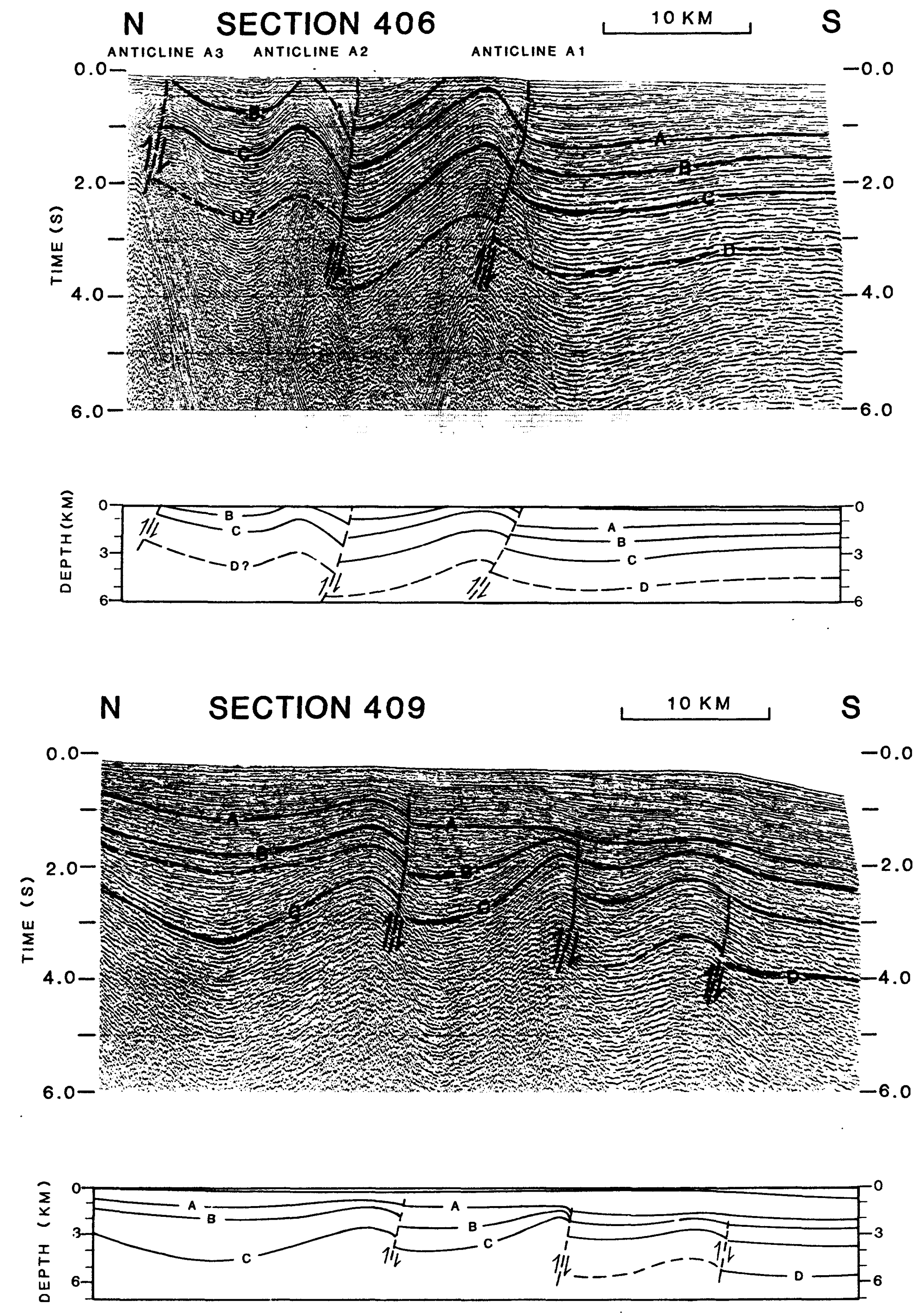


Figure 18. Interpreted seismic sections for lines 406 and 409 with true-scale depth sections, Yakataga segment. Horizon C corresponds to mapped horizon of Figure 17. Horizons A and B are about middle Pleistocene and latest Pliocene respectively (Fig. 7); maps of these horizons are shown in Bruns and Schwab (1983). Horizon D is at the base of the late Miocene and younger Yakataga Formation (Fig. 7). Location of lines shown in Figure 17. V.E. at seafloor 5:1.

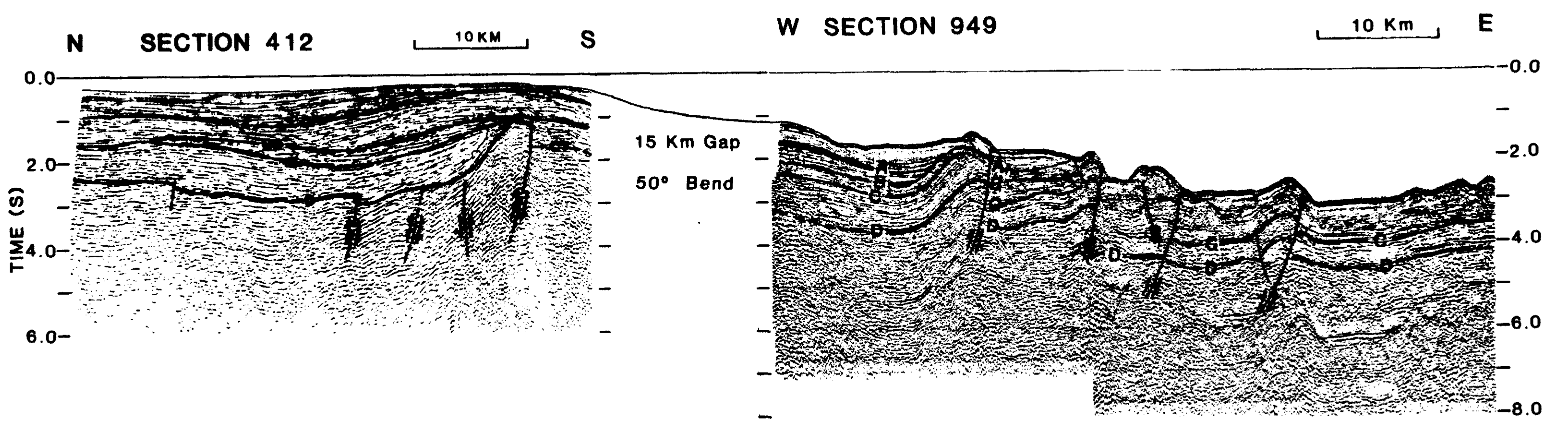


Figure 19. Interpreted seismic sections for lines 412 and 949, Yakataga segment. Horizons U2 is an unconformity within the section and is discussed in Bruns and Schwab (1983); other horizons as discussed in Figs. 7, 18 and text. Location of lines shown in Figure 17. V.E. at seafloor 5:1.

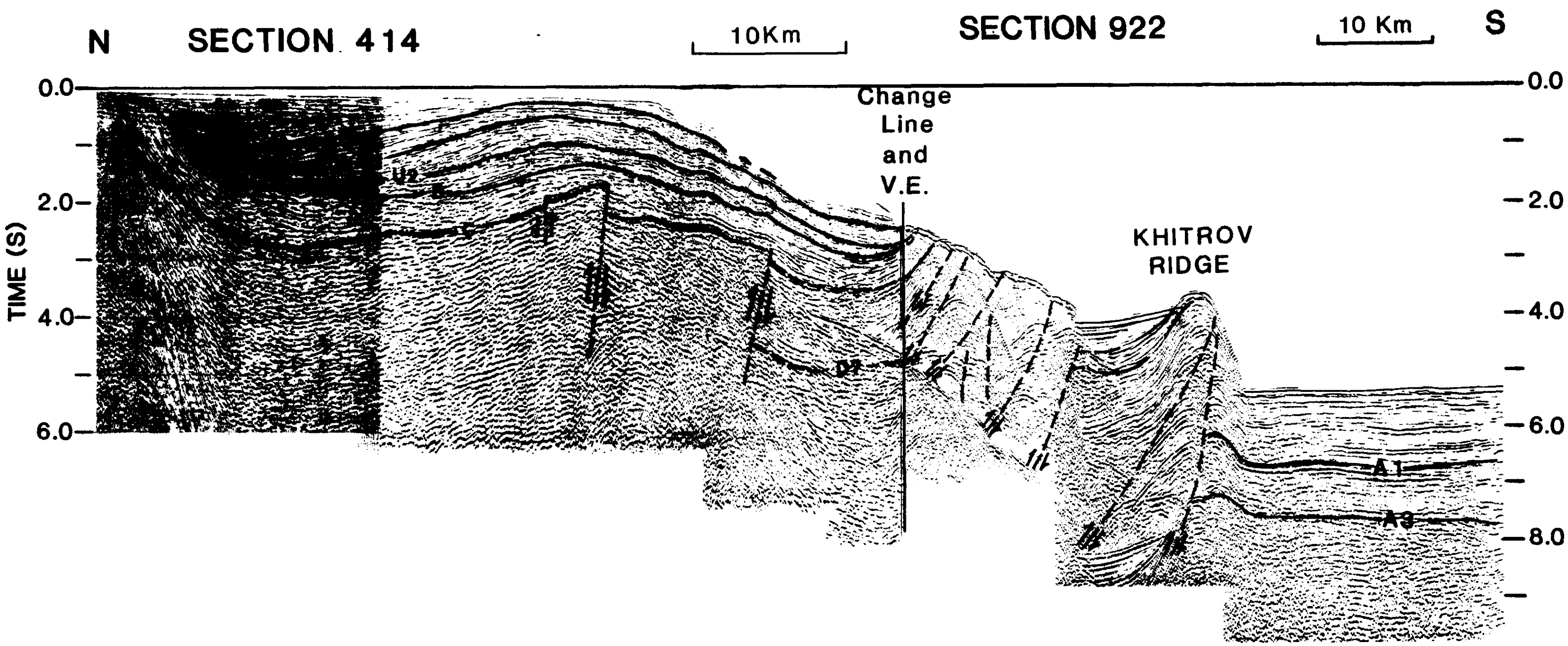


Figure 20. Interpreted seismic sections for lines 414 and 922, Yakataga segment. Horizons U1 and U2 are unconformities within the section and are discussed in Bruns and Schwab (1983); horizons A1 and A3 are base of Pleistocene strata and oceanic basalt respectively; other horizons as discussed in Figs. 7, 18 and text. Location of lines shown in Figure 17. V.E. at seafloor 5:1 for line 414 and 6.7:1 for line 922.

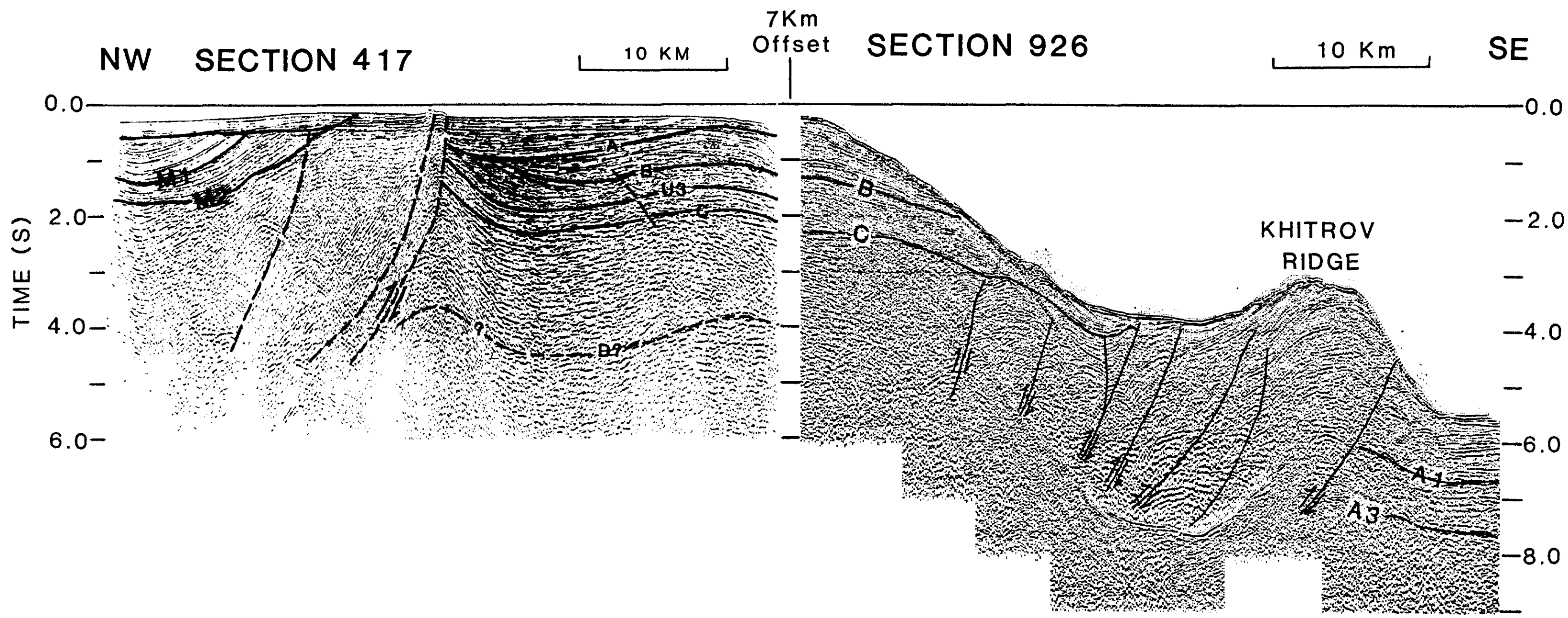


Figure 21. Interpreted seismic sections for lines 417 and 926, Yakataga segment. Horizons as in Figs. 7, 18-20, and discussed in text. Location of lines shown in Figure 17. V.E. at seafloor 5:1.

Slope and base-of-slope structure

The structural continuations of the shelf folds trend obliquely across the slope. These structures often have pronounced bathymetric expression, as for example at Pamplona Spur and Khitrov Ridge (Figs. 17-21; Atwood and others, 1981; Bruns and Schwab, 1983).

Pamplona Spur, a 25 km long, 650 m high ridge south of Cape Yakataga, is underlain by a tightly folded, complex anticline. The major bathymetric expression of the ridge dies out abruptly, but the structural trend of Pamplona Spur continues to the southwest along discontinuous, splaying anticlines (Fig. 17, and line 949, Fig. 19). These anticlines are more open and gently deformed than beneath Pamplona Spur. Deformation of these anticlines is highly variable, as seismic data shows anticlines along the same structural splay may die out or show a marked change in total relief between seismic lines about 10 km apart. The structures within these splays are young, and deform middle and late Pleistocene strata (post-horizon B strata). The more landward structures are currently surrounded and buried or partly buried by sediment prograding across the continental shelf and slope (line 923, Fig. 14 and line 949, Fig. 19).

The largest of the slope structures underlays a major bathymetric high, Khitrov Ridge, at the lower slope south of Kayak Island (Fig. 17 and lines 922 and 926, Figs. 20, 21). Khitrov Ridge is about 70 km long by 12 km wide, with total relief above the adjacent seafloor of up to 2200 m (Atwood and others, 1981). The ridge dies out to the northeast and southwest both as a major structural fold and as a bathymetric feature. The structure is a late Quaternary feature, affecting even the youngest sediment on the flanks of the anticline and in Khitrov Basin, the bathymetric low and structural syncline north of the ridge. Seismic reflectors from the adjacent abyssal section can be traced into or beneath the fold (lines 922 and 926, Figs. 20, 21), and oceanic magnetic anomalies are continuous beneath the fold (discussed later; Schwab and others, 1980). The Khitrov Ridge structure is most likely underlain by uplifted, folded oceanic strata.

Landward of the ridge is a zone of complex faulting and folding that underlies Khitrov Basin and the continental slope north of the basin (lines 922 and 926, Figs. 20 and 21). Deformation in this zone is older than in the structure below Khitrov Ridge, since the structural zone is partially buried beneath prograding shelf and slope sediments. Both of these zones of deformation end abruptly near 59° N., 145° W. where the Aleutian Trench turns northeast along the base of Khitrov Ridge.

Sequential development of folds

The seismic data and the mapped seismic horizons show sequential development of the Yakataga segment folds, with earliest deformation to the northwest and youngest to the southeast (Fig. 22; Rogers, 1977; Bruns, 1979; Bruns and Schwab, 1983).

The oldest structures, developed during about late Pliocene to early Pleistocene time include the landward-most structures of the shelf (Fig. 22). On these structures, seismic mapping and seismic stratigraphic analysis (Bruns and Schwab, 1983), shows that initial growth began about horizon C

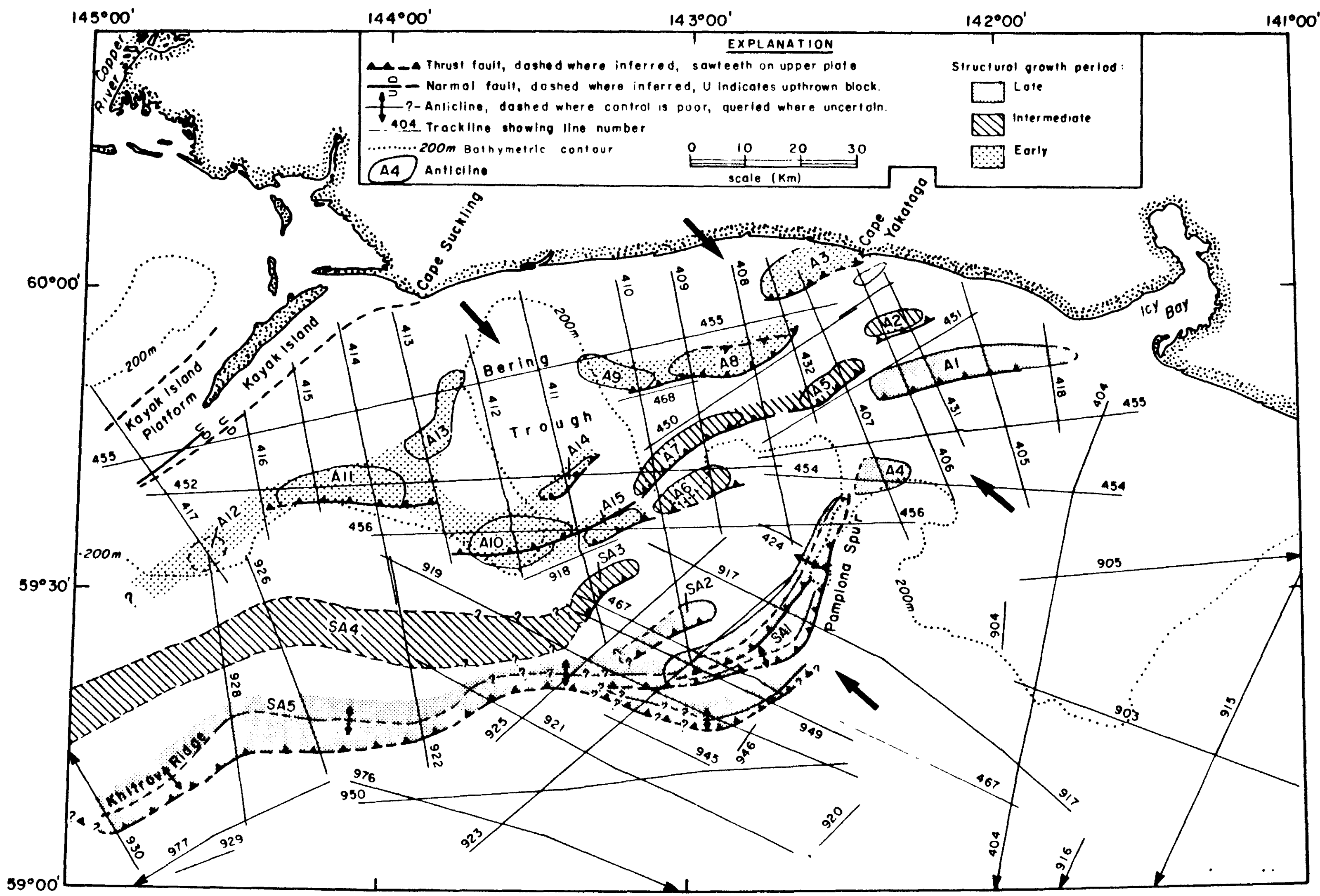


Figure 22. Generalized correlation of structural trends that developed during about the same time period, characterized as early, intermediate, or late structural growth. Overall pattern shows a south-southeastward shift of structural growth over time from oldest to youngest structures. Arrows indicate zones where a significant change in strike or age of structural trends occurs. Numbers on anticlines refer to a more detailed discussion in Bruns and Schwab (1983).

(middle Pliocene to earliest Pleistocene) time, and was followed by subsidence after horizon B (early to middle Pleistocene) time and renewed, more gentle uplift after horizon A (late Pleistocene) time. This sequence of events is best illustrated on line 412 (Fig. 19), and is also seen on line 414 (Fig. 20), where pre-horizon C strata are significantly more deformed than the overlying strata, B-C strata onlap the C horizon, A-B strata are deposited over the anticline, and post-A uplift has gently bowed up the anticline.

Early and middle Pleistocene deformation (B-A time) includes development of anticlines in the central part of the shelf (as for example, the two seaward anticlines on line 409, Fig. 18), and the zone of faulting and folding beneath the slope and basin north of Khitrov Ridge (Fig. 22, and lines 922 and 926, Figs. 20 and 21). Strata at the crest of the shelf anticlines are truncated at horizon A, and buried by up to 2 km of gently dipping, post-horizon A strata. Similarly, the slope structural zone is partly covered by undeformed post-horizon A strata (lines 922 and 926, Figs. 20 and 21, and the westernmost anticline on line 949, Fig. 19).

The youngest deformation, developed during late Pleistocene and Holocene time (post-horizon A time), occurred on the large shelf anticline southwest of Icy Bay (seaward anticline on line 406, Fig. 18), on Pamplona Spur and its structural splays across the continental slope, and on Khitrov Ridge. These structures all deform even the youngest strata of the shelf and slope.

Although the general pattern is clear, the growth patterns on individual anticlines are complex in detail, as for example on lines 412 and 414 (Figs. 19 and 20) where unconformities are developed between the mapped horizons.

The observed deformation has occurred as a continuous, rather than an episodic, process during late Pliocene and younger time (Bruns and Schwab, 1983). For example, on line 409 (Fig. 18), early deformation on the landward structure ceased prior to horizon B time, and truncation occurred within the upper part of the C-B strata (dashed line between horizons C and B). Growth on the center anticline began somewhat before horizon B time, as indicated by thinning in the C-B sequence, and continued through horizon A time, as indicated by truncation of B-A strata at horizon A. Growth on the seaward anticline occurred primarily after horizon B time, with thinning in the B-A sequence, and continued until just after horizon A time, demonstrated by bowing of the A horizon over the anticline. By horizon A time, major growth was beginning on the seaward anticline on line 406 (Fig. 18). Other lines exhibit similar features (Bruns and Schwab, 1983). Thus, continuous growth occurred within the Yakataga segment during post-middle Pliocene time. Compression across the margin, and the tectonic process causing this compression, must also have been continuous during that time.

Structural shortening

The amount of structural shortening across the Yakataga segment folds is a measure of how much Yakutat block-North America or Pacific-North America convergence is taken up along thrusts within the block. The minimum amount of shortening can be determined from the mapped seismic horizons. However, the maximum shortening cannot be determined, since significant imbrication could have occurred on the thrust faults bounding the structures, and not be resolvable on the seismic data.

For the shelf structures, shortening on horizon C is about 2 km due to folding and about 4 km allowing for maximum dip on the faults at horizon C, where dip is constrained by well-defined seismic reflectors on either side of the faults. The amount of shortening on the slope structures is less clear. Neither the positions of the mapped seismic horizons or the amount of imbrication on the bounding faults can be accurately determined. For lines 922 and 926 (Figs. 18 and 19), I estimate that at least 3 to 6 km of shortening has occurred in the folds, based on the dip of observed seismic reflectors and on allowing maximum dip on the bounding faults. Thus, within the resolution of the seismic data, shortening across the Yakataga segment fold belt is at least 10 km, or about 10 percent, since horizon C, or middle to late Pliocene, time.

The maximum amount of shortening offshore may not be much greater than 10 km. Magnetic modeling (next section) and refraction data (Bayer and others, 1978) indicate that the Paleogene source rocks for the magnetic Slope anomaly lie at a depth of around 5 to 7 km south of Kayak Island. Severe imbrication of these rocks would lead to disruption of the magnetic anomaly form or trend; such disruption is not observed. Therefore, a detachment thrust underlying these structures would lie above the Slope anomaly source rocks. Major (tens of kilometers) imbrication along such a thrust would cause thickening of the sedimentary section. Erosion of these thickened strata would then be necessary to maintain the observed strata thickness. Although numerous unconformities are present in the sedimentary section, only at the crests of some anticlines have great thicknesses (1 to 2 km) of strata been removed by erosion. Therefore, major imbrication or underthrusting on the offshore thrust faults seems unlikely.

Tectonic implications

The structural style of the Yakataga segment is that of a decollement fold and thrust belt (Fig. 23). This fold belt has resulted from the continuous southeastward propagation of an evolving deformation front during at least Pliocene and Quaternary time. I infer that a decollement lies above a basaltic basement, where magnetic data indicate the continuity of the Yakutat segment basalts beneath the Yakataga segment (next section). The spacing of the faults, the amount of offset and imbrication on the faults, and the degree of deformation of strata between the faults all increase from south to north across the basin. The maximum deformation occurs adjacent to the Chugach-Saint Elias fault and along the Kayak zone. In these areas, Yakutat block strata are thrust beneath and juxtaposed against Chugach terrane and Orca Group rocks respectively, which have significantly differing ages and geologic histories.

The Yakataga segment deformation reflects at least two processes. First, the overthrusting requires convergence between the Yakutat block and southern Alaska. Second, the depositional history of the Yakutat block has been favorable for creating overpressure within the sedimentary sequence covering the block. A thick Paleogene and early Miocene section has been rapidly covered by thick, impermeable mudstones of the late Miocene and younger Yakataga Formation. Thus, pore water cannot easily move out of the formation, and overpressure within the Paleogene section or within sandstones of the Yakataga Formation provides zones of weakness along which thrust faults can propagate. Indeed, in wells drilled in the Yakataga segment folds, both

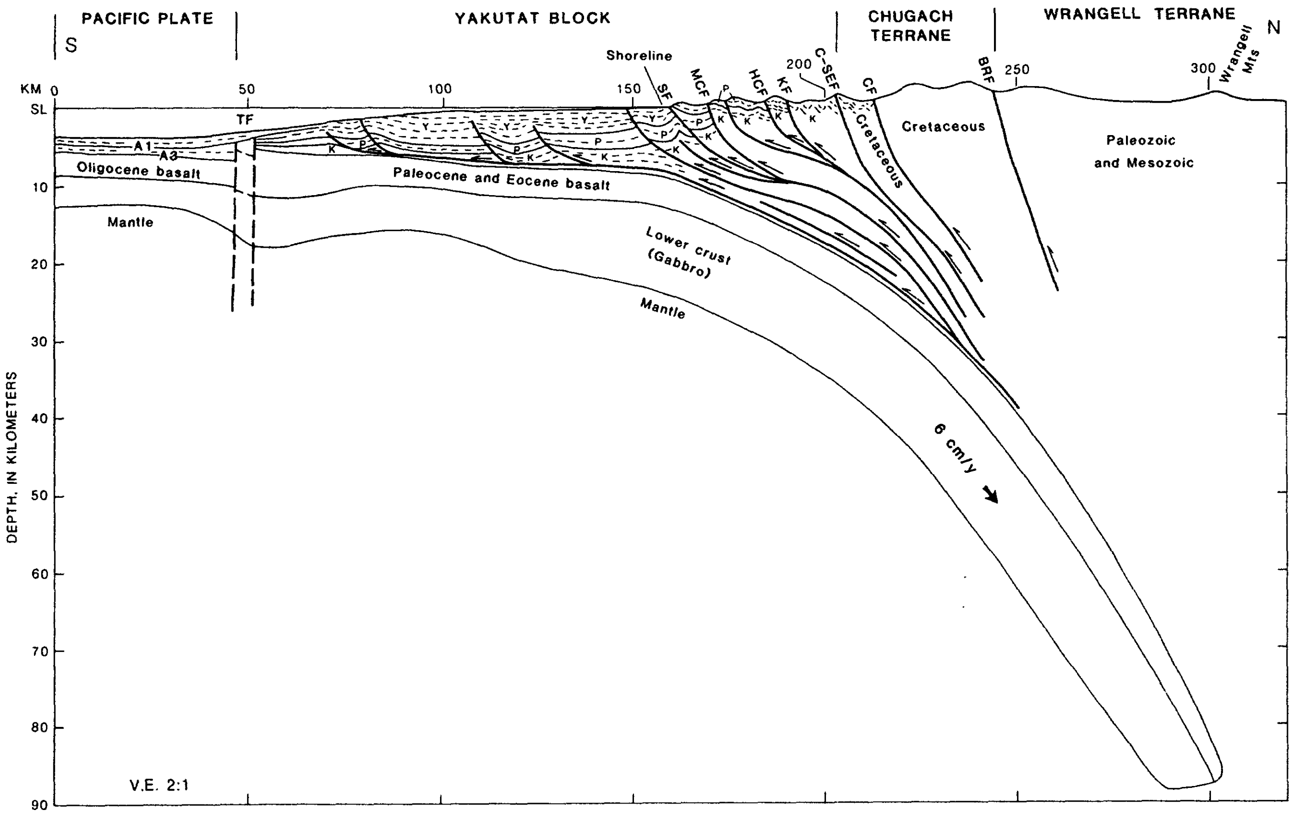


Figure 23. Schematic diagram of the deformation style across the Yakataga segment of the Yakutat block. Deformation results from seaward propagating thrust faults as the Yakutat block moves towards and subducts beneath southern Alaska. The fold and thrust belt is likely underlain by a decollement surface within strata overlying Paleocene and Eocene oceanic basalt. The degree of faulting and deformation increases from south to north, reaching a maximum adjacent to the Chugach-Saint Elias fault. The earliest developed shelf anticlines are covered by undeformed strata of Pleistocene age, as is the Transition fault at the base of the continental slope. Thickness of offshore sedimentary rocks, basalt, and lower crust are based on seismic mapping, seismic refraction data, and gravity and magnetic modeling; section corresponds to cross-section B-B' of Figs. 25 and 29. Onshore structure and sediment thickness is based on cross-section of Miller (1971) which extends north from Cape Yakataga. Position of subducted slab is based on depth of Wrangell Benioff zone of Stephens and others (1984) and on position of active volcanoes of the Wrangell Mountains. Diagram is similar to structural style inferred by Stoneley (1967) and Perez and Jacob (1980). The main difference from the cross-section of Perez and Jacob (1980) is that the Yakutat block is moving with the Pacific plate rather than being underthrust by it. Abbreviations as in Fig. 4 and Y-Yakataga Formation; P-Poul Creek Formation; K-Kulthieth Formation; C-CEF-Chugach Saint Elias Fault; CF-Contact Fault; BRF-Border Ranges Fault; TF-Transition Fault.

abnormally high pore pressures and high northwest-southeast horizontal earth stresses were measured (Hottman and others, 1979).

The fold and thrust belt has developed within strata of the Yakutat block as a result of collision of the Yakutat block and southern Alaska. This is indicated by three considerations. First, the structure of the Transition fault along the Yakutat segment indicates the Yakutat block has moved with the Pacific plate for Pliocene and Quaternary time. Second, the average strike of structures within the Yakataga segment, about N. 65^{o} E. (Bruns and Schwab, 1983), is almost perpendicular to the convergence direction between the Pacific and North America plates, suggesting this convergence is the cause of the deformation. Third, the structures have developed along the northwest part of the Yakutat block, the zone of maximum convergence between the block and southern Alaska as the block moves northwest with the Pacific plate (Fig. 4). To the southwest, convergence is largely accomodated by strike-slip faulting along the Fairweather Fault. Thus, deformation of the Yakataga segment is a result of thrusting within strata of the Yakutat block as the block moves with the Pacific plate towards, and subducts beneath, southern Alaska (Fig. 23).

Magnetic and gravity data

Interpretation of magnetic and gravity data adds more information about the seaward limit of the Yakutat block, the character of the transition from oceanic crust to Yakutat block crust at the Transition fault, and the character of the Yakutat block basement and lower crust. The magnetic data indicate that the Yakutat block is a continuous geologic terrane, and suggest the block lies in the subducted plate between Kayak Island and the Kenai Peninsula.

Magnetic data--the Slope anomaly.

Magnetic anomalies in the northern Gulf of Alaska are divisable into two distinct types separated by a linear magnetic high (Fig. 24; Naugler and Wageman, 1973; Taylor and O'Neill, 1978; Schwab and others, 1980). The northern group is characterized by low amplitude anomalies and is associated with the continental shelf. The southern anomalies are oceanic magnetic anomalies 7 through 20, ranging in age from 25 my (anomaly 7) on the east off Fairweather Ground to 46 my (anomaly 20) on the west (Naugler and Wageman, 1973; LaBrecque and others, 1977; Schwab and others, 1980). The three western anomalies (anomalies 18 through 20) have been subducted with the Pacific plate beneath the continental margin west of Kayak Island (Schwab and others, 1980).

The two anomaly patterns are separated by a linear magnetic high, the Slope anomaly, which trends northwest over the continental shelf and upper slope for approximately 330 km from south of Yakutat Bay to Kayak Island, and continues westward at least 160 km across the continental shelf to Montague Island and possibly 220 km to the Kenai Peninsula (Fig. 24). The western part of the Slope anomaly, as well as the adjacent, subducted oceanic anomalies, are characterized by significantly lower amplitudes (more than 100 nT lower) than are seen to the east.

The Slope anomaly is disrupted at its intersections with the low amplitude continental shelf anomalies along the segment from Fairweather

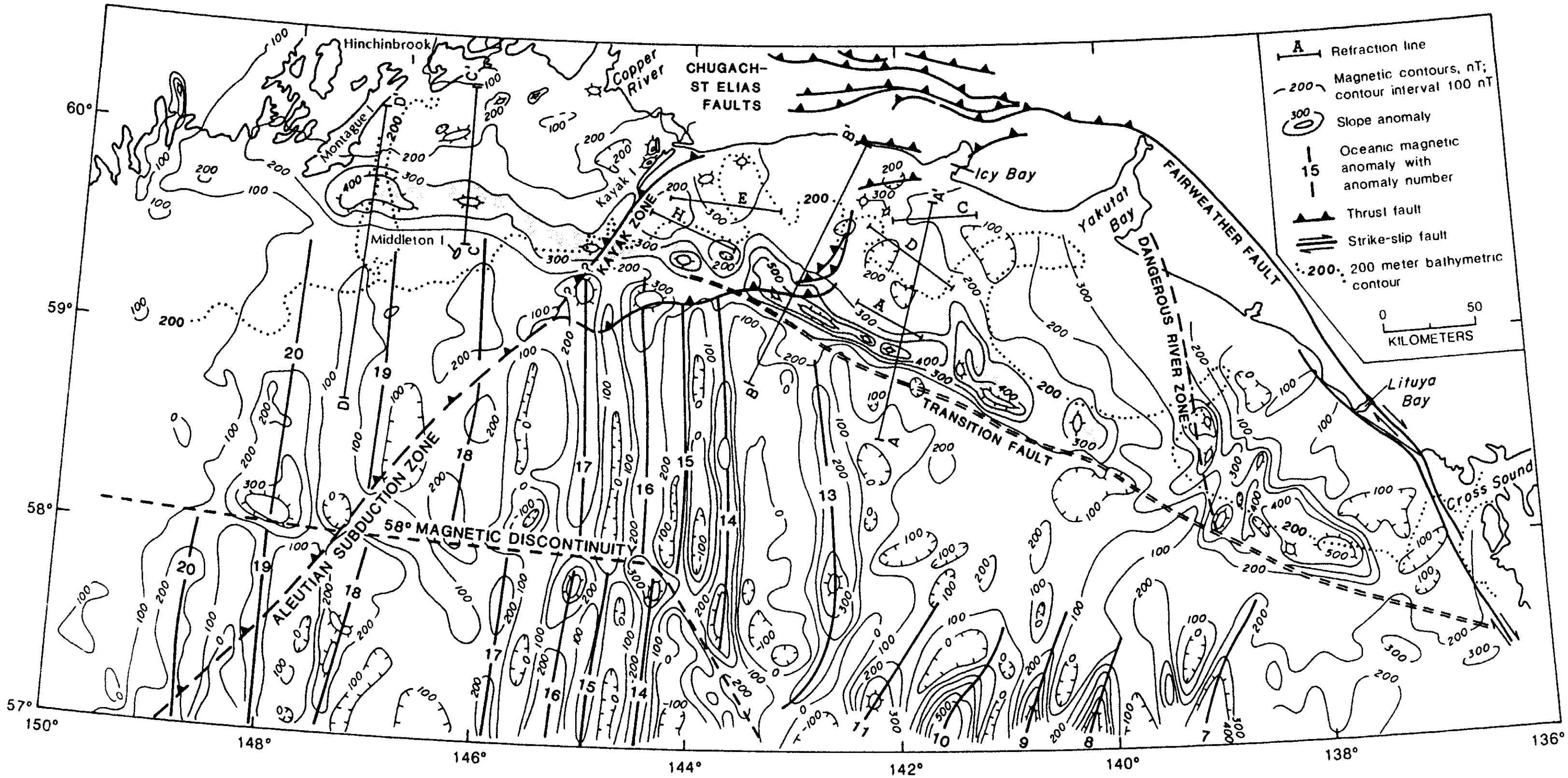


Figure 24. Residual magnetic map of the northern Gulf of Alaska with major tectonic features superposed; from Schwab and others (1980). Cross sections correspond to models shown in Figures 25 and 26. Refraction line locations are for data of Bayer and others (1978); bathymetry from Atwood and others (1981).

Ground to Kayak Island. The shelf anomalies do not correspond to late Cenozoic structures (Miocene and younger), but are associated, at least in part, with structural breaks in the underlying rocks. Thus, the source body for the Slope anomaly is of pre-late Cenozoic age, and is within rocks of the continental shelf and slope (Schwab and others, 1979, 1980; Bruns and others, 1979) The source body is almost certainly the basalt sequence sampled at the continental slope by Plafker and others (1980).

If the Yakutat block has been moving with the Pacific plate during Pliocene and Quaternary time, as suggested by the seismic reflection data interpretation, then the source rocks for the Slope anomaly should be in the subducting plate west of Kayak Island. The equal attenuation of the Slope anomaly and the adjacent subducted oceanic anomalies suggests that this is indeed the case. At the current Pacific-North America convergence rate (6 cm/yr), the observed 220 km of subduction required 3.7 m.y. (Bruns and others, 1979; Schwab and others, 1979, 1980)

<u>Magnetic models.</u>

Modeling of the Slope anomaly shows that the anomaly most likely arises from a significant increase in the thickness of source rocks at the Transition fault relative to the adjacent ocean plate rocks.

Magnetic models of the Slope anomaly were constructed along four cross-sections, A-A' through D-D' from east to west, respectively (Fig. 24). The eastern two cross-sections lie on the Yakutat block; the western two on the Middleton segment, west of Kayak Island, over the attenuated part of the anomaly. Locations were chosen to avoid major areas of disruption of the anomaly, and, for the two eastern models, to lie near refraction profiles (Bayer and others, 1978) and seismic reflection profiles that provide good subsurface control.

Models east of Kayak Island provide information on the possible shape and thickness of the source rocks. Models west of Kayak Island indicate that the source rocks can lie in the subducted plate.

<u>Assumptions</u>. Magnetization is assumed to be induced; no data are available on whether a remnant magnetization is present in the source bodies.

The magnetic susceptibility for the Pacific plate basalts is assumed to be .005, a value that is typical for oceanic basalts. The magnetic susceptibility of the Yakutat block basalts is assumed to be .0055, the maximum value measured on the basalts dredged along the continental slope (Plafker and others, 1980). The value of .0055 is higher than the average measured value of about .003, but reasonable if the susceptibility of the dredged basalts is assumed to be reduced by weathering at the continental slope. With a regional field of 0.54 Oe, the assumed susceptibilies give magnetizations of .0027 emu/cc and .003 emu/cc for oceanic and Yakutat block basalts respectively.

A seaward-decreasing regional gradient was visually determined for each area from magnetic anomaly profiles. For cross-sections A-A' and B-B', the average regional gradient is 1.5 nT/km, and for C-C' and D-D', 0.8 nT/km. The effect of removing the regional gradient is that the Slope anomaly source body thins landward; otherwise, the body maintains about the same thickness as at the Transition fault.

Refraction data of Bayer and others (1978) provide control on the depth to the probable Slope anomaly source body. Refraction lines E and H, west of section B-B' (Fig. 24) show a landward dipping body with velocities of greater than 5 km/s lying at a depth of 5 to 7 km (Fig. 25). This body overlays a 7 km/s layer at a depth of about 11 km. The 6 km thick, 5 km/s body is assumed to be the source body, as such a velocity is typical of basalts. This body is projected onto section B-B' (Fig. 25).

Refraction data over section A-A' (Fig. 24) do not show a 5 km/s body, but show a landward-dipping layer of 7 km/s at a depth of 6.5 to 10 km (Bayer and others, 1978; Von Huene and others, 1979). I assume that a thin (2 to 3 km thick), 5 km/s layer is present, since dredged rocks from the slope included basalts. The layer may be too thin to be observed in the refraction data, possibly because the shot interval was too wide to adequately define first arrivals for the layer. I assmue that the magnetic source body top lies at or near the 7 km/s layer; the depth to the top is consistent with the acoustic basement seen on seismic reflection data over the continental slope and outer shelf.

For cross-sections A-A' and B-B', the depth to the oceanic basalt adjacent to the Transition fault is controlled by seismic reflection data.

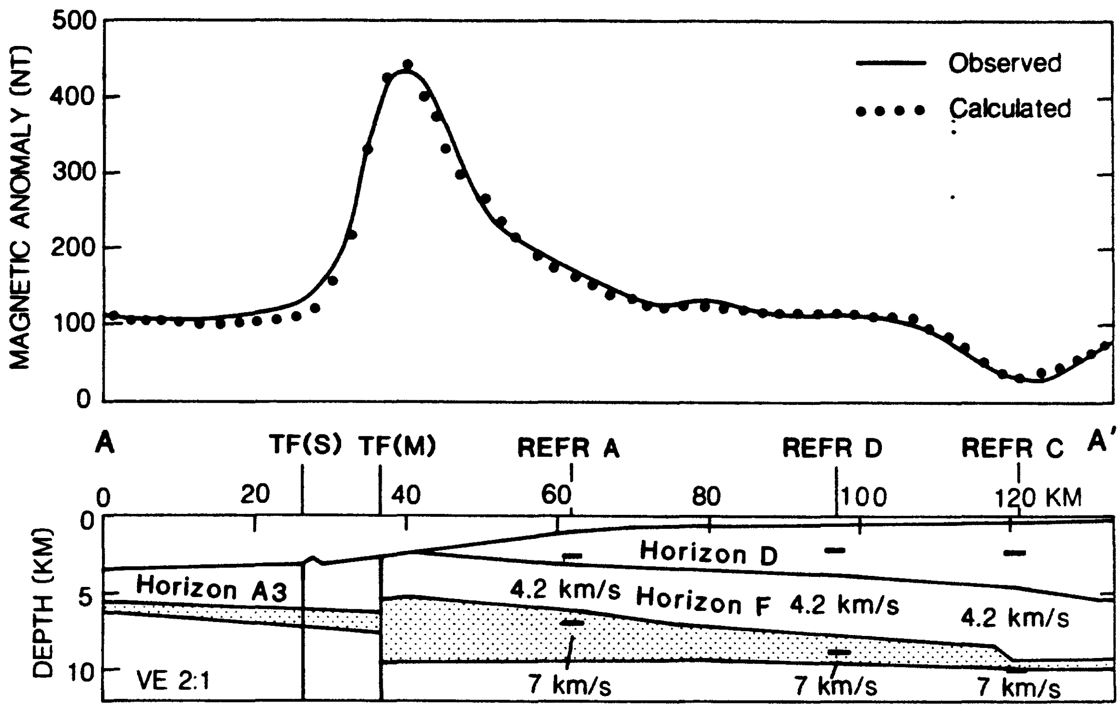
No refraction data are available over cross-sections C-C' and D-D', and there are no constraints on the depth to or thickness of the Slope anomaly source rocks. For these cross-sections, a model similar to B-B' is assumed, and the depth changed to provide an estimate of whether the source body can lie in the subducted plate.

The models assume that the source bodies are two-dimensional. Modeling was performed with a program written by Saltus and Blakely (1983).

Results. Modeling on cross-sections A-A' and B-B' shows that the Slope anomaly is due to greatly increased thickness of magnetic rocks north of the Transition fault relative to those south of the fault.

Models for cross-sections A-A' and B-B' (Fig. 25) show an anomaly-causing body 4 to 6 km thick at the Transition fault that dips and thins landward. Ocean plate rocks thicken slightly towards the fault, to about 1.5 km thick. The upper boundary of the Slope anomaly source body is consistent with the depth to the continental slope Eocene basalts as shown by dredge, refraction, and seismic reflection data. On cross-section B-B', the thickness of the modeled layer is also consistent with the thickness of the 5.5 km/s layer seen in refraction data. Therefore, with the stated assumptions, the Slope anomaly is caused by an approximately 4 to 6 km thick basalt layer that is juxtaposed against a 1.5 km thick oceanic basalt layer at the Transition fault.

The Transition fault extends landward in a 6 to 10 km wide fault zone along at least part of the margin. The position of the fault determined by seismic reflection data does not coincide everywhere with the basalt thickness change required by magnetic modeling of the Slope anomaly. East of about 59° N., 141° 30' W. (Fig. 15), the positions determined by the two methods are the



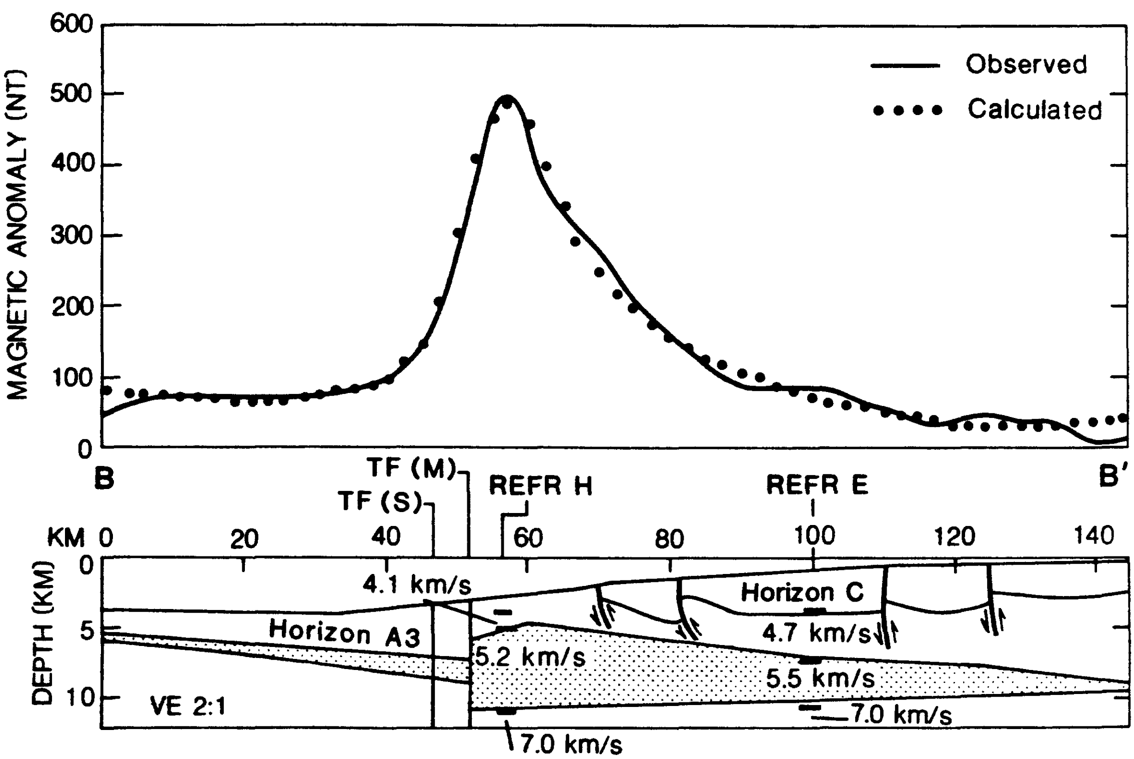


Figure 25. Magnetic models for cross-sections A-A' (top) corresponding to seismic section 404, Figure 14, and B-B' (bottom) across Yakutat block; locations shown in Figure 24. Observed magnetic anomaly curve has a regional trend removed; see text for discussion. Shaded block corresponds to modeled magnetic body. Location of refraction data and Transition fault as determined by seismic data, TF(S), and magnetic data, TF(M), shown at top of section; shallow refraction horizons (velocity less than about 5 km/s) not shown. Labeled horizons correspond to mapped seismic horizons of Figures 8, 9, and 17. Slope anomaly in this model arises from truncation of thick volcanic sequence at the Transition fault.

same. West of this position, the Slope anomaly transition occurs about 6 to 10 km landward of the seismically mapped position of the Transition fault (Fig. 25), with magnetic modeling indicating a thin or low susceptibility magnetic layer underlying the area between the two positions. This area also correlates to the zone where no reflections are seen on the seismic reflection records (see line 404, Fig. 14). This 6 to 10 km wide zone could be an area of deformation associated with tectonism along the Transition fault.

Subduction of the Slope anomaly

Interpretations of seismic reflection data across the Transition fault suggest that the Yakutat block and the Pacific plate have been locked during Pliocene and Quaternary time and subducting along the Kayak zone. Thus, the Slope anomaly source rocks would lie in the subducted plate west of Kayak Island. The attenuation of both the Slope anomaly and the oceanic anomalies also suggests subduction. Therefore cross-sections C-C' and D-D' provide a test of whether the Slope anomaly can lie in the subducting plate.

Models similar to B-B' were calculated for various depths, to match the magnetic anomalies on cross-sections C-C' and D-D'. The range of depths for which model fits can be obtained is large; the main requirement with increasing depth is a greater thickness for the Slope anomaly source body. For a maximum thickness of 6 km, as modeled on cross-section B-B', the upper boundary for models on C-C' and D-D' would lie at a depth of 6 to 7 km. If the maximum thickness is allowed to increase slightly to 7 to 8 km, then the top of the source body can lie at a depth of about 9 km; these models are shown in Fig. 26. Since both the thickness and susceptibility of the Slope anomaly source body can be variable, additional information, from seismic refraction or reflection data is necessary to determine the actual depth to the anomaly causing body. The main point of the models on cross-sections C-C' and D-D' is to determine if the source body can lie in the subducting plate.

The determination of whether or not the Slope anomaly is subducted is critically dependant on the dip of the subducting plate. The dip of the initial 150 km of the subducting plate along the northern Aleutian trench is not well determined. The Benioff zone dips gently beneath the shelf and slope, as shown by hypocenter and geologic cross-sections in the area of Prince William Sound (Plafker and others, 1982a) and near Kodiak Island (Von Huene and others, 1978, and in press). On these cross-sections, dip changes continually northward along the downgoing plate, but averages 3^{o} to 5^{o} for 275 km landward from the trench, depending on which hypocenters are used to define the downgoing plate. Within 50 km of the trench, the dip of the subducting plate may be as little as 1^{o} to 2^{o}, based on the depth to the downgoing oceanic basalt layer on seismic reflection data (Plafker and others, 1982; Von Huene and others, 1983) and about 2^{o} based on the depth to a 7 km/s velocity layer on seismic refraction data off Kodiak Island (Shor and Von Huene, 1972). Fisher and others (1983) find deep reflectors on seismic reflection data near Kodiak Island that could be from the downgoing plate; if so, the average dip for 275 km landward of the trench is 2^{o}. Further to the south, the dip of the Benioff zone beneath the Shumagin Islands averages 3^{o} for 110 km landward of the trench (Reyners and Coles, 1982). Thus, reasonable estimates of the dip of the subducting plate in the vicinity of the Slope anomaly range from 2^{o} to 5^{o}, but data do not permit a more precise estimate.

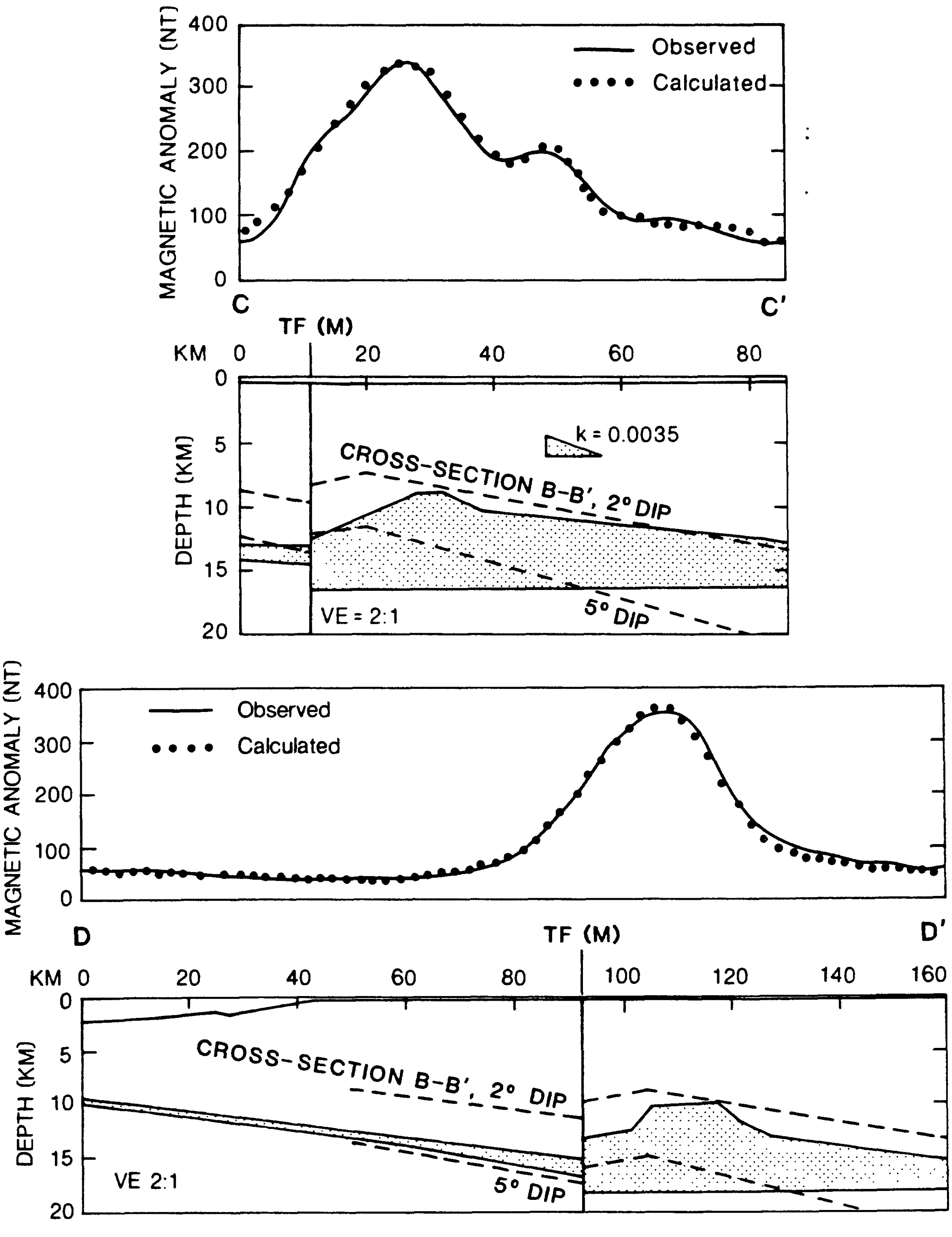


Figure 26. Magnetic models for cross-sections C-C' (top) and D-D' (bottom) across Middleton segment; locations shown in Figure 24. Observed magnetic anomaly curve has a regional trend removed; see text for discussion. Shaded block corresponds to modeled body. Dash lines show projection of the top of the source body modeled on cross-section B-B', assuming subduction at 2° and 5° angles beginning at the Aleutian Trench and the Kayak zone. For 2° to 3° dip, magnetic bodies can lie in the subducted plate. See text for discussion.

Using 2° and 5° dip estimates, the depth to the top of a subducted model B-B' magnetic body is shown on cross-sections C-C' and D-D' (Fig. 26). The projection assumes subduction begins at the Aleutian trench and along the Kayak zone, with depths as determined on model B-B', and occurs in a direction of N. 20° W., the Pacific-North America convergence direction near Kayak Island (Minster and Jordan, 1978).

A comparison of the magnetic models for cross-sections C-C' and D-D' with this projection shows that reasonable models for the Slope anomaly source rocks can lie within the subducting plate for 2° to 3° dip, but are substantially above the subducting plate for 5° dip. The source body could lie below the 5° dip line only if the body had a substantially greater susceptibility or were much thicker than modeled on cross-section B-B'. The magnetic models for the Slope anomaly are consistent with a source body that lies within the subducting plate, but substantially more data are needed to determine the actual configuration and depth of the source body.

Gravity data

Free air gravity anomalies (Fig. 27, Burkhard and others, 1980a, b; Bruns and others, 1981a, b) are primarily associated with major bathymetric features that obscure the anomaly component caused by density changes in the underlying rocks. Seismic reflection and refraction data provide control on thickness and density of the sedimentary rocks of the shelf and at the base of the slope. Thus, gravity modeling can provide constraints on the lower crust and mantle of the Yakutat block, and on the density distribution of rock types juxtaposed across the Transition fault.

The free-air gravity anomalies are characterized by a regional low at the base of the slope, with values as low as about -85 mgal off Fairweather Ground and the Bering Trough, and a regional high along the edge of the shelf, with maximum values as high as 137 mgal over Fairweather Ground, decreasing to about 75 mgal south of Icy Bay and Kayak Island. Landward of the shelf edge, the free-air gravity field decreases rather uniformly towards the coast to a low of -90 mgal near Dry Bay, about -60 to -20 mgal from Yakutat Bay to Kayak Island, and about -5 mgal west of Kayak Island. The main disruptions to the regional gradients are in the areas of bathymetric highs at Pamplona Spur, Khitrov Ridge, and Yushin Ridge.

Gravity models. Three gravity models were constructed; two correspond to the magnetic cross-sections A-A' and B-B', and the third, E-E', is across the margin south of Yakutat Bay (Fig. 27). As with the magnetic models, seismic refraction data (Bayer and others, 1978; Von Huene and others, 1979) and reflection profiles (Bruns and Schwab, 1983; Bruns, 1983b and this report) provide control on upper layer depths and thicknesses, and on depth to the mantle on the ocean plate (Von Huene and others, 1979). Gravity values for profiles A-A' and E-E' were taken from shipboard acquired values (and correspond to seismic sections 404 and 403 respectively, Figs. 14 and 13), and for profile B-B', from Burkhard and others (1980). The basement layer is herin considered to be the layer with a velocity of 5.5 km/s and a density of 2.65 gm/cc; the lower crustal layer as having a velocity of 7 km/s and a density of 2.9 gm/cc, and mantle as having a velocity of 8 km/s and a density of 3.3 gm/cc.

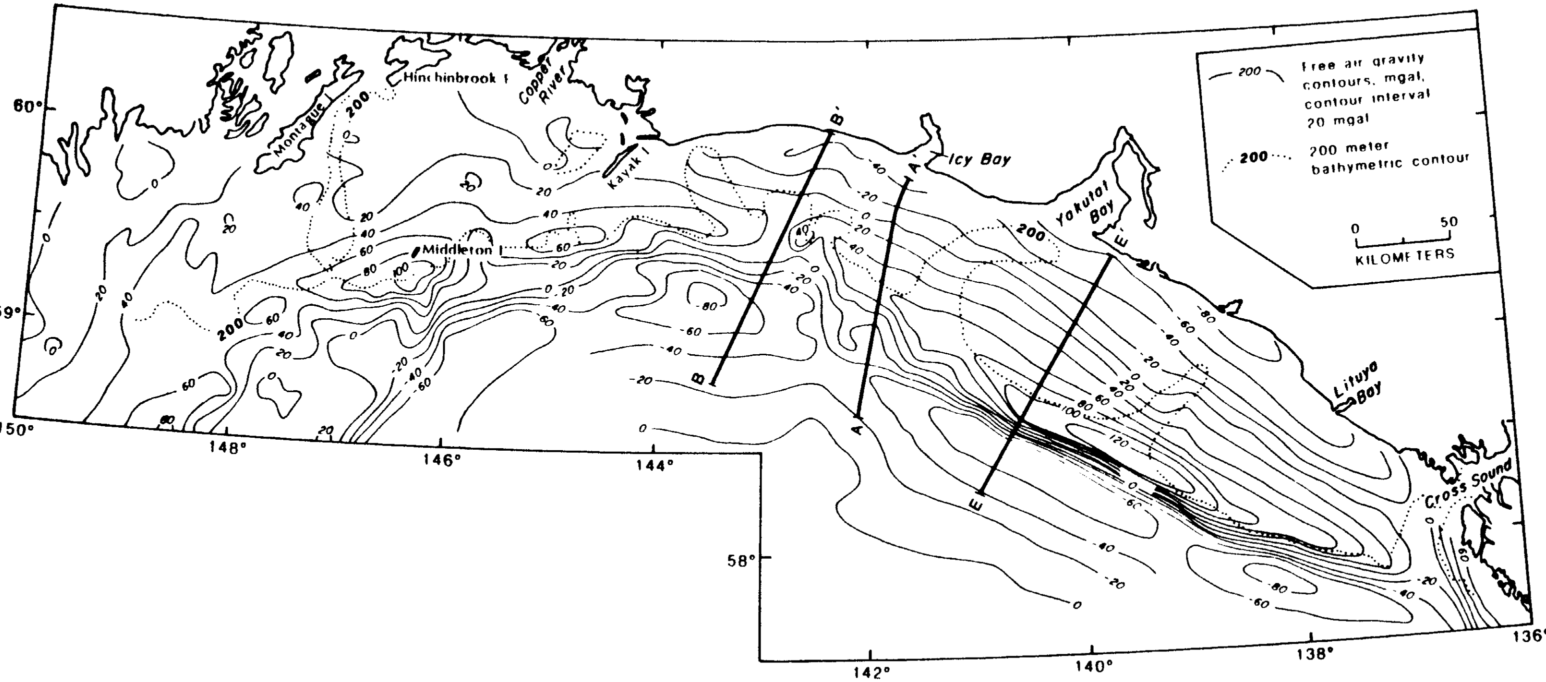


Figure 27. Free-air gravity map of the northern Gulf of Alaska from Burkhard and others (1980a, b) and Bruns and others (1981a, b). Bathymetry from Atwood and others (1981). Cross sections correspond to models shown in Figures 28 and 29.

Assumptions. The modeling assumes that structures are two-dimensional and that the methods of Talwani and others (1959) can be used to compute the gravity anomalies. Densities were obtained from seismic velocities using the Nafe-Drake curve (Ludwig and others, 1970). I also assume that the free air gravity anomalies are caused by density variations above a uniform compensation depth of 30 to 40 km. If mantle densities differ across the Transition fault, the density beneath the older Yakutat block would likely be slightly greater than beneath the younger Pacific plate. This would in turn require a thicker lower crustal layer than shown in the models.

Refraction data of Von Huene and others (1979) provide control on the thickness of the basalt layer and the mantle for the oceanic section south of Yakutat Bay. At the base of the slope, near cross-section E-E', oceanic basalt (velocity of about 5.5 km/s) ranges from 2.8 to 3.8 km thick, and thins seaward to about 1 km thick, 100 km from the base of the slope. The lower crustal layer (velocity of 7 km/s) is between 4.5 and 6.5 km thick, thinning to 3 to 5 km thick 100 km from the base of the slope. Based on these data, the seaward end of section E-E' has a basement layer about 3.5 km thick, and lower crustal layer about 4 km thick. These values are assumed for the seaward end of the other two profiles as well.

The oceanic section is the only one on which refraction data define the thickness of the lower crustal layer and the depth to the mantle. Thus, the seismically determined section at the seaward end of each profile is used as the standard reference for each of the gravity models, against which the rest of the model is balanced. This standard reference also makes the gravity models comparable to each other--that is, changes in basement and lower crustal layer thickness from model to model are related to the observed gravity values and crustal layer thicknesses, and not to an arbitrary datum change. If the reference section does vary from model to model, however, the overall effect is relatively minor, since any change in thickness of the reference section layers can be accomodated by a similar change in the same layer in the rest of the model.

Further assumptions are line specific. On section A-A', as on the magnetic models, I assume that a 5 km/s layer (basement layer) is present and further assume that it is 2.5 km thick. Since basalts were recovered from the continental slope near the modeled cross-section, this assumption appears to be justified. If this layer were assumed to be of lower crustal density instead, the crust/mantle boundary would be about 1.2 km deeper than in the model.

On the lower slope part of section A-A', a small gravity high of about 18 mgal is present (Figs. 27, 28). This high is part of a local anomaly associated with a linear bathymetric ridge that ends about 5 km west of the line. I assume that the local gravity high reflects the subsurface continuation of this bathymetric ridge. Therefore, I first present models that match the regional field, and then show models which suggest the cause of the local gravity high.

On section B-B', the thickness of the basement layer is assumed to be the same as discussed under the magnetic model for this cross-section.

On section E-E', no refraction data are available for the shelf segment

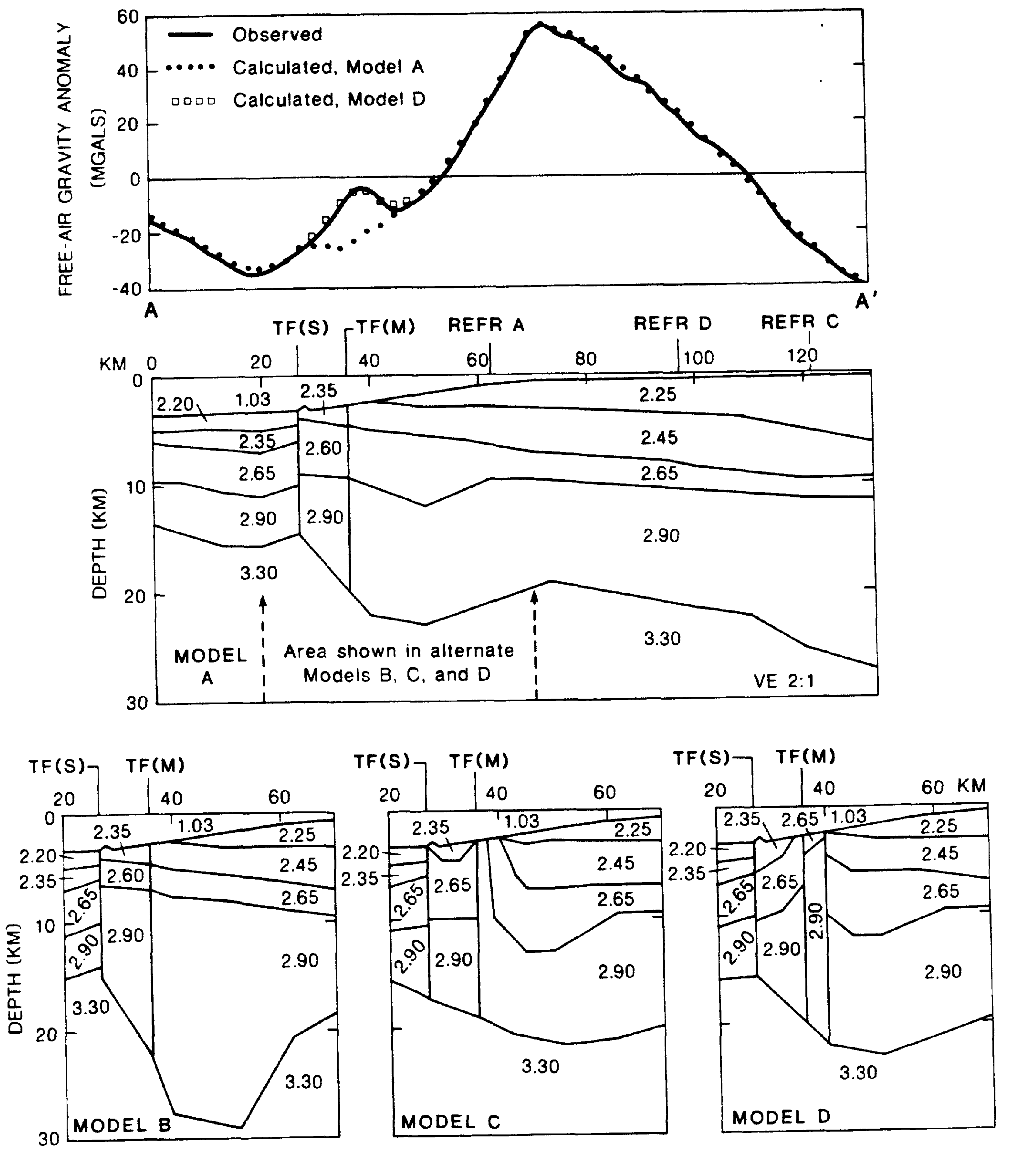


Figure 28. Gravity models on cross section A-A' (corresponding to seismic line 404, Figure 14); location shown in Figure 27. Density in gm/cc shown for each layer is derived from refraction and reflection velocities and the Nafe-Drake velocity-density curve (Ludwig and others, 1970). Configurations of layers above the 2.65 gm/cc basement layer are based on mapping on seismic reflection data. Models A and B match the regional gravity gradient, and ignore the local gravity high between 30 and 50 km. Alternatives are model A, a thickened basement layer (density = 2.65 gm/cc), or model B, a thickened lower crustal layer (density = 2.9 gm/cc). Models C and D match the local gravity high and require a near surface high density layer in the Transition fault zone. See text for further discussion of models.

of the model. The basement layer is therefore assumed to be 3.5 km thick, as seen on refraction line E-E' of Bayer and others (1978). If a different thickness is used, the crust/mantle boundary moves about 0.5 km shallower or deeper for each kilometer that the basement layer is thickened or thinned respectively. The basement layer on this cross-section must be at least 1.5 km thick at the shelf edge, as determined by dredging results of Plafker and others (1980).

Results. Gravity models show that the outer shelf and upper slope of the Yakutat block are characterized by a mass deficiency relative to the adjacent ocean plate and continental shelf. The models require either a thickened basement layer (density of 2.65 gm/cc) or a thickened lower crustal section (density of 2.9 gm/cc). When the gravity models are combined with magnetic models and refraction data, the resulting preferred gravity model has a thickened basement layer. With the thickened basement layer model, the gravity modeling then defines a secondary requirement that the lower crust of the Yakutat block thins to the west, changing from a continental-like thickness to an oceanic-like thickness from east to west.

The geometry of the upper crustal layers is defined by seismic refraction and reflection data except along the Transition fault. The major variables in the models are therefore the thickness of the lower crustal layer below the shelf and slope, and the thickness of the basement layer where this thickness is not controlled by refraction data, primarily below the outer shelf and slope.

Modeling on cross-section A-A' (Fig. 28) illustrates the main requirement of a mass deficiency below the outer continental shelf and slope. If a uniformly thick basement layer is assumed, then the slope is underlain by a lower crustal layer that doubles in thickness from 10 km beneath the shelf to over 20 km below the slope (Fig. 28b). Alternatively, if a relatively constant thickness lower crustal layer, 10 to 12 km thick, is assumed, then the basement layer thickens from 2.5 km below the shelf to 6 km below the slope (Fig. 28a). A thickened basement layer agrees with the magnetic modeling, and also agrees with the refraction thickness of this layer as found by Bayer and others (1978) near Kayak Island. Thus, my preferred interpretation is that the basement layer is 2.5 km thick beneath the shelf, and thickens to 6 km beneath the slope (Fig. 28a). This geometry for the basement layer is also used for models on cross-sections B-B' and E-E' (Fig. 29).

With this preferred model for the basement layer, the gravity models require that the lower crustal layer below the shelf and slope thins markedly from east to west. On model E-E' (Fig. 29), the lower crustal layer is 15 to 17 km thick nearshore, maintains this thickness to midshelf, then thins to 11 km at the Transition fault. However, on model A-A', the layer thins from 15 km near shore to 10 to 12 km within about 20 km, and maintains this thickness to the Transition fault (Fig. 28a). On model B-B', the layer thins even more, from 14 km nearshore to 6 km beneath much of the shelf and slope (Fig. 29). On model B-B', the thickness of the lower crustal layer, from about mid-shelf to the Transition fault, is similar to that of the adjacent ocean plate lower crustal layer. Thus, the the crust of the Yakutat block crust thins westward to an oceanic-like thickness.

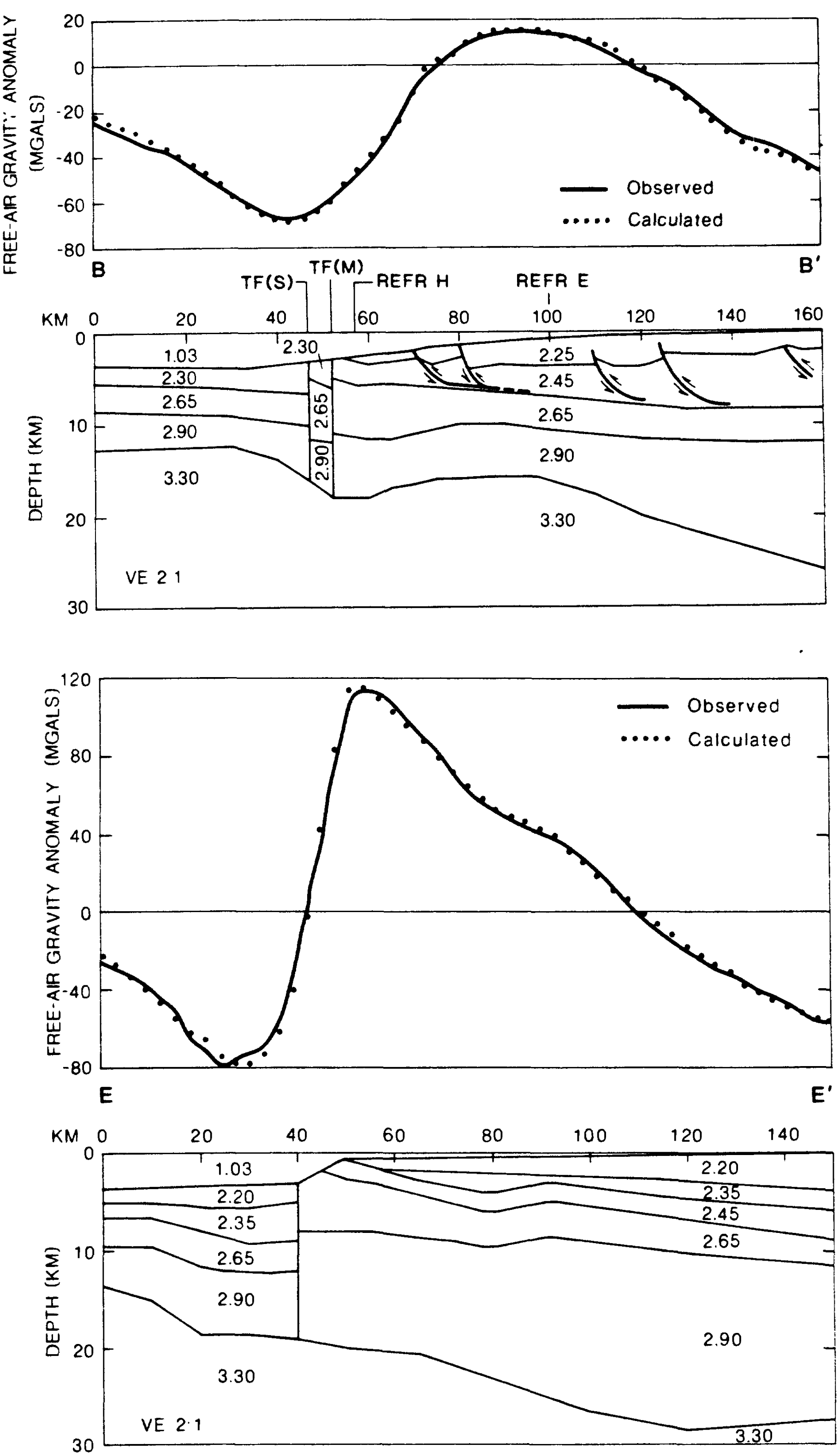


Figure 29. Gravity models on cross-sections B-B' (top) and E-E' (bottom; corresponding to seismic section 403, Figure 13); location shown in Figure 27. Configurations of layers above 2.65 gm/cc basement layer are based on mapping on seismic reflection data. Density in gm/cc shown for each layer. Structure on section B-B' from Figure 17.

As previously discussed, seismic reflection data and magnetic data define a 6 to 10 km wide fault zone along the transition fault on cross-sections A-A' and B-B'. The gravity anomaly across this zone can be modeled with basement and lower crustal thicknesses similar to those of either the adjacent oceanic plate or the Yakutat block. Dredge data along cross-section A-A' suggest that the outer part of this zone, at Yushin Ridge, is underlain by Yakutat block rocks (Plafker and others, 1980). Therefore, I model this zone with layer thicknesses similar to those of the Yakutat block. The magnetic models, however, require a thin or low susceptibility magnetic source body below this zone, similar to the ocean plate source body. The magnetic and gravity models may be compatable if this zone is a fault zone along which the basement layer susceptibilities have been lowered by weathering of fractured and sheared rocks.

The local gravity high between about 27 km and 40 km on cross-section A-A' requires high density rocks near the surface along the fault zone. The high does not strictly satisfy the requirements for two-dimensional modeling, nor is there sufficient seismic reflection or refraction control to define a unique model. Nevertheless, such modeling gives an idea of what subsurface rocks must underlie the high. Two alternative models are shown in Fig. 28. In model 28c, the anomaly and associated bathymetric ridge could be due to an upturned section adjacent to the Transition fault that brings basement and lower crustal rocks near the surface; this model corresponds to an uplifted lower crustal section. In model 28d, the Transition fault is flanked by undeformed rocks, and the fault zone is underlain by an uplifted, seaward dipping section; this model could correspond to a slice of high density material carried in or emplaced along a fault zone. In either case, high density basement and lower crustal rocks must be present at shallow depths to match the observed gravity high.

These models suggest that the 6 to 10 km wide zone along the Transition fault could be underlain by rocks like those of the adjacent Yakutat block sections which have been locally uplifted relative to the Yakutat block. The shallow basement and lower crustal rocks required by the gravity models are not matched by a requirement on the magnetic models for high susceptibility rocks. This zone is apparently underlain by rocks of higher density and lower susceptibility than on either side or elsewhere along the fault zone. At least in the area of cross-section A-A', the fault zone is characterized by rocks in which the susceptibility may have been reduced by weathering of fractured and faulted high density rocks. The fault zone may be underlain by a thin, fault-bounded crustal sliver that has been locally uplifted along the fault zone, and perhaps moved along the fault zone.

Tectonic implications of magnetic and gravity models

The magnetic data delineate both the seaward edge and the subducted part of the Yakutat block, and define the block as a coherent, continuous geologic feature. The Slope anomaly is caused by truncation at the Transition fault of a thickened volcanic sequence that underlies the outer shelf and slope of the Yakutat block. Since the Slope anomaly is a linear feature, the source body is also a linear, continuous feature throughout the length of the anomaly. The Slope anomaly source body can lie in the lower, subducted plate west of Kayak Island. The transition of the Slope anomaly source body from the continental margin in the Yakutat block to the lower, subducting plate west of

Kayak Island occurs in the vicinity of Kayak Island. Therefore, the Yakutat block is subducting along the Kayak zone and extends in the lower plate to at least the Kenai Peninsula.

With the Yakutat block moving with the Pacific plate, as suggested by structural features along the Transition fault, then, at the present Pacific-North America convergence rate, subduction of the Slope anomaly source body would have required at least 2.8 my to reach Montague Island, and 3.7 my to reach the Kenai Peninsula (Schwab and others, 1979; Bruns and others, 1979). Thus, the observed extent of the Slope anomaly indicates that the Yakutat block has moved with the Pacific plate for much of Pliocene and Quaternary time.

The Yakutat block may be a truncated, northwest trending Paleogene continental margin. Gravity models indicate that the lower crust underlying the Yakutat block thins to the west, approaching an oceanic thickness. Structural data discussed earlier indicate that the basin margin at the Dangerous River zone and the depositional axis of the basin both trend northwest. The Paleogene section also thins to the west. Thus, the Paleogene Yakutat block may have been a continental margin, now trending northwest, with a continental shelf and slope on the northeast along the Dangerous River zone, a basin low at the base of the paleoslope at the Dangerous River zone, and an oceanic section to the southwest. This northwest trending margin is now obliquely truncated by the west-trending Transition fault.

The Transition fault is a sharp boundary along the eastern part of the Yakutat block, but comprises a 6 to 10 km wide zone west of about Yakutat Valley. Seismic data across this zone show no coherent reflections. Thus, this zone may be a fault zone along which rocks have been intensely deformed and faulted, with the susceptibility of the rocks reduced by weathering during deformation. At least locally, high density basement and lower crustal rocks have been uplifted along this fault zone, but these rocks have a relatively low susceptibility. Locally, basement and lower crustal rocks of the Yakutat block may have been uplifted and tilted relative to the Yakutat block.

CONVERGENT MARGIN-THE MIDDLETON SEGMENT

The Middleton segment, the margin segment west of and including the Kayak zone, is the offshore part of the convergence boundary between the Yakutat block and southern Alaska (Figs. 4, 30). Further, the segment includes the transition from the Yakutat block collision zone to the Pacific-North America subduction zone that extends southwest along the Aleutian trench. The structure and geologic history of the segment should therefore show where the western boundary of the Yakutat block is, and what affects, if any, the Yakutat block collision has on the segment.

Onshore geology and structure

The geology of onshore areas bordering the Middleton segment is critical to defining what rocks underlie the adjacent offshore area. Montague Island, Hinchinbrook Island, much of Wingham Island, and the Copper River area west of the Ragged Mountain Fault and north of the Chugach-Saint Elias fault (Fig. 30) are underlain by the Paleocene and early Eocene(?) Orca Group and Eocene intrusive rocks of the Prince William terrane (Plafker, 1974; Winkler, 1976;

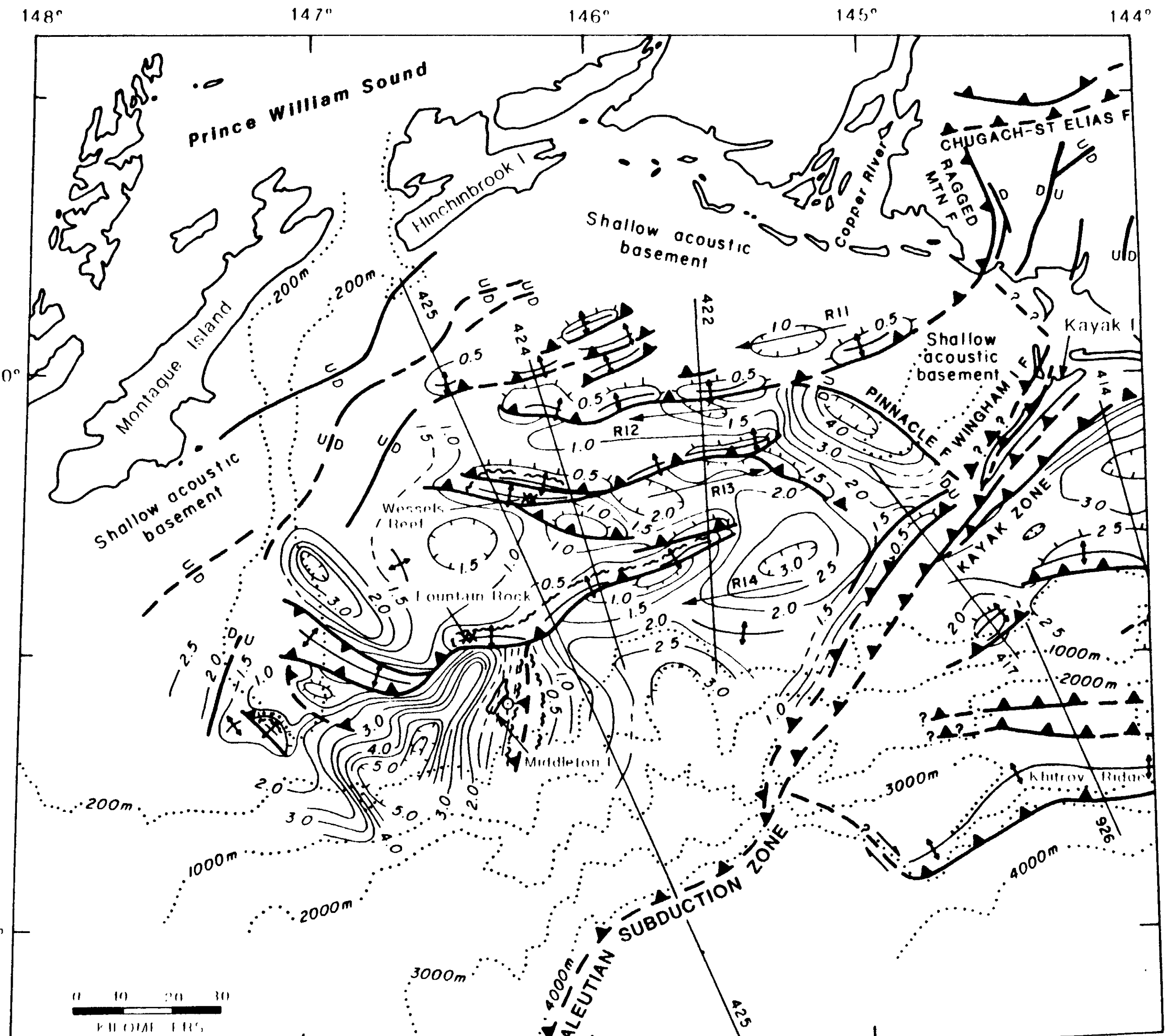


Figure 30. Middleton segment structure contours on seismic horizon M2 at base of late Miocene and younger strata. Contours east of Kayak Island on seismic horizon C, in middle to late Pliocene strata (see Fig. 17 and text for further discussion). Lines R11-R14 show location of refraction lines. Other numbered lines show location of seismic lines in Figs. 31-33. Location of Tenneco Middleton Island well shown near Middleton Island. Contour interval 0.5 km. Other explanation as in Fig. 8.

Winkler and Plafker, 1981a; Helwig and Emmit, 1981). The Orca Group consists of a variably metamorphosed, highly deformed sedimentary and volcanic sequence. The thickness of the unit is estimated as many thousands of meters, possibly on the order of 6,000 to 10,000 m. These rocks are interpreted as an accreted submarine fan complex. Following accretion and deformation, the Orca Group was intruded by granitic plutons of early Eocene age, thus dating the time of accretion (Winkler and Plafker, 1981a).

The Wingham Island, Ragged Mountain, and Chugach-Saint Elias faults form a fundamental boundary along which post-Orca Group sedimentary rocks are thrust relatively beneath and against the older, more competant Orca Group (Winkler and Plafker, 1981a). The Ragged Mountain fault has a very shallow dip, and the block west of the fault has been transported at least 6.4 km to the east during the Neogene (Tysdale and others, 1976; Winkler and Plafker, 1981a). The Wingham Island fault may be an offset continuation of the Ragged Mountain fault. The Wingham Island fault dips steeply at the surface, but becomes more shallow at depth. Horizontal offset along the fault, and presumably vertical offset as well, is upwards of several kilometers, since the fault juxtaposes metamorphosed rocks of the Orca Group against unmetamorphosed post-Orca rocks (Plafker, 1974; Winkler and Plafker, 1981a).

Kayak Island marks a major zone of convergence and structural shortening. The island is underlain by Oligocene through Miocene clastic sedimentary rocks and subordinate intercalated volcanic rocks. These rocks strike north to northeastward, and generally dip steeply westward or are overturned with tops facing northwest. The sequence shows imbrication into narrow slices by displacement on at least five large up-to-the-northwest reverse faults. Displacement on these faults is not known, but may be as much as 4.5 km on the more important faults (Plafker 1974; Winkler and Plafker, 1981a).

Vertical displacement between the rocks of the Yakutat block and those of Kayak Island must be greater than 6 km. Exploratory wells east of Kayak island penetrated almost 4 km of Pliocene and younger section (Lattanzi, 1981), and seismic mapping suggests at least 6 km of section that postdate the strata exposed on Kayak Island (Line 417, Fig. 20; also previous section and Bruns and Schwab, 1983). Thus, several faults of the Kayak zone have vertical separation exceeding 4 km, Kayak Island strata are juxtaposed against Wingham Island on a fault with horizontal offset of several kilometers, and all these faults are within a zone 10 to 15 km wide characterized by intense deformation and imbrication.

On Middleton Island, approximately 1200 m of lower Pleistocene marine strata of the Yakataga Formation are exposed (Plafker and Addicott, 1976). Tilting, faulting, and uplift of the shelf-edge high on which the island is located has occurred during late Pleistocene and continues to the present, as indicated by uplifted marine terraces (Plafker and Rubin, 1978), and uplift of about 4 m during the 1964 Alaska earthquake (Plafker, 1969).

Tenneco Middleton Island well

A well drilled in 1969 near Middleton Island by Tenneco Oil Co. (Fig. 30) provides additional subsurface control on the age of rocks underlying the Middleton segment.

Biostratigraphic studies of samples from the well (Rau and others, 1977; Keller and others, 1984) show that the lower part of the drilled section (3658 to 890 m) includes strata from late middle Eocene through latest Oligocene or early Miocene age. Foraminifera indicate deposition of these strata occurred in lower to middle bathyal water depths (greater than 1500 m). The upper part of the well, shallower than 700 m, consists of strata of late Miocene to Pleistocene age (undifferentiated) deposited in upper bathyal to neritic water depths (1000-300 m). A hiatus is present between the early and late Miocene strata (Keller and others, 1984).

Faunal studies by Keller and others (1983, 1984) also indicate closure of at least 10° latitude between the Yakutat block and the Middleton segment since Oligocene time. Faunal assemblages from the Middleton Island well were deposited in significantly cooler water during the Paleogene than the coeval Yakutat block assemblages. Correlations to onshore sections of North America, and paleolatitude determinations by Keller and others (1983, 1984) indicate that the oldest strata sampled in the well (late middle Eocene, 40-42 Ma), were deposited at high latitudes, north of $50^{\circ}\pm5^{\circ}$. The Middleton Island well Paleogene fauna are a significantly cooler water assemblage than fauna in equivalent age strata from the Yakutat block, with an absolute paleolatitude of $44^{\circ}\pm5^{\circ}$.

Middleton segment structure

The structure of the Middleton segment is characterized by more tightly folded and extensively faulted structures than on the adjacent Yakutat block. The major onshore faults of Kayak Island and the Ragged Mountain fault can be traced offshore, indicating that the thrusting observed on these faults also occurs on the shelf.

Seismic horizons

The structural configuration of the Middleton shelf (Fig. 30) is shown by structure contours on a horizon, the M2 horizon (Figs. 7, 31-33), that is correlated on seismic reflection data to the top of latest Oligocene or early Miocene age strata at a depth of 890 m in the Middleton Island well. The M2 horizon is mapped on an unconformity over much of the shelf (lines 422, 424, and 425, Figs. 31-33). This unconformity correlates to the early to late Miocene hiatus observed in the well. Therefore, strata above horizon M2 are late Miocene and younger, and according to Keller and others (1984) younger than about 6.5 m.y.

The M2 unconformity also marks a change in the character of the basin strata. Structural deformation below the unconformity is, at least in part, greater than in the overlying section (for example line 422, Fig. 31). Seismic refraction velocities show an abrupt change from 2.2 to 3.2 km/s above the unconformity to 4.5 to 4.9 km/s below the unconformity (refraction velocities shown on line 422, Fig. 31). The unconformity is similar to one observed on the Kodiak shelf, which Fisher and Von Huene (1980) believe to be a middle to late Miocene subaereal unconformity, with Paleogene and lower to middle Miocene rocks below the unconformity, and gently deformed upper Miocene and younger rocks above the unconformity. The section above the M2 unconformity is approximately age correlative with the onshore Yakataga

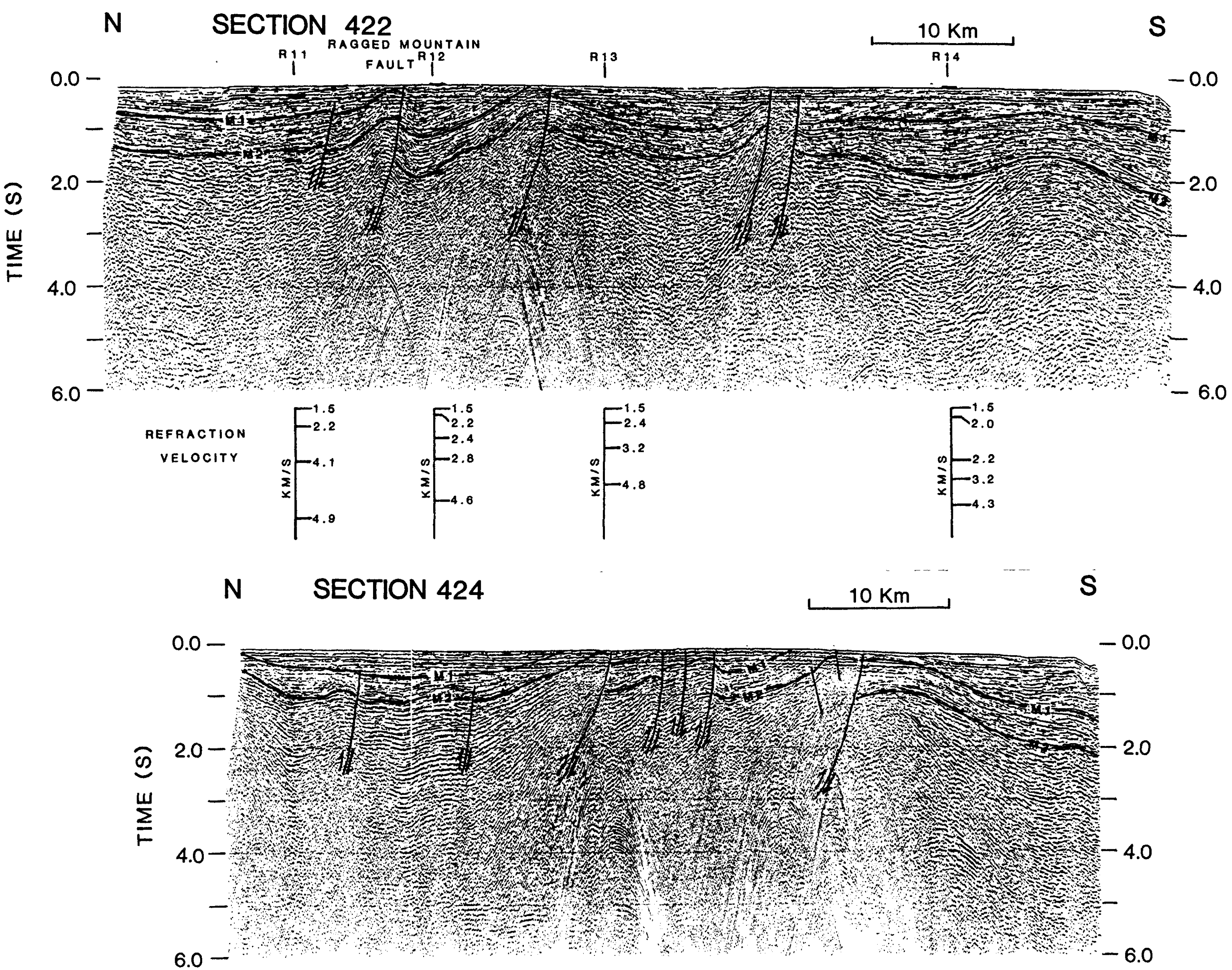


Figure 31. Interpreted seismic sections for lines 422 and 424, Middleton segment. V.E. 5:1 at seafloor. Horizon M2 corresponds to mapped horizon of Figure 30. Location of refraction lines (R11 through R14) indicated at top of line 422; horizontal bars on section indicate velocity breaks, and values in km/s are shown below section. See Fig. 30 for location of seismic reflection and refraction lines.

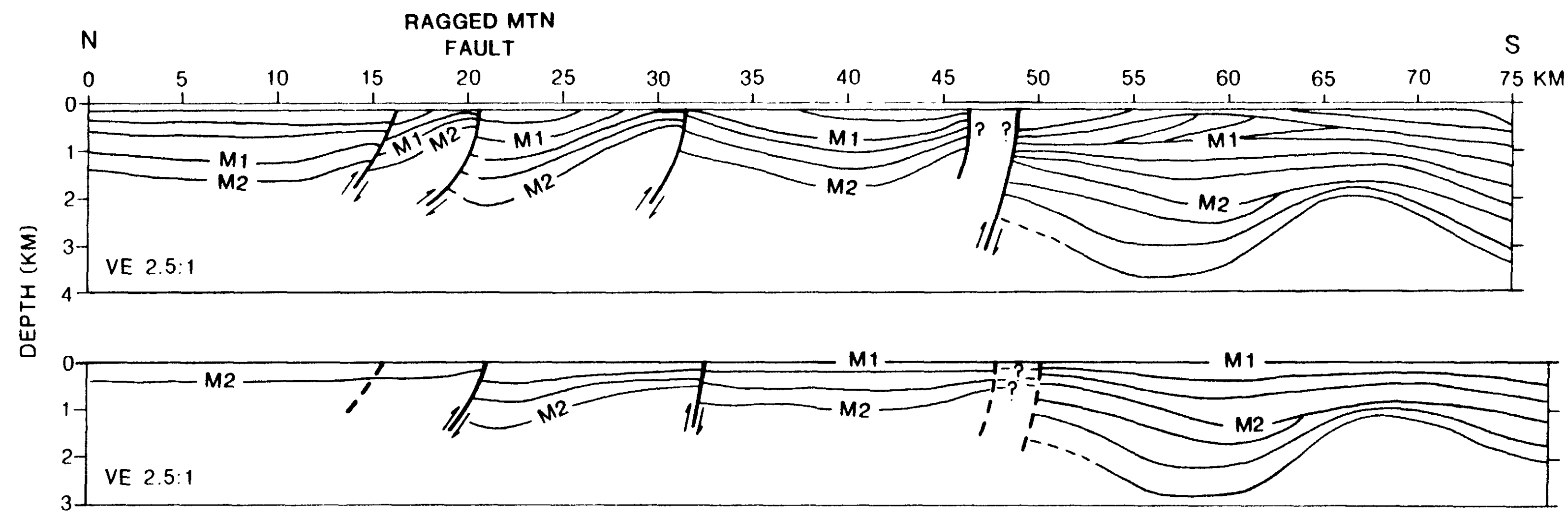


Figure 32. Depth section for line 422 (top), flattened on M1 horizon (bottom). Flattened section shows that most of structural growth has occurred after horizon M1 time, or after about middle Pleistocene time.

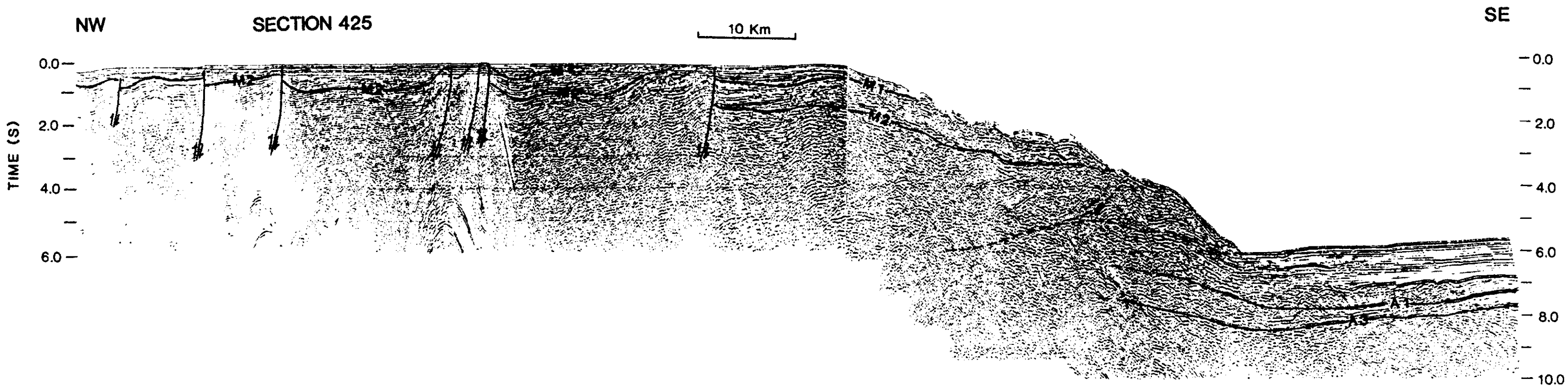


Figure 33. Interpreted seismic section for line 425; location shown in Figure 30. V.E. 5:1 at seafloor.

Formation and with strata above horizon D in the Yakutat and Yakataga segments (Fig. 7).

A second horizon, the M1 horizon (Fig. 7) is correlated throughout parts of the shelf seismic grid (Figs. 31-33). This horizon is in strata of about middle to upper Pleistocene age, based on a tie to the Middleton Island well, and on strike projections that indicate it overlies the strata exposed on Middleton Island (Bruns, 1979). The significance of the horizon (discussed below) is that much, and perhaps most, of the deformation of the shelf strata took place after horizon M1 time.

Shelf structure

The most prominant structural features of the shelf are the Middleton Island high, the offshore extensions of the Kayak Island structural trend and the Ragged Mountain fault, a fault or fault zone herein termed the Pinnacle fault, and a basin cut by numerous tightly folded and faulted anticlines (Fig. 30).

Major faults or fault zones. The offshore extension of the Kayak Island structural belt, the Kayak zone, can be traced on seismic reflection data southwest across the continental shelf and slope (Fig. 30). On the seismic reflection data, the Kayak zone is characterized as an area where no reflectors are present (for example, line 417, Fig. 20), indicating steep dips and intense deformation similar to that mapped on the island (Bruns and Schwab, 1983). Based on the geology of Kayak Island (Plafker, 1974), the Kayak zone is an area of major vertical uplift, imbrication, and structural shortening.

The seaward extension of the Ragged Mountain Fault trends southwest for about 40 km, then turns to a more westerly trend (Fig. 30). The western extension of the thrust is not well delineated by the seismic data, but may merge into the set of north to northeast trending faults east of and parallel to Montague Island.

Rocks landward of the Ragged Mountain fault are likely equivalent to onshore Orca Group rocks. Onshore, the fault separates Orca Group rocks from post-Orca Group rocks. The seismic acoustic basement landward of the offshore fault and off Montague and Hinchinbrook Islands is shallow, and refraction velocities of the acoustic basement are greater than 4 km/s, indicating indurated rocks. Thus, a 30 to 60 km wide area seaward of the Copper River, and Hinchinbrook and Montague Islands is likely underlain by Orca Group equivalents.

The offshore Ragged Mountain Fault is an area of moderate Neogene eastward thrusting. At least 6.4 km of eastward thrusting has occurred onshore. The offshore fault extension is characterized by numerous, small anticlines in post-horizon M2 strata (Figs. 30-33). The degree of anticlinal deformation along the fault decreases to the east, and the structures are at least partly covered by undeformed post-horizon M2 strata (line 424, Fig. 31). Thus, although some motion has occurred offshore, the amount of deformation observed along the fault suggests that thrusting is not significantly greater than observed onshore, and may be less. The Ragged Mountain Fault is probably not an area of large-scale Pliocene and Quaternary thrusting and imbrication. However, the fault could be and probably is an area of pre-Pliocene major thrusting.

The Pinnacle fault is an extensive fault or fault zone beginning near the southern tip of Kayak Island and trending northwest to west across the shelf (Fig. 30). This fault juxtaposes over 4 km of Neogene strata (post-horizon M2 strata) on the south side of the fault against seismically non-reflective strata on the north side. This fault merges with the offshore Ragged Mountain fault almost 40 km to the west.

Seismic acoustic basement in the area bounded by the Pinnacle fault, the offshore Ragged Mountain fault, and the Wingham Island fault is shallow (Fig. 30), and is probably on Orca Group rocks correlative with those exposed on Wingham Island. The inferred connection of the Ragged Mountain fault to the Wingham Island fault would then form the remaining boundary of this Orca block. This Orca block has been thrust relatively eastward of the Ragged Mountain fault, and forms a backstop against which post-Orca rocks of Kayak Island have been deformed and faulted (Winkler and Plafker, 1981a).

Basins. The shelf seaward of the probable Orca basement contains deep basins disrupted by numerous zones of anticlinal deformation (Fig. 30).

The thickest strata of the shelf are contained in a series of four basins below the outer shelf and slope, between the Kayak zone and the anticlines of the central shelf. The basins are separated by structural highs, two of which are low relief features (seaward anticline, line 422, Fig. 31), and one of which forms the Middleton Island shelf edge high. These basins extend below the upper slope.

In these basins, seismic reflectors are seen below horizon M2 on the seismic data (lines 422, Fig. 31), indicating the presence of stratified rocks of Paleogene and early Miocene age equivalent to those observed in the Middleton Island well. Between the basins and the areas of shallow acoustic basement near Montague and Hinchinbrook Islands, these rocks are either truncated in the subsurface, or become markedly more deformed and indurated, and form the acoustic basement. The four basins form a structural low that is relatively unaffected by the extreme deformation of the adjacent Kayak zone.

The thrust-faulted anticlines of the shelf tend to be asymmetric, with major bounding faults on the south side of the highs. The crests of the anticlines are deeply eroded and truncated at the seafloor, exposing probable lower and middle Tertiary rocks (pre-M2 horizon rocks) at or near the seafloor. Two of the highs form subaereal reefs at Wessels Reef and Fountain Rock (Fig. 30). The structures are more tightly folded and faulted than the structures on the Yakataga segment (compare with Figs. 18-21), with numerous areas at the crests of the anticlines where seismic data do not resolve the structure due to steep dips, probably greater than about 30°.

The anticlines are young, actively growing structures. On all the anticlines, even the shallowest reflectors are deformed and truncated at the seafloor. Thinning is present in strata on the flanks of most of the structures above horizon M1 (Figs. 31-33), whereas little thinning occurs below horizon M1, and in some cases, the M2-M1 strata and pre-horizon M2 strata thicken seaward (seawardmost anticline, line 425, Fig. 33). None of the anticlines are covered by undeformed strata. The strata of the basin appears to have been deformed rapidly and almost simultaneously during post-horizon M1 time. The most likely time for initiation of uplift is middle to late Pleistocene time, in accord with the onset of uplift on Middleton Island. Ongoing uplift of Middleton Island, and the presence of reefs on the crests of the structures indicates that the uplift process is still active.

Prior to uplift, the shelf strata formed a seaward thickening, relatively undeformed basin. For example, flattening on horizon M1 on line 422 (Fig. 32) shows the configuration of shelf strata prior to uplift. On the flattened section, faulting and uplift is present on the Ragged Mountain fault, and on the fault at 32 kilometers, but not on the major structure between 45 and 50 km. For most of late Miocene through early Pleistocene time (M2-M1 time), the Middleton segment basin was primarily characterized by subsidence and deposition in shallow water.

Slope and base-of-slope structure

On a multichannel line that extends across the slope and the base of the slope (line 425, Fig. 33), the strata of the slope are relatively undeformed. On line 425, the M2 horizon can be traced below the continental slope to very near the trench axis (Plafker and others, 1982). Dredge data in this area has recovered Paleogene strata that correlates with that from the Middleton Island well (Plafker and Bruns, 1982). In this area, the Pacific plate-North America plate convergence vector indicates major subduction of the Pacific plate. Yet, on the seismic data, undeformed oceanic strata, largely of Miocene and younger age, have clearly been underthrust beneath the Eocene and younger continental margin section along a decollement concordant with bedding. There is no appreciable sediment accretion or major deformation of the overlying strata.

The structure and tectonic style seen on line 425 is markedly anomalous with respect to the structure seen on all other seismic lines across the Aleutian convergent margin. Major deformation has occurred on Khitrov Ridge, about 45 km to the northeast, and on a single channel seismic line about 30 km to the north. Only 60 km to the southwest of line 425, multichannel seismic data (R. von Huene and M.A. Fisher, personal communication, 1984) shows the tectonic style typical of the Aleutian subduction zone between Middleton Island and Kodiak Island. In these areas, the margin is marked by a highly deformed, lower slope accretionary prism (Seeley, 1977; von Huene, 1979; von Huene and others, 1979a, 1979b, 1979c, 1983; Fisher and von Huene, 1980; and von Huene, in press).

What might cause this anomalous tectonic style? One possibility is that high pore fluid pressures at the subduction zone help to decouple the subducting plate from the overriding plate. Von Huene (1984) notes that modeling (Davis and others, 1983; Von Huene and Lee, 1983) indicates an early increase of pore pressure during subduction, and is a basic reason for both sediment subduction and the structural diversity observed along active subduction zones. High pore pressure was measured at the Barbados Ridge deformation front by Moore, Biju-Duval and others (1982), who suggest that thrusting of an undeformed, acoustically layered sequence beneath deformed, offscraped strata is facilitated by the high fluid pressures at the structural boundary between the two units. Aubouin, Von Huene and others (1982) observed elevated pore pressures on the Middle America Trench off Guatemala, and suggest the overpressure helped to explain the non-accretionary character of the margin along which soft sediment is subducted beneath a mass of hard ophiolitic rock. Thus, the anomalous structure observed on line 425, and the high degree of decoupling required, is almost certainly related to high pore pressures within the thick sedimentary strata on both the subducting and overriding plate.

A problem with using only high pore pressures to explain the lack of deformation on line 425 is that other regions along the Aleutian Trench, also with thick sediment on both the overriding and subducting plate, are not similarly effected. A second possible process, unique to the northern Aleutian Trench, is that the passage of the Yakutat block beneath the margin may have influenced the structural development of the margin.

Conceptually, as the Yakutat block approaches and passes beneath the margin, unconsolidated, deformed lower slope deposits and part of the more rigid shelf and upper slope rocks may be tectonically eroded from the margin and carried down the subduction zone with the subducting Yakutat block. After passage of the block, normal oceanic crust would again enter the subduction zone, probably accompanied by subsidence of the margin as the thick Yakutat block strata are removed by continued subduction.

Line 425 may then record the configuration of the margin shortly after passage of the Yakutat block, in this case about 0.5 to 1 m.y. after passage, based on the position of the Slope anomaly. The margin could have been tectonically eroded and truncated, with subsided, relatively undeformed shelf and slope rocks now exposed near the trench. As subduction of normal ocean plate crust resumes, a lower slope accretionary wedge may again develop, as seen in seismic data 60 km to the southwest. The suite of seismic lines along the northern Aleutian Trench may therefore record the development of the subduction zone after passage of the Yakutat block, from almost no accretionary wedge, as on line 425, to the well defined accretionary wedge observed further to the southwest.

Structures beneath Khitrov Ridge are apparently abyssal strata that are folded into the continental margin. Thus, there must be a marked change in the mechanics of subduction southwest of Khitrov Ridge, and a major tear fault or ramp must be present between the uplifted Khitrov Ridge strata and the subducted strata to the southwest.

Tectonic implications

The structure of the Middleton segment has tectonic implications on the geologic history of the Middleton segment, on where the Yakutat block is subducting, and on the effects of the Yakutat block subduction process on the Middleton segment.

For several reasons, the Kayak zone is a major tectonic boundary, a subduction zone, along which the Yakutat block is thrust beneath the Middleton segment.

First, the structure of the Kayak zone is characterized by major deformation, imbrication, and convergence. Several faults have offset greater than 4 km, and horizontal offset of unknown amount juxtaposes metamorphosed rocks of the Orca Group against unmetamorphosed post-Orca rocks on the Kayak Island and Wingham Island faults. Also, faunal assembledges from the Tennaco Middleton Island well are very different from Yakutat block equivalent age assembledges, and indicate 5^{o} to 10^{o} of closure between the Yakutat block and the Middleton segment since the late Eocene (Keller and others, 1984). The Kayak zone is therefore a major tectonic boundary along which dissimilar terranes are juxtaposed, as the Yakutat block is thrust beneath the Middleton segment.

Second, there is no place west of the Kayak zone along which major Pliocene and Quaternary subduction could have occurred. On the Middleton segment, the Ragged Mountain fault is not a zone of post-horizon M2 major deformation. The major anticlines of the shelf primarily developed in middle to late Pleistocene time. Thus, the Kayak zone forms virtually the only place where major subduction can occur during the last 5 m.y.

Third, the magnetic data indicate that the Slope anomaly and the oceanic anomalies on the adjacent Pacific plate are subducted below the Middleton segment in the vicinity of Kayak Island. Thus, the Kayak zone marks the subduction zone for the Yakutat block.

The geologic history of the Middleton segment from late Eocene through Quaternary time (post-Orca-Group accretion) includes four main events. During late middle Eocene through earliest Miocene time, deposition took place in deep water, with minor hiatus in the section reflecting changing ocean circulation patterns (Keller and others, 1983, 1984). Between earliest Miocene and late Miocene time, a major hiatus in the Middleton Island well suggests a marine regression, uplift, and possibly subaereal erosion of the Middleton segment. During late Miocene time, subsidence began and continued through about middle to late Pleistocene time, with seismic data indicating little deformation of the shelf or slope strata. Finally, rapid anticlinal deformation affected the shelf strata during middle to late Pleistocene time, and continues to the present.

The first three events are similar to the geologic history of the Kodiak shelf (Fisher and Von Huene 1980), and form a consistent pattern for the continental shelf from the Middleton segment to southwest of Kodiak Island. The rapid middle to late Pleistocene deformation of the shelf is not observed to the southwest. On the Kodiak shelf (Fisher and Von Huene, 1980) and the Shumagin shelf (Bruns and Von Huene, 1977), many areas exhibit little deformation of shelf and upper slope strata during Pliocene and Quaternary time. In these areas subduction of the Pacific plate does not necessarily cause major deformation of the shelf and upper slope, although both major deformation and accretion are observed on the lower slope. What event might have caused the young, rapid deformation of the Middleton segment?

A possible cause of this deformation is subduction of the thickened crust of the Yakutat block, especially near the Transition fault. Assuming the Slope anomaly source body moves beneath the Middleton segment at 6 cm/yr, the body would have moved towards and passed beneath Middleton Island within the last 0.5 m.y., and currently lies beneath Wessels Reef. This is about the time period that the anticlines of the shelf formed. The initiation of anticlinal deformation and passage of the Slope anomaly source body beneath the deforming zone at about the same time could be coincidence, but could also indicate a cause and effect relationship. The greater relief of the body, and presumably greater rigidity compared to thinner crust on either side may lead to enhanced coupling between the overriding and subducting plates, resulting in deformation of the upper plate rocks.

The subduction of the Yakutat block at the Kayak zone otherwise has little affect on the structure of the Middleton segment. During late Miocene through early Pleistocene time, only gentle deformation of the segment occurred, even though subduction was presumably an ongoing process along the Kayak zone. The thick basin strata within 40 to 60 km of the Kayak zone are undeformed, except very near the zone. Apparently a thick sedimentary sequence can subduct along a narrow, 10-15 km wide zone without causing major deformation of the overriding plate.

DISCUSSION

Pliocene and Quaternary constraints on Yakutat block tectonics

The previous sections lead to several important constraints on the boundaries and tectonics of the Yakutat block and the northern Gulf of Alaska.

Magnetic, geologic, and structural interpretations define a geologic terrane, the Yakutat block, extending from Cross Sound to almost the Kenai Peninsula, that has moved with the Pacific plate for at least the last 5 m.y. The Yakataga formation, a distinctive late Miocene and younger glaciomarine sequence derived from the adjacent mountains overlies the older rocks onshore and offshore, except near the onshore bounding faults, and demonstrates continuity of the Yakutat block during Yakataga time. Magnetic data demonstrates continuity of the basement rocks offshore. Magnetic data also indicate that west of about Kayak Island, the terrane is subducted beneath the Middleton segment, with subduction beginning at the Kayak zone. The seaward limit of the block lies at the Transition fault, and in the subducted part of the block, is defined by the location of the Slope anomaly. Onshore, the current boundaries of the block are defined by fault studies and seismicity as lying on the Fairweather Fault and the Chugach-Saint Elias fault system.

Offshore, the basement rocks of the Yakutat block consist of a probable Mesozoic to Paleocene subduction complex east of the Dangerous River zone, and Paleocene to early Eocene oceanic basalt to the west. A thick Paleogene sedimentary section overlies the basalt west of the Dangerous River zone, and the zone may mark the Paleogene basin edge. Both the Paleogene sedimentary section and the lower crust thin to the west, suggesting that the Yakutat block was originally a continental margin, now trending northwest and obliquely truncated by the Transition fault. The thickness and extent of the Paleogene strata indicates that a large source area, probably a continental margin, was adjacent to the Yakutat block during the Paleogene.

Continuity between onshore and offshore pre-late Miocene rocks (pre-Yakataga Formation rocks) of the Yakutat block has not been established. The onshore Eocene shallow marine and continental strata may be present in the subsurface adjacent to the Dangerous River zone, with these rocks becoming deep-water facies where sampled on the continental slope southwest of the Dangerous River zone. Alternatively, the basin could have filled from the northwest, with continental and shallow water facies represented in the onshore sections, changing to a deep-water facies to the southeast along the axis of the basin. Until lithologic relations and faulting within these older rocks is better defined, the character of the pre-late Miocene Yakutat block will remain unknown.

A major fault could be present between the onshore and offshore Paleogene rocks of the Yakutat block; in this case, these rocks could have different source terrains and tectonic histories. The Yakutat block defined by Pliocene and Quaternary geologic and tectonic features could be underlain by sutured pre-Neogene terranes, with features that would demonstrate this largely concealed beneath the thick Yakataga Formation.

The Transition fault, the southern margin of the Yakutat block, is a major tectonic boundary between the block and the Pacific plate. Prior to Pliocene time, the fault was an active tectonic feature that juxtaposed Oligocene oceanic crust against Cretaceous and Paleogene strata of the Yakutat block shelf and slope and removed part of the Paleogene basin of the Yakutat block.

The Transition fault has not been an active boundary during Pliocene and Quaternary time. Undeformed Pliocene and Quaternary strata cover the Transition fault at both the west and east ends. There is no apparent offset of Pliocene and younger fans at the base of the slope from their probable source areas. There is only local deformation along the fault, primarily associated with the Pliocene and younger uplift of the Fairweather Ground. Thus, the Yakutat block has been attached to and moving with the Pacific plate for at least Pliocene and Quaternary time and colliding with southern Alaska.

Northward motion of the Yakutat block is taken up by a process of subduction beneath the Middleton segment and in the Wrangell Benioff zone of Stephens and others (1983, 1984), by major crustal shortening and thickening, and by mountain building, as suggested by Von Huene and others (1979), Perez and Jacob (1980), and Hudson and Plafker (1983). Spectacular evidence of this collision process are the high Saint Elias and Fairweather mountain ranges on the northern margin of the block.

The primary affect of the collision process on the Yakutat block is the development of a seaward-propagating fold and thrust belt on the northwest margin of the block, in the area of maximum convergence between the Yakutat block and southern Alaska. The degree of deformation within the fold belt increases from south to north across the Yakutat block, reaching a maximum along the Kayak zone and adjacent to the Chugach-Saint Elias fault. The rest of the Yakutat block has undergone little deformation, since motion along the Yakutat segment is largely accomodated by transform faulting along the Fairweather-Queen Charlotte fault.

The Yakataga Formation indicates that the collision of the Yakutat block with southern Alaska and the uplift of the Chugach-Saint Elias mountains began in the late Miocene. The Yakataga Formation is derived from these mountains, and indicates active tidewater glaciation and initialization of rapid sedimentation (Plafker and Addicott, 1974). Thus, the Yakutat block began to collide with southern Alaska at about the end of the Miocene, initiating the rapid uplift orogeny that currently characterizes southern Alaska.

The northward motion of the Yakutat block must have occurred along transform faults of southeastern Alaska. Part of this motion could be accomodated along the Chatham Strait fault, which has been offset about 100 km during post-Oligocene time. However, most of this motion must have occurred along the Queen Charlotte fault which truncates the crystalline basement of southeast Alaska. The northward continuation of this fault is into either the Fairweather fault or the Icy Point-Lituya Bay fault. A problem is that only limited motion is recognized on the Fairweather fault, and definitive data are lacking to even show that the Icy Point-Lituya Bay fault could be a strike-slip fault. There are at least three possibilities why only limited offset is observed on the Fairweather fault: (1) The Fairweather fault is in fact a young fault with only limited offset, and collision has been accomodated on faults that are currently unrecognized in the geology of southern Alaska; (2) much greater offset has occurred on the Fairweather Fault, but is currently unrecognized; and (3) the Fairweather fault or other faults are a suture zone along which oblique subduction occurs, but which also have a strike-slip component so that they appear as transform faults. What is clear is that substantial closure between the Yakutat block and southern Alaska must have occurred by subduction of ocean crust or Yakutat block-like terrane during the late Cenozoic.

The effects of the Yakutat block collision on the Middleton segment are substantially less than along the northwestern margin of the Yakutat block. Deformation of the Middleton segment related to subduction of the Yakutat block appears to be confined to rapid Pleistocene deformation of the shelf strata. This deformation may be related to the passage of the thickened basement layer of the Yakutat block (the Slope anomaly source body) beneath the shelf. Otherwise, the Yakutat block has passed beneath the segment with little effect on the structure of the segment. This passage is marked by only a 10 to 15 km wide zone, the Kayak zone, along which major deformation and faulting has occurred. Apparently, the thick sediment sequence of the Yakutat block is subducting without causing major deformation of the overriding plate.

Constraints on pre-Pliocene tectonics

Geological and geophysical data establish several constraints on the pre-Pliocene tectonics of the Yakutat block. These constraints concern the source and volume of Paleogene strata of the block, the northward displacement of faunal assemblages of the block, and the nature of the Transition fault.

Source terrain.

The Yakutat block was adjacent to a large source area during the Paleogene. The Paleogene strata of the Yakutat block are at least 4.5 km thick beneath the continental shelf and up to 6 km thick onshore. The volume of included rocks requires a large source area. Onshore Paleogene rocks are mainly shallow marine and continental facies, while coeval rocks offshore are shallow to deep marine with a large terrestrial component. It is likely that the Yakutat block was adjacent to a continental margin during Paleogene time.

Plafker and others (1980) suggest that the composition of sandstones from the block requires a plutonic-metamorphic source terrain. However, this conclusion is based on modal analysis of only ten dredge samples from a poorly controlled position within the Yakutat block stratigraphic section. Further, Eocene volcaniclastic sandstones dredged from several places on the continental slope were not included in the modal analysis. Thus, the sandstones studied may not be representative of the entire Paleogene stratigraphic section, or of the source terrain from which these strata were derived.

Constraints on northward motion of the Yakutat block

There is evidence that the Yakutat block is a far-traveled terrane. Flora and fauna from the onshore Paleogene strata, and microfaunal assemblages from rocks dredged from the continental slope are similar to those found off California, Oregon, and Washington (Wolfe, 1977; Rau, 1979, 1981; Plafker and others, 1980, Keller and others, 1983, 1984). Keller and others (1984) find that the block has moved $30^{\circ} \pm 5^{\circ}$ north to its present position since the early Eocene (about 50 m.y.). They further find that there has been 5° to 10° of closure between the Yakutat block and the Middleton segment since the middle Eocene. This amount of displacement requires movement of the Yakutat block with the Kula and Pacific plates since early Eocene time (Bruns, 1983; Keller and others, 1984).

Other evidence for displacement of the Yakutat block includes observations by Zuffa and others (1980) and Winkler and Plafker (1981b) that onshore Cretaceous rocks (Yakutat Group) of the Yakutat block contain sandstones with a distinctively different mineralogy, and therefore a different source terrain, from that of coeval Chugach terrane sandstones adjacent to, but not part of the block. Winkler and Plafker (1981b) further suggest substantial tectonic transport of the Yakutat block with respect to the northern age equivalent rocks. Plafker and others (1980) further find that the mountains adjacent to the block could not have been the source terrain for the Paleogene strata, and suggest a southeast Alaska or British Columbia source. Thus, the Yakutat block has undergone substantial northward tectonic transport during the Cenozoic.

Pre-Pliocene tectonics along the Transition fault

The main geophysical constraints for pre-Pliocene tectonics of the Transition fault are that: (1) tectonism has juxtaposed rocks of markedly different ages along the Transition fault and truncated the Paleogene basin of the Yakutat block, and (2) this tectonic process caused no major deformation of or accretion along the margin. The tectonic mechanism operative along the fault, and timing of faulting are unknown. The most likely mechanism is transform faulting, but subduction cannot be ruled out on the basis of the geophysical data alone.

In the following sections, I will first discuss the possibility of subduction along the Transition fault, then examine what movement of the Yakutat block would be consistent with only strike-slip motion along the fault. Then, I will discuss two models that have been proposed for the origin and evolution of the Yakutat block.

Constraints on subduction at the Transition fault. Subduction can occur without major deformation or accretion if the subducting plate is almost totally decoupled from the overriding plate. An example of this process is the current subduction boundary of the western margin of the Yakutat block. In this area, a narrow zone of intense deformation records the underthrusting of the Yakutat block along the Kayak zone, and no deformation is observed on seismic line 425 (Fig. 33). However, this area is markedly anomalous with respect to the rest of the Aleutian subduction zone. Only 60 km southwest of line 425, a more typical subduction morphology characteristic of the Aleutian subduction zone is present, with a well defined 15 to 30 km wide accreted wedge at the base of the slope. As suggested earlier, the anomalous character of the northern Aleutian trench along line 425 may in part be a result of the Pliocene and Quaternary subduction of the Yakutat block.

More commonly, subduction zones in which the descending ocean plate is overlain by a moderate amount of sediment have a well-defined accretionary wedge at the base of the slope, as along the Aleutian subduction zone. If the Transition fault was a subduction zone prior to the Pliocene, the incoming Pacific plate would presumably have carried a thick sedimentary sequence derived from the North American continental margin. For example, off southeast Alaska, the sediment at the base of the slope is currently 3 to 5 km thick. I suggest that with a relatively thick sediment input, subduction at the Transition fault would most likely be characterized by a well-developed accretionary wedge. Even in failed subduction zones, at accretionary wedge is commonly preserved, as, for example, in failed subduction zones at the Palawan Trench (Hamilton, 1979), the Bering Sea (Cooper and others, 1981), and off central California (D. McCulloch, personal communication, 1984). However, there is currently no evidence for such a wedge along the Transition fault. Unless such deformed or accreted strata has been removed by transform fault (next section), I conclude that subduction at the Transition fault is unlikely.

Constraints on transform faulting at the Transition fault. Post-subduction strike-slip faulting along the Transition fault could have removed deformed or accreted strata. What possible motion of the Yakutat block might occur, assuming that only transform motion occurs along the fault, and that the fault has an orientation different from a Pacific-North America transform fault?

This model requires, in effect, motion of the Yakutat block independent of either the Pacific or the North America plates. A vector analysis of three plates, Pacific, North America, and Yakutat block, gives an idea of motions required to maintain only transform motion of the Transition fault. This analysis uses the current configuration of the Yakutat block and the present Pacific-North America convergence vector and assumes rigid plates (Fig. 34).

In this case, the constraints are Pacific-Yakutat block relative motion along the Transition fault at an unknown rate and direction, but at an aximuth of about N. 63^{o} W., Pacific-North America relative motion on the Queen Charlotte fault at about 6 cm/yr at an aximuth of about N. 15^{o} W. (Minster and Jordan, 1978), and unknown Yakutat block-North America relative motion.

Pacific-Yakutat block relative motion has not been accomodated by a left-lateral transform at the Transition fault. Such motion would require the

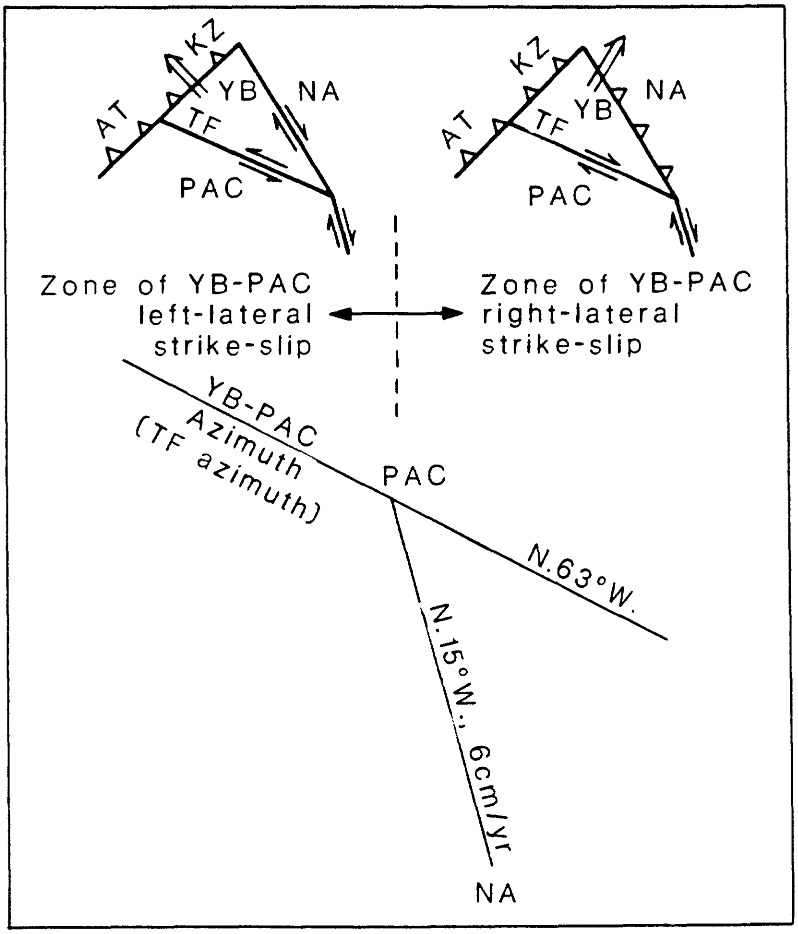


Figure 34. Vector analysis assuming Pacific-Yakutat block transform motion on Transition fault in a direction of about N. 67° W. but at an unknown rate, and Pacific-North America motion along the Queen Charlotte fault at 6 cm/yr and N. 21° W. North America-Yakutat block and Pacific-Yakutat block motion would be defined by a vector from North America point to Pacific-Yakutat block azimuth line. Simplified map view of motions at top; large arrow indicates general direction of North America-Yakutat block convergence with indicated motion on Transition fault. AT-Aleutian Trench; KZ-Kayak zone; NA-North America plate; PAC-Pacific plate; TF-Transition fault; YB-Yakutat block.

juxtaposition of terranes of the opposite age to what is observed; that is rocks of the Yakutat block would be younger than the adjacent rocks of the ocean crust, and the ocean crust would be older to the east. Also, the missing, oceanward part of the Yakutat block would presumably be found to the east on the adjacent Pacific plate. However, only Oligocene oceanic basement is present along southeast Alaska and the Yakutat block. Thus, left-lateral faulting is the wrong sense of motion to match the observed geology.

If Pacific-Yakutat block relative motion is taken as a dextral transform at the Transition fault, then the aximuth for Yakutat block-North America motion would be more northerly to northeasterly than the Pacific-North America aximuth (Fig. 34). The missing part of the Yakutat block would have ridden with the Pacific plate into the Aleutian subduction zone. Yakutat block-North America relative motion would be accomodated by subduction of the north and east parts of the proto-Yakutat block beneath southern and southeastern Alaska. This observation will be used next to construct a possible model for Yakutat block motion.

Speculative models for Yakutat block motion

Two very different models have been proposed for the origin and movement history of the Yakutat block. Bruns (1983a) and Keller and others (1984) present models with over 30^{o} of northward motion for the block in the last 50 m.y. Plafker (1983) and Nye (1983) propose a model in which the Yakutat block originates off southeast Alaska and has moved only about 5^{o} north in the last 25 m.y. Either model can satisfy geophysical constraints for the Transition fault, and each appears to be a mechanically feasible plate tectonic reconstruction. Thus, the determination of which model is correct will be decided from other evidence, such as paleomagnetic measurements or comparisons of the geology of the Yakutat block with the geology of the North American continental margin.

Bruns (1983a) suggests that the Transition fault formed during the Paleogene as a Kula-Farallon transform, then Pacific-Farallon transform after the demise of the Kula-Pacific spreading center, and that the transform was active until about the close of Oligocene time. In this model, subduction of the Kula-Farallon spreading center detached the Yakutat block from the North America continental margin, and the block has since moved northward with the Kula and Pacific plates. This model requires only transform motion along the Transition fault, and predicts that the fault has been inactive since about the end of Oligocene time. This model is presented in Bruns (1983a) and further details are not discussed here.

The main advantage of this model is that it is in good agreement with the faunal data of Keller and others (1984) which also indicate 30^{o} of northward motion of the Yakutat block. A disadvantage is that during this northward motion, the Yakutat block would pass by a variety of source terrains for the Paleogene strata of the block, thus not matching the requirement of Plafker and others (1980) for a plutonic and metamorphic source terrain.

In marked contrast to this model, Plafker (1983) and Nye (1983) propose that the Yakutat block was sliced off the southeast Alaska continental margin south of Chatham Strait about 25 m.y. ago, and displaced northward to its current position by about middle Miocene time (by about 15 m.y.).

Concurrently, an additional 900 km of dextral displacement occurred between the Yakutat block and the Pacific plate along the Transition fault. The primary reason for the initial location of the Yakutat block in their model is that the Yakutat block would be adjacent to a plutonic and metamorphic source terrain during the Paleogene.

The main assumptions of the model are: (1) that the onshore Yakutat Group of the Yakutat block and the offshore Mesozoic rocks east of the Dangerous River zone were once the southeastward continuation of the Chugach terrane; (2) that the block began northward movement when motion began on the Chatham Strait fault, and (3) that the Yakutat block was in the northern Gulf of Alaska by the beginning of deposition of the Yakataga Formation, dated by Plafker and Addicott (1977) as about middle Miocene time. The model further requires about 45° of counterclockwise rotation of the Yakutat block during the collision process to account for the current trend of the Transition fault.

I alter this model by requiring that the Transition fault be locked from about 5 m.y. to present, thus requiring about 300 km of northward movement of the block during this time. I also assume that the block began the collision process at about the close of the Miocene, in accord with the age of the Yakataga Formation given by Lagoe (1983), and that rotation occurred during the early stages of the collision. Finally, I assume that Pacific-North America convergence is partitioned along two parallel transform faults moving at different rates, with the Yakutat block lying between the two faults. Total displacement along these faults would be about 1500 km (6 cm/y for 25 m.y.).

In this model (Fig. 35), Pacific-North America motion is taken up by a transform fault on the seaward side of the Yakutat block prior to 25 m.y. (Fig. 35a); this transform fault will eventually be the Transition fault. At about 25 m.y., motion begans on the Chatham Strait fault, separating the proto-Yakutat block from the North American continental margin (Fig. 35b). Between 25 and 5 m.y., both the Transition fault and landward fault are active, with displacement on the Transition fault of about 900 km, at 4.5 cm/yr, and displacement on the landward fault of about 300 km, at 1.5 cm/yr. The landward fault is initially the Chatham Strait fault, with maximum offset of around 100 km, but shifts to the ancestral Queen Charlotte fault, cutting across the Chatham Strait fault and isolating the presumed Chugach terrane rocks of the Yakutat block from the rest of the Chugach terrane (Fig. 35c).

Towards the end of the Miocene, as the Yakutat block begins to collide with and subduct beneath southern Alaska, the block also starts a counterclockwise rotation. If transform motion continues on the Transition fault during this rotation, the Yakutat block would move independently of the Pacific and North America plates, moving progressively north to northeast during continued rotation (Fig. 35d), as suggested in the discussion for Fig. 34. By about 5 m.y., after about 45° of rotation, the Transition fault locks, and the Yakutat block attaches to the Pacific plate (Fig. 35e). From 5 m.y. to present, the Yakutat block would then move an additional 300 km northwestward with the Pacific plate, with motion taken up on the Queen Charlotte fault (Fig. 35f).

An advantage of this model is that the Yakutat block would be close to

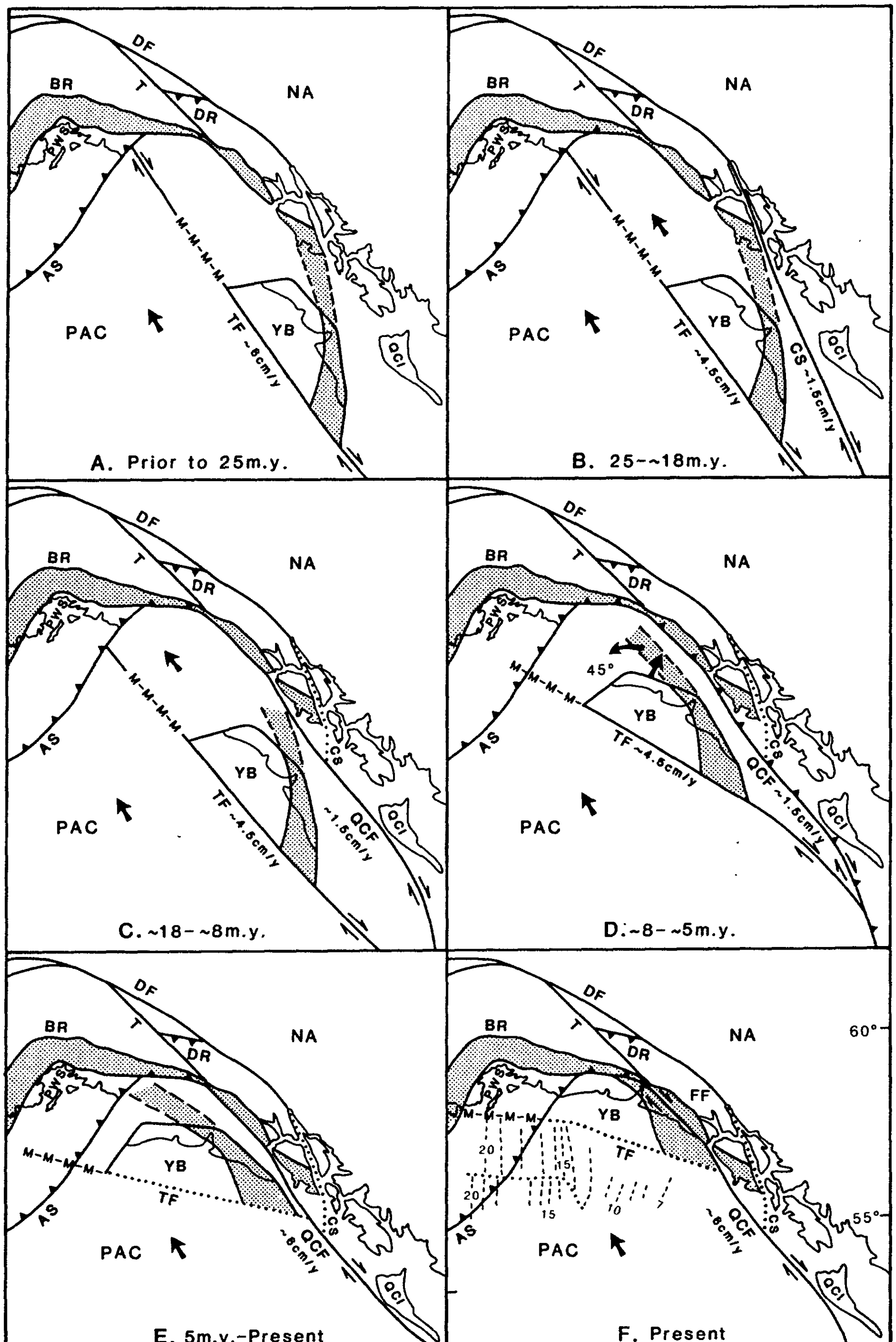


Figure 35. Model for limited northward movement of Yakutat block. Pacific-North America motion partitioned between two transform faults, with about 45^{o} of counterclockwise rotation during northward movement. Shaded area--Chugach terrane. Onshore faults shown for reference only; otherwise, solid line--active fault; dotted line--inactive fault; barbs--subduction zone. Heavy arrows indicate plate motion direction; other symbols as in Fig. 1. AS-Aleutian subduction zone; BR-Border Ranges fault; CS-Chatham Strait fault; DF-Denali fault; DR-Duke River fault; NA-North America plate; PAC-Pacific plate; PWS-Prince William Sound; QCI-Queen Charlotte Islands; TF-Transition fault; YB-Yakutat block; -approximately. A. Pacific-North America motion on fault seaward of Yakutat block. B. Movement on both Transition fault and Chatham Strait fault at different rates; Yakutat block moves between faults, independently of Pacific plate. C. Queen Charlotte fault cuts across Chatham Strait fault, which becomes inactive; Chugach terrane offset. D. Yakutat block rotates about 45^{o}, accompanied by north to northeast movement of block as transform motion continues on both Transition fault and Queen Charlotte fault. E. Transition fault locks; Pacific-North America motion taken up on Fairweather fault; Yakutat block moves with Pacific plate. F. Present simplified, idealized setting of Yakutat block. See text for further discussion.

the Coast Range Plutonic Complex of British Columbia during Eocene and Oligocene time. This complex was uplifted during the Paleogene and about 10 to 20 km of overburden stripped off (Hollister, 1979). Hollister (1979) suggests that the resulting sediment would be deposited along the continental margin as slope and deep-sea fan deposits and subsequently displaced northwards by transform faulting along the North American margin. Thus, this complex could have served as the source terrane for the Yakutat block Paleogene strata, as suggested by Plafker and others (1980).

However, the model is in marked disagreement with the faunal correlations of Keller and others (1984). If the faunal data are correct, than the Yakutat block, assumed by Plafker (1983) and Nye (1983) to be the southern extension of the Chugach terrane, could not have been adjacent to the British Columbia Coast Range throughout the Paleogene, and the Coast Range could not have served as the sole source for the Yakutat block Paleogene strata.

The principle difference between the models is that the Bruns (1983a) model accounts for the large northward displacement required by microfaunal assemblages from the Yakutat block, while the Plafker (1983) and Nye (1983) model, which suggests considerably less northward displacement, places the Yakutat block adjacent to a possible source terrain for the Yakutat block Paleogene strata.

An alternative possibility is that during the late Eocene and Oligocene, the Yakutat block was extensive enough to receive sediment from the Coast Range Plutonic Complex. About 120 km of subducted Yakutat block may be present in the Wrangell Benioff zone that underlies southern Alaska; additional parts of the block may lie in the Aleutian subducted slab. Drainages could have connected across now subducted parts of the Yakutat block to the Coast Range Plutonic Complex.

Also, the model presented here for limited motion could accomodate substantially greater northward motion by assuming different rates on the faults bounding the Yakutat block. If most of Pacific-North America motion were accomodated on the inboard fault, the total northward motion of the Yakutat block would be almost the same as in the Bruns (1983a) model. However, the missing seaward part of the Yakutat block could then have moved north of the block and either subducted beneath or accreted onto southern Alaska.

Clearly the most determinative evidence for Yakutat block motion, the microfaunal correlations of Keller and others (1984), favors substantial northward movement for the Yakutat block. Also clearly, an independent assessment of Yakutat block northward motion with paleomagnetic data from the block would substantially improve our understanding of the problem. Until then, however, I find the paleolatitudes indicated by the microfauna to be more compelling than a possible source location for the Paleogene strata, and I favor a model with substantial, rather than limited northward drift of the Yakutat block during the Cenozoic.

Tectonic implications of the Yakutat block collision

The Yakutat block collision and accretion provides an opportunity to study an actively accreting terrane, and to examine the effects of the accretion process on the deformation and tectonic history of the terrane. The Yakutat block is a modern analog to events which have amalgamated the collage of terranes that now form southern Alaska. Several important tectonic implications, questions, and needs for further study emerge from the study of the Yakutat block.

Much, and perhaps most, of the late Cenozoic closure between the Yakutat block and southern Alaska has been accomodated by subduction of oceanic or Yakutat block crust north of the advancing Yakutat block. The collision of the Yakutat block has been an ongoing process for at least the last 5 m.y., and probably since about late Miocene time. During that time, closure between the Yakutat block and southern Alaska has been at least 300 km. This closure has been accomodated in part by mountain building and continental thickening. However, subduction has been the dominant mechanism for accomodating Pacific-North America convergence. Evidence for subduction includes volcanism in the Wrangell mountains since about the middle Miocene (Denton and Armstrong, 1969; Deininger, 1972; Nye, 1983) and the presence of a Benioff zone beneath southern Alaska (Stephens and others, 1983, 1984). The Wrangell Benioff zone extends to at least 85 km, indicating a subducted slab about 120 km long; thus, almost one-third of late Miocene to Quaternary Yakutat block-southern Alaska closure is accounted for in the still present slab. The Wrangell volcanism indicates continuity of subduction for most of the late Cenozoic. Since subduction has been the dominant process for accomodating Yakutat block motion, than structural deformation and offset on major strike-slip faults will not necessarily indicate the total amount of closure that has occurred, since these faults may be zones of oblique subduction. Therefore, it is perhaps not surprising that offset on the onshore strike-slip faults of Alaska is far less than is necessary to account for late Cenozoic Pacific-North America convergence.

The subduction of the Yakutat block beneath the Middleton segment is an example of subduction of a thick, low density sedimentary sequence. A common assumption is that such a low density, buoyant terrane would resist subduction. Yet the Yakutat block is apparently subducting beneath the Middleton segment with almost total decoupling from the overriding plate, and with no accretion or major mountain building resulting within the Middleton segment from the subduction process. Only a 10 to 15 km wide zone of intense deformation is observed at the Kayak zone. Apparently, subduction of such a block is not only possible, but may leave only a narrow zone of deformation behind to mark passage of the block.

The collision of the northern margin of the Yakutat block is causing major uplift of the Saint Elias and Fairweather mountain ranges. The partition of the Yakutat block into continental crust and oceanic crust at the Dangerous River zone approximately coincides with the mountain building and non-mountain building deformation along the Chugach-Saint Elias mountains and Kayak zone respectively. This partition suggests that collision of continental crust might be a necessary condition for mountain building, whereas oceanic crust, even with a thick overlying sedimentary sequence, may subduct without major tectonic effects and with little geologic evidence left behind to mark its passage.

The Wrangell volcanoes have been a site of voluminous magmatism (about 10 times the normal arc magmatism production rate) during the Pleistocene (Nye, 1983). Nye (1983) suggests that the collision of the Yakutat block with southern Alaska has a causal effect on this magmatic event, with compression during microplate collision forcing the rise and extrusion of what would otherwise become deep-seated intrusive bodies. Perhaps anomalously voluminous magmatism in the geologic record could be used as an indicator of a collision event.

This study has an important implication for seismic risk potential in the northern Gulf of Alaska. Published tectonic models infer subduction of the Pacific plate beneath the Yakutat block beginning at the Transition fault, and assume that the block is underlain by a major detachment fault (Perez and Jacob, 1980; Lahr and Plafker, 1980). Instead, based on structural data along the Transition fault, I rule out a subduction component for at least Pliocene and Quaternary time, and conclude the Yakutat block is not underlain by a major detachment fault.

However, a possible end product of a terrane collision and accretion process is a shift of the subduction zone either across or outboard of the colliding terrane as the presumably buoyant, accreting terrane jams the subduction zone. One area where such a process could be occurring is adjacent to the Fairweather Ground high. Several Quaternary folds at the base of the slope have a trend almost perpendicular to the Pacific-North America convergence vector. These folds could mark the initial deformation associated with a subduction shift outboard of the accreting Yakutat block. Subduction along the Transition fault could therefore now be occurring, but only as a result of a latest Quaternary or Holocene adjustment to the collision process. More study is needed in this area to determine if it might mark a major ongoing change in the tectonics of the Yakutat block.

The structure along the Kayak zone provides extreme examples of the deformation process at a subduction zone. The thick sediment of the Yakutat block is subducting at the Kayak zone with little accretion, and marked by only a narrow zone of deformation. Similarly, south of Middleton Island seismic data show a thick sedimentary section subducting with little deformation or accretion (line 425, Fig. 33). However, major deformation occurs at Khitrov Ridge, where oceanic strata are folded into the large structure underlying the ridge (Figs. 17, 20, 21), and about 60 km southwest of line 425, where a well developed accretionary complex is developed at the base of the slope. Thus, within a short geographic distance, subduction occurs with both little deformation and major deformation. Further study is needed to resolve the question of how such extreme variability in the mechanics of the subduction process can occur within such a limited area, and in the case of the oceanic strata, with essentially the same sediment input arriving at the subduction zone. This variability could in part be due to the subduction of the Yakutat block below the Middleton segment, followed by the reestablishment of the more typical Aleutian subduction margin.

The structural deformation of the Yakataga segment offers an opportunity to study the mechanics of deformation within an accreting, colliding terrane. The deformation could also be similar to that which occurs in accretionary wedges. Geologic information from exploratory wells drilled on the folds can be combined with the seismic reflection data to better delineate the stratigraphy, structure, and timing of deformation in the fold belt. Such a study may yield an analog for processes which have occurred in accreted strata in the geologic record, and which may be occurring along convergent continental margins.

The structure of the Yakutat block indicates that elements of the block may be rotated during the collision process. Such a process may be recorded in the anticlines of the Yakataga segment. The large anticline southwest of Icy Bay was probably continuous with the anticline underlying Pamplona Spur (Bruns and Schwab, 1983). On these structures, maximum deformation and faulting occurs where they are closest together, and the intensity of folding decreases away from this point. The strike is also notably different from the regional trend, trending east-west and north-south respectively. Thus, these anticlines appear to have been rotated about a hinge line through the center point, with an undeformed part of the Yakutat block acting as an indenter. Similarly, onshore structures generally parallel the major bounding faults at the Kayak zone and the Chugach-Saint Elias fault, perhaps rotating towards these faults during convergence. The bounding faults may also reflect rotation, with the Yakutat block acting as an indenter. Such rotated elements might be left in the geologic record as an accreting block breaks up during the collision process. If so, direction indicators such as paleomagnetic or paleocurrent data could indicate markedly different rotations within relatively small geographic areas. Also, direction indicators cannot necessarily be used to indicate rotation of an allochthonous terrane during translation; they may instead record localized processes that occurred within the terrane during the final stages of collision and accretion.

The Yakutat block collision has implications for hydrocarbon potential. Exploratory drilling on folds of the Yakataga segment, primarily into Neogene and Quaternary strata, and south of Yakutat Bay, into Paleogene strata, has not discovered commercial hydrocarbons. Dredge samples from the slope indicate that both source and reservoir rocks are present in the Paleogene section of the Yakutat block, but that the source rocks are immature to marginally mature for hydrocarbon generation (Plafker and others, 1980). These source rocks are subducting with the Yakutat block and are carried deep within the crust. There may therefore be enhanced potential for hydrocarbon maturation, generation, migration, and trapping along the collision zone. Both structural and stratigraphic traps may be common, and faults may provide an avenue for updip hydrocarbon migration into the numerous known onshore oil seeps. The collision zone could be analogous to the overthrust belt of the Rocky mountains. The ongoing hydrocarbon exploration in the northern Gulf of Alaska has so far not focused on this possibility, and it may be an important area for future research and exploration.

CONCLUSIONS

The Yakutat block is bounded by the Fairweather-Queen Charlotte fault, the Chugach Saint Elias fault system, the Kayak zone, and the Transition fault. The block is colliding with and accreting to southern Alaska, causing a major orogenic event in the Saint Elias and Fairweather mountains. Magnetic data suggest that the block is subducting beneath the continental margin west of Kayak Island and extends to at least the Kenai Peninsula in the subducted plate.

Major deformation of the Yakutat block occurs along the northwest margin of the block, where maximum convergence occurs between the block and southern

Alaska. Uplift of Fairweather Ground during the Pliocene and Quaternary may reflect local reactivation of part of the otherwise locked Transition fault. Elsewhere, offshore strata of the block are undeformed and characterized primarily by regional subsidence.

The marine geophysical and geological data define the Pliocene and Quaternary tectonic setting of the Yakutat block, and impose major constraints on the pre-Pliocene origin and tectonic history of the block. These constraints are: (1) The basement rocks of the Yakutat block consist of a probable Mesozoic to Paleocene subduction complex east of the Dangerous River zone, and Paleocene and Eocene oceanic basalt to the west; the Dangerous River zone most likely formed the edge of the Paleogene basin. (2) A thick Paleogene section underlies the block, and is truncated at the continental margin. This section requires a large source area adjacent to the block during the Paleogene, probably a continental margin. (3) Faunal assemblages from the Paleogene strata of the Yakutat block require substantial northward motion of the block, $30^{\circ} \pm 5^{\circ}$ in the last 50 m.y., and closure of 5° to 10° between the Yakutat block and the Middleton segment. (4) The Transition fault is a major tectonic boundary on the south side of the block. The fault has been inactive during Pliocene and Quaternary time, since it is overlain by undeformed strata of this age, and fans at the base of the slope are not offset from their probable source area. (5) the Yakutat block has moved with the Pacific plate for at least the last 5 m.y. This motion has largely been accomodated by subduction of the Yakutat block beneath southern Alaska, but also includes structural shortening and major uplift onshore. (6) Prior to the Pliocene, major tectonism along the Transition fault juxtaposed Oligocene oceanic basement against Paleogene and Mesozoic rocks of the Yakutat block and truncated the Paleogene basin of the block. (7) The Transition fault is most likely a transform fault. Tectonism along the fault occurred without causing major deformation of the Yakutat block or accretion along the Transition fault. Subduction along the Transition fault is unlikely.

Two speculative models have been proposed for the origin and movement history of the Yakutat block, requiring either 5° or 30° of northward motion. I conclude that the model which best satisfies the constraints listed above is that the Yakutat block originated as a composite oceanic-continental terrane during subduction of the Kula-Farallon spreading center beneath North America about 45 m.y. ago. The Yakutat block has since moved north with the Kula and Pacific plates. Further study is needed, however, to better determine the geologic history of the Yakutat block, especially of paleomagnetics of the block, of source terrains for the Yakutat block strata, and of correlations of Yakutat block faunal and floral assemblages with coeval North American assemblages.

The tectonic setting of the Yakutat block offers an opportunity to study an ongoing collision and accretion process that is a modern analog to events which have brought together the numerous tectonostratigraphic terranes that comprise southern Alaska. Examples of tectonic processes occurring due to the Yakutat block collision are: (1) subduction of a thick, low density crust at the Kayak zone with only a narrow zone of complex structure marking the suture zone; (2) the development of a fold and thrust belt that may be analogous to an accretionary wedge at a convergent margin; (3) a possible relation of mountain building versus non-mountain building to subduction of continental versus oceanic crust; (4) extreme end members of almost complete subduction and accretion processes along the Kayak zone within a relatively short distance; (5) the rotation of elements of the block during the collision process; (6) subduction of potential hydrocarbon source rocks that may lead to enhanced potential for hydrocarbon generation, migration and accumulation along the collision zone; and (7) a subduction shift outboard of or across the Yakutat block that could be occurring during late Pleistocene to Holocene time.

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