UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

PETROLEUM POTENTIAL, ENVIRONMENTAL GEOLOGY, AND THE TECHNOLOGY FOR EXPLORATION AND DEVELOPMENT OF THE KODIAK LEASE SALE AREA #61

by

Roland von Huene, Michael A. Fisher, Monty A. Hampton

and

Maurice Lynch

U.S. Geological Survey

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This report is preliminary and
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for conformity with Geological
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SUMMARY

The Kodiak lease area is along a convergent ocean margin where active subduction is probably the greatest single influence on the geology. This influence is indicated by the Aleutian Trench, the Aleutian chain of volcanoes, and a well developed Benioff zone of earthquakes. Crustal structure under the Kodiak Shelf is intermediate between continental and oceanic. The thickness of sedimentary rock is 8 ± 3 km, which is greater than beneath the island. The proposed lease-sale area is on a submerged shelf extending 100 km or more seaward from the Kodiak group of islands, and it is more than 400 km long. The Kodiak Shelf still retains a glacial topography which has been modified by tectonically uplifted banks along the shelf edge and across the shelf. These banks are readily detectable signs of recent tectonism. Not so easily detectable are three deep offshore Neogene basins formed by depression of an unsampled presumed Paleogene sedimentary section. The basin floors have subsided 5 to 7 km since middle (?) Miocene time; the basins are filled with late Miocene and younger sediment that is only gently deformed.

A sudden increase in seismic velocity occurs across the contact between the basin fill and the presumed Paleogene rocks that underlie it. This discontinuity in seismic velocity, the smooth character of the basin surface, and the truncation of dipping beds beneath it, are the basis for inferring subaerial erosion of the Paleogene section. If this inference is correct, the structure in some places requires at least 3000 m of subsidence followed by an uplift of even greater magnitude in Neogene time. The vertical tectonism offshore might produce reservoir rock and different source rock than encountered onshore.

Source and reservoir characteristics of the outcropping rocks on Kodiak Island are poor and offer little encouragement for finding commercial quantities of liquid hydrocarbons if these charcteristics continue offshore. Thermal maturity onshore was found only in Paleogene rocks and the organic carbon is of a kind more conducive for production of gas and gas condensate. These same source and reservoir characteristics may not be found under the Kodiak Shelf, because the rocks on the island have probably been deeply eroded to expose rock subjected to metamorphism at depth. Therefore, the potential for finding commercial hydrocarbon resources beneath the Kodiak Shelf will depend on discovery of source and reservoir conditions better than those onshore. The potential traps offshore are both structural and stratigraphic. The geologic history of the Kodiak Shelf indicates that coarse transgressive sediment may rest on the truncated Paleogene section. If the coarse material has an underlyng Paleogene source and is sealed by overlying Neogene caprock, migrating hydrocarbons may have accumulated in a stratigraphic trap. A resource appraisal of the Kodiak Shelf area out to a 200 m water depth indicates that at a 5 percent probability, 2.21 billion barels of recoverable oil and 10.87 trillion cubic feet of recoverable gas may be in the area; at a 95 percent probability 0.2 billion barrels of oil and 2.50 trillion cubic feet of gas may be in the area. The statistical mean of the appraisal is 0.87 billion barrels of oil and 5.70 trillion cubic feet of gas.

The geo-environmental setting of Kodiak Island shelf is perhaps more favorable than farther east in the Gulf of Alaska, because the sedimentary cover is more coherent. The hazards to resource exploration and development include shaking from seismic events, active faulting at the ocean floor, and possible strong bottom currents. It seems likely that a major earthquake in a seismic gap to the southwest (Shumagin gap) will cause shaking along the Kodiak Shelf and perhaps generate a tsunami sometime during the lifetime of an oil or gas field. Moderate local earthquakes in the vicinity of southern Albatross Bank will continue to occur, but historically these have not been accompanied by significant tsunamis. Volcanism on the Alaska Peninsula may result in some ash falls but is unlikely to be a major nuisance to offshore operation. The sedimentary bedrock appears to provide relatively strong foundations, and unconsolidated sediment should not pose problems outside the relic glacial troughs. Slope instability is not a major problem outside of channels on the shelf, but could be a cause for concern if exploration is extended onto the upper continental slope.

INTRODUCTION

This paper is a summary of the geology and geophysics within and surrounding the proposed Kodiak Shelf lease-sale area, and of the environmental geology, and an estimate of petroleum potential, and of the manpower requirements needed for exploration and development. The area proposed for nomination (Fig. 1) includes the continental shelf, where water is less than 200 m deep, although some areas under as much as 5000 m of water are also included. The nomination area is bounded on the east by 148°W longitude and on the north and west by the Kenai Peninsula and the Kodiak group of islands. The south boundary lies along the 56°N and the 58°N parallels of latitude. The area does not include Shelikof Strait on the northwest side of Kodiak Island.

This prenomination summary report succeeds a previous one (von Huene and others, 1976) that was based on less data. Since the earlier report, a series of studies has resulted in publications and papers in preparation to address various aspects of (1) regional geology (Connelly, 1978; Connelly and Moore, 1977; von Huene and others, 1979a & b; von Huene, 1979; Fisher and others, in press); (2) the structure and petroleum potential of the area (Fisher, 1979; Fisher and Holmes, 1980; Fisher and von Huene, 1980; Fisher, in press); and (3) the environmental geology (Hampton and Bouma, 1979; Hampton and others, 1979; Thrasher, 1979; von Huene and others, in prep.). A revised resource estimate was prepared on the basis of these new data. This report summarizes those publications and the prior work.

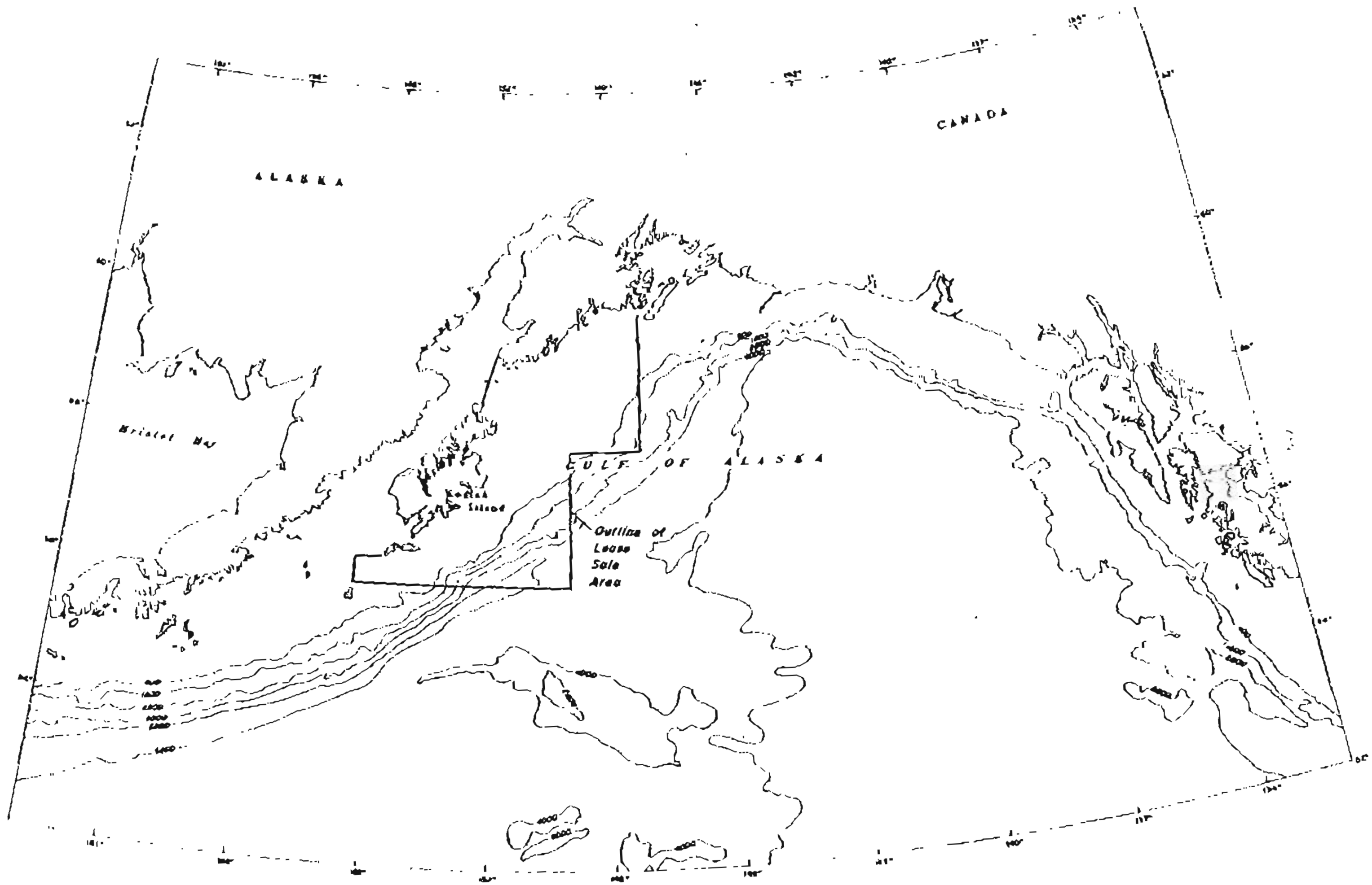

FIG. 1

Map of the north Pacific showing location of Kodiak area proposed for leasing.

The first publicly available offshore data on the shelf are from the late 1960's and are concerned with the Alaska earthquake of 1964 (see Oceanography and Coastal Engineering Volume, National Academy of Sciences, 1972). The Glomar Challenger of the Deep Sea Drilling Project was used to drill 4 holes in deep water off Kodiak Island for scientific research in 1971 (Kulm, von Huene, and others, 1973). Regional studies in areas with petroleum potential, were begun by the Geological Survey's Office of Marine Geology in 1975 by collection of seismic-refraction, CDP, and high-resolution seismic-reflection data. By 1977 regional coverage in all but the northeastern part of the area had been acquired (fig. 2). No further support has been available to the Office of Marine Geology to complete the geophysical coverage. The Conservation Division of the Geological Survey collected a closely spaced grid of high resolution seismic and bathymetric data under contract with the Petty-Ray Geophysical Company (Thrasher, 1979).

FRAMEWORK GEOLOGY

The Regional Plate-Tectonic Context

Plate-tectonic boundaries in the Gulf of Alaska consist of a transform fault along British Columbia and southeast Alaska that joins the convergent margin along the Aleutian Trench through a complex oblique convergent segment (fig. 3). This plate tectonic model provides a simple but generalized structure of the Gulf of Alaska to use as a conceptual hypothesis within which to interpret local observations (von Huene and others, 1979a and b; Bruns, 1979).

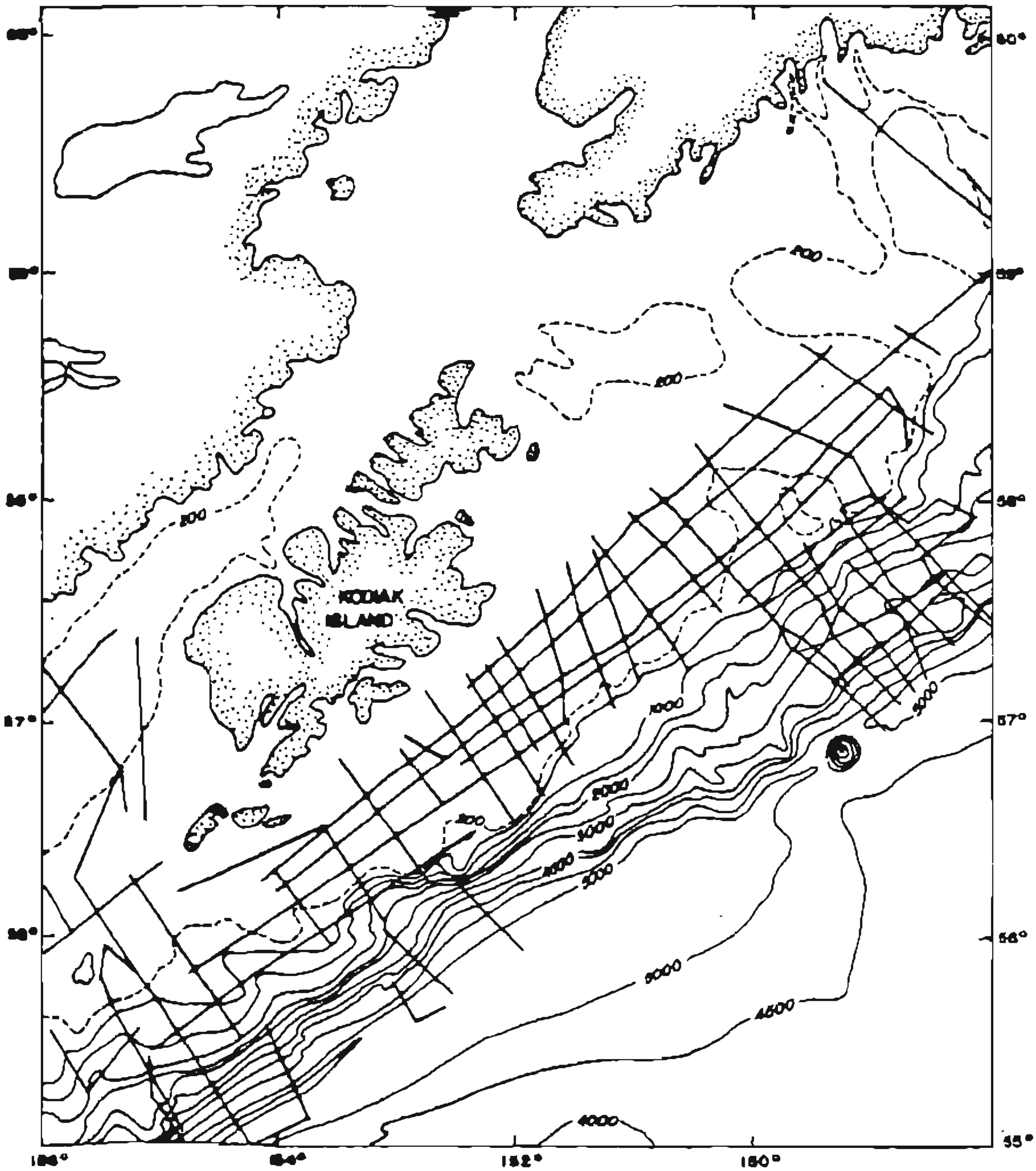

FIG. 2

U.S. Geological Survey 24 channel CDP seismic reflection lines on the Kodiak shelf, Alaska.

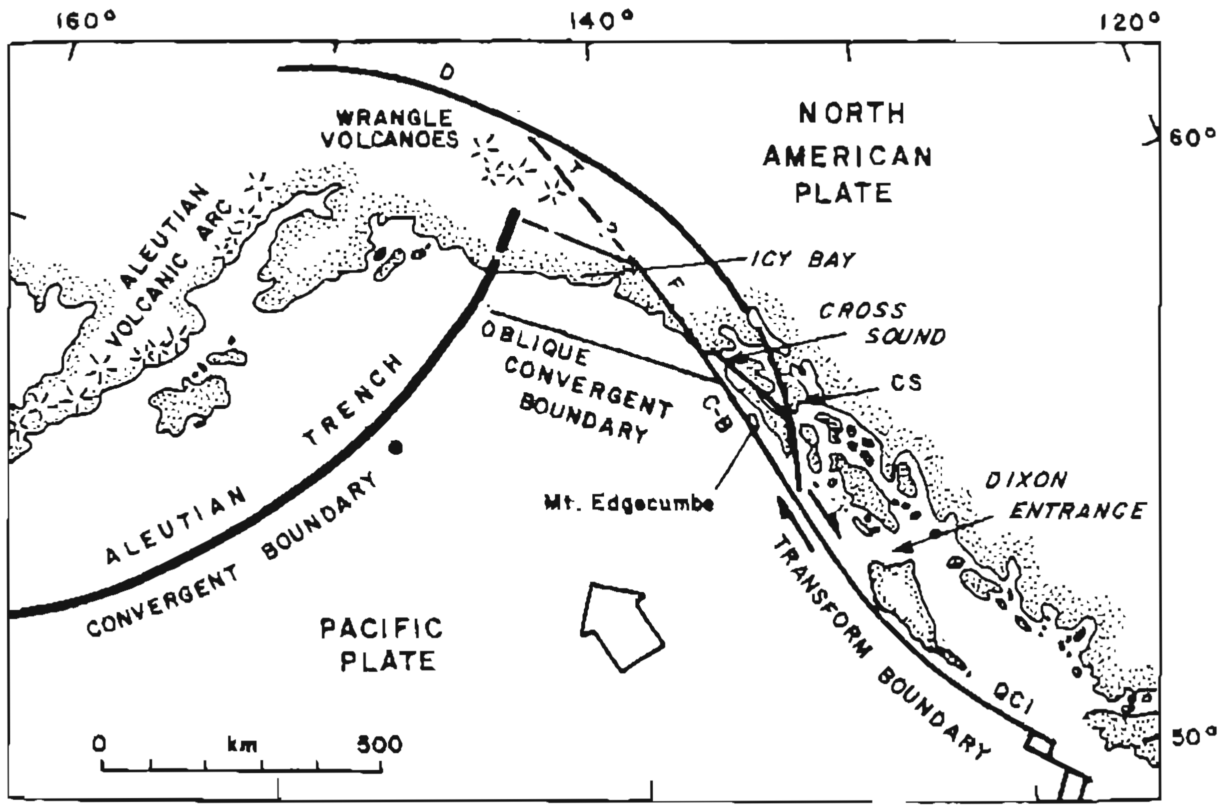

FIGURE 3

Diagram of major late Cenozoic plate tectonic boundaries. The Denali, Totchunda, Fairweather, Chatham Strait, Chicagof-Baranof, and Queen Charlotte faults indicated by D, T, F, CS, and QC respectively (from von Huene and others, 1979).

The transform plate boundary is commonly shown as a single feature that starts north of the Juan de Fuca spreading ridge and crosses the continental shelf to join the Fairweather fault. In closer detail there appear to be three segments of the fault zone although the data here are only of a reconnaissance nature. At the south, the Queen Charlotte transform fault zone extends north from the Alaska-British Columbia border to Chatham Strait, where it becomes the Chichagof-Baranof fault zone, and then merges with the Fairweather fault at a 20° angle. The details of the intersections are not well known, but these fault zones are main zones of active tectonism, and all exhibit evidence of right-lateral movement. This margin clearly was truncated, perhaps in early Neogene time, but no simple reconstruction fits missing pieces together to give the Paleogene paleogeography.

The Queen Charlotte-Chichagof-Baranof faults can be traced into both the Fairweather fault and a fault paralleling the Fairweather fault but just offshore. Lateral displacement of about 5 cm/yr has been observed along the Fairweather fault in Quaternary time, however, there is other evidence that the Fairweather fault has much less Neogene displacement than required by plate-tectonic reconstructions (Plafker and others, 1978; Hudson and others, 1977). Thus large thrust motions have been proposed to occur at the base of the continental margin in the central Gulf of Alaska despite the lack of much seafloor evidence (von Huene and others, 1979b, Bruns, 1979).

The obliquely convergent plate boundary in the central Gulf of Alaska includes a zone of continental or transitional lithosphere that is as much as 300 km wide and that extends inland to the Denali fault from a buried trench or from a pre-Pliocene fan at the foot of the continental slope (Bruns, 1979). At the seaward edge, seismic records show outcrops of sediment buried deeply beneath the shelf from which Eocene and younger rocks have been recovered (Plafker and others, 1979). The overlying thick late Cenozoic section is much less deformed, indicating little deformation from the proposed late Cenozoic convergence at this tectonic boundary. A block bounded by the continental slope on one side, and by the Fairweather fault and its westward branches on the other, appears to have been moving in a similar direction but slower than the Pacific plate since the present motion began on the Fairweather fault. The plate geometry requires that the northwestern edge of this block, in the vicinity of Kayak Island, impinges against the Alaskan subcontinent at possibly 4 cm/yr to form a zone of convergence between two continental blocks. West of Kayak Island, earthquake foci outline a Benioff zone, thereby supporting the plate-tectonic implications of continental collision.

The convergent margin is defined by the Aleutian Trench, with its associated Benioff zone, and by the Aleutian chain of volcanoes. The forearc area contains several late Cenozoic basins, which are depressed areas in older sedimentary units (Fig. 4). The present convergent margin is perhaps the latest in a series of such margins that have existed since the mid-Mesozoic, as deduced from periods of intense magmatic activity.

In multichannel reflection records from a transect across the trench slope off the Kodiak shelf, the zone of major subduction, where beds are steeply tilted, occurs near the trench midslope terrace and involves sediment that has been tectonically consolidated on the trench lower slope (Fig. 5B; von Huene, 1979). Northeast and southwest of this transect, the structure of the trench slope is different (Fig. 5A,C), and in general, the subduction-zone structure appears more variable than has previously been implied (von Huene and others, 1979a).

Some areas of different trench structure are separated by transverse tectonic boundaries that sometimes form the ends of aftershock areas accompanying great earthquakes (Sykes, 1971). Such boundaries exist at the northeast and southwest ends of the Kodiak group of islands, which are an uplifted block (Fisher and others, in press). Evidence for the transverse boundaries includes offset volcanic lineations, termination of structural trends onshore and under the continental shelf, and the areal distribution of epicenters. The boundaries seem to be broad zones of disruption that began to form by at least the late Miocene or Pliocene. Although oceanic fracture zones and seamount chains intersect the continental margin near the boundaries, subduction of these features to cause the tectonic boundaries is not certain. Studies of global plate motion indicate that the fracture zones and seamount chains have swept northeastward toward the margin, at least since the late Pliocene, because of the direction of convergence of the Pacific and North America plates. Therefore the alignment is fortuitous unless global plate motion is incorrectly deduced.

The continental shelf along the Aleutian Trench contains numerous basins separated by broad transverse structures (Fig. 4). Stevenson, Albatross, Tugidak, and Shumagin basins are formed by depressed Paleogene and older sedimentary rock, and are filled with generally mildly deformed Neogene sediment. An unconformity or disconformity on the top of the depressed older sediment forms the acoustic-basement surface that underlies a sequence of gently folded younger strata. The seaward limits of the basins are commonly formed by an uplift that blocked sediment transport beyond the shelf. During Pleistocene time, the uplifted areas were often eroded. Sanak Basin is about 7 km deep and has a unique structure. The fault bounded northeast and

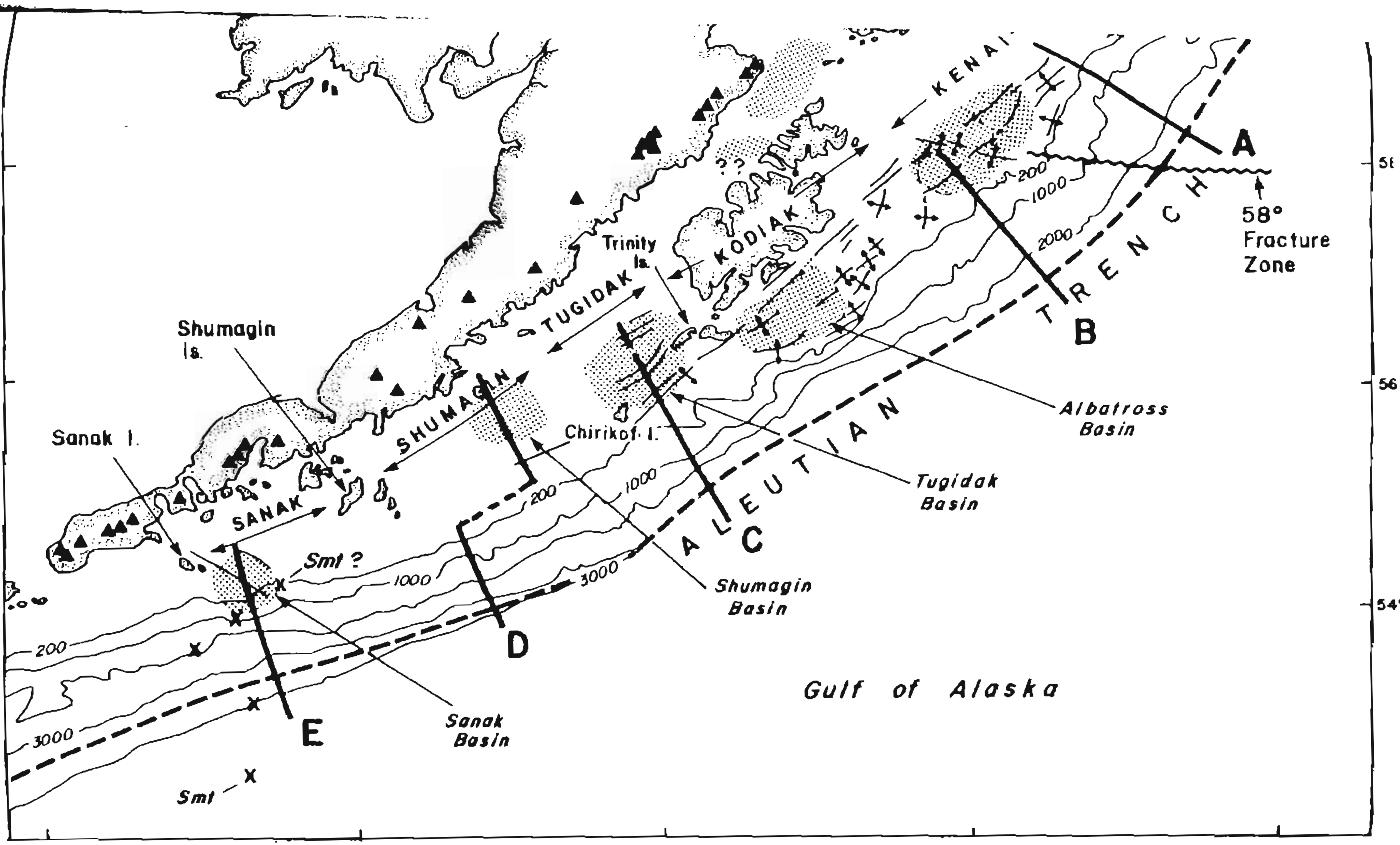

FIGURE 4 Neogene basins and structure on the Kodiak and Shumagin shelves. Lines A to E indicate location of sections in Figure 5 (from von Huene and others, 1979).

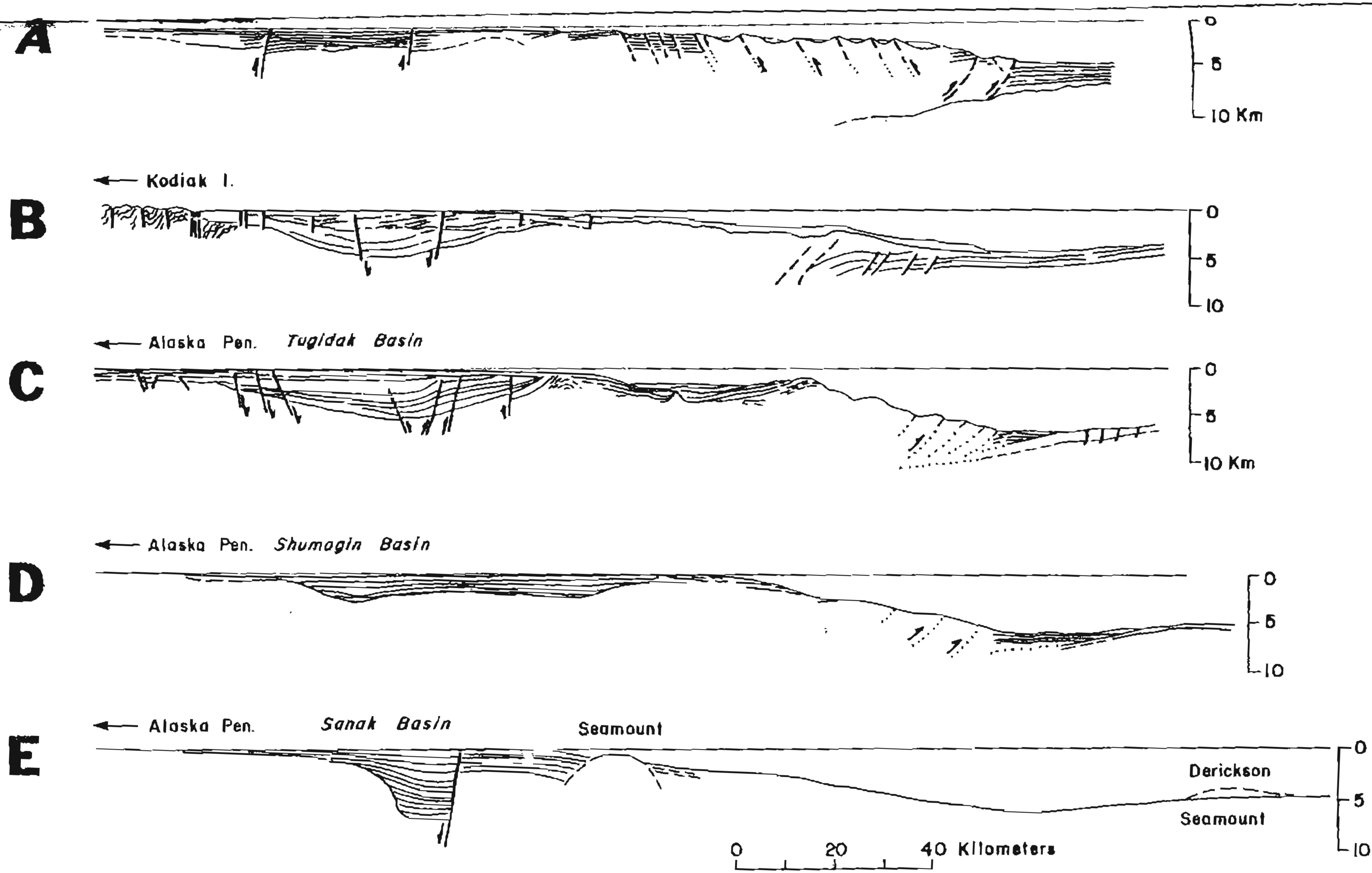

FIGURE 5 Sections across the convergent margin from the Kenai Peninsula to Sanak Island. Solid lines are reflections, dashed lines are inferred from reflections, and dotted lines are inferred from conceptual models of convergent margins. Stratified sequences are late Cenozoic except under Kodiak Island.

southwest flanks of that basin seem to be underlain by Cretaceous sedimentary rock and by early Tertiary intrusions exposed on the nearby outer Shumagin and Sanak Islands. All of these shelf basins may have formed at about the same time.

The shelf southeast of the Alaska Peninsula and the shelf southeast of Kodiak Island are similar; however, Paleogene sedimentary rock are exposed on Kodiak Island whereas rocks on the Semidi, Shumagin, and Sanak Islands are no younger than Cretaceous. This difference may be related to a difference in the amount of vertical movement across a transverse tectonic trend that appears to terminate the Kodiak group of islands on the southwest. Sanak Island seems to be the southwest extent of a terrain in which small forearc basins are separated by ridges. Southwest of Sanak Island, which is distinguished by the transverse strike of the rocks exposed there, another transverse boundary may separate two offshore forearc areas of different structure. Thus major differences in geologic history of terrains on opposite sides of transverse boundaries are likely.

The simple plate-tectonic model for the Gulf of Alaska is a useful framework for quickly grasping a regional tectonic overview. This overview indicates that the present relative tectonic motion consists of a transform boundary in the eastern Gulf and a direct convergence boundary at the Aleutian Trench. However, individual basins depart from this simple universal model, which therefore must be applied with decreasing confidence as the scale becomes larger and the age of the rocks increases.

Onshore Geology of the Kodiak Group of Islands

The onshore geology is described by Moore (1967, 1969), Allison (1978) and Nilsen and Moore (1979), and is summarized briefly by Fisher and von Huene (1980) and in cross sections by George Moore and Casey Moore (in von Huene and others, 1979). The rocks of Kodiak Island may be grouped into: (1) lower Mesozoic sedimentary, plutonic, and metamorphic rocks; (2) Mesozoic through Tertiary deformed sedimentary deposits, and (3) Paleocene plutonic rocks (Fig. 6). The contact between the lower Mesozoic rocks and the Mesozoic and Tertiary rocks is an extension of the Border Ranges fault, a feature that extends from southeastern Alaska around the Gulf of Alaska to Kodiak Island (MacKevett and Plafker, 1974; Plafker and others, 1976; Beikman, 1978). Rocks on the northwest side of the fault are of early Mesozoic age and include Triassic volcaniclastic turbidites and pillowed greenstone (Shuyak Formation of Connelly and Moore, 1977) Lower Jurassic dioritic plutons (188 ± 5 m.y.; Carden and others, 1977) that intrude the Triassic strata (Connelly, 1978) and schist that grades from blueschist facies in the southeast to epidote amphibolite in the northwest (Carden and others, 1977; Connelly, 1978).

Rocks on the southeast side of the Border Ranges fault are Mesozoic and Tertiary sedimentary rocks in belts that trend northeast. Strata within the belts decrease in age southeastward from the Border Ranges fault to the Pacific shore of Kodiak Island. The Uyak Complex, adjacent to the southeast side of the Border Ranges fault, is a tectonic melange that contains blocks of argillite, ultramafic rocks, pillow basalt, and radiolarian chert in a matrix of argillite (Connelly, 1978; Moore and Wheeler, 1978). Chert in the complex yields Paleozoic to Early Cretaceous microfossils (Connelly, 1978).

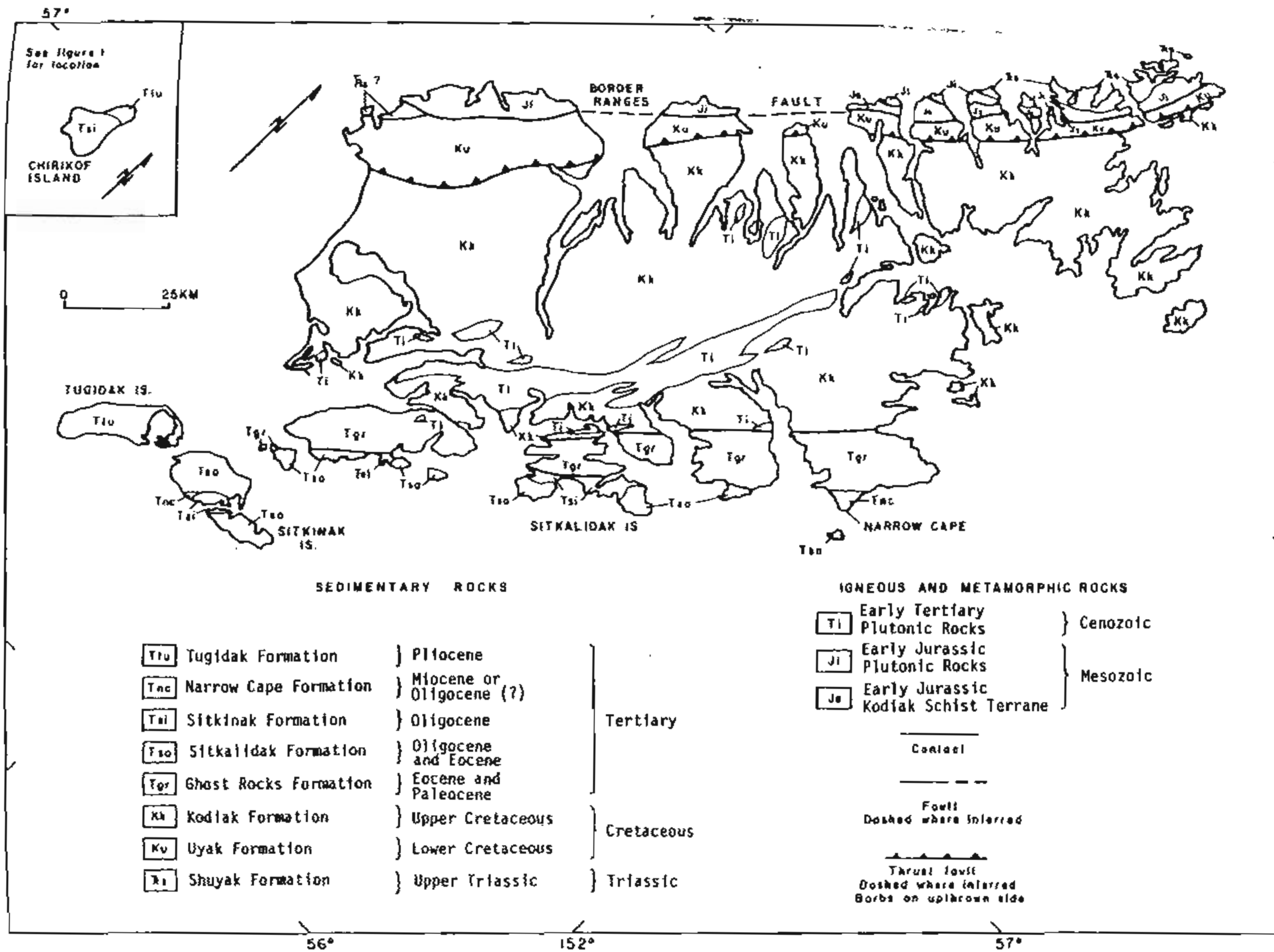

FIG. 6

Simplified geologic map of Kodiak Island based on mapping by G. W. Moore (1969) and J. C. Moore and Connelly (1978). Lines A and B show location of geologic sections, In fault contact with the Uyak Complex is the Kodiak Formation, a sequence of Upper Cretaceous (Maestrichtian; Jones and Clark, 1973) presumed deep water turbidites and hemipelagic deposits. Most of the turbidites were probably deposited on an oceanic basin plain and the remainder on a continental slope (Nilsen and Bouma, 1977; Nilsen and Moore, 1979). Strata in this unit generally dip steeply northwest, and in many places are deformed into tight folds and offset by shear zones that are at low angles to the adjacent bedding planes (Moore, 1967,1969).

The oldest unit in the Cenozoic section is the Paleocene and Eocene Ghost Rocks Formation that is faulted on the northwest against the Upper Cretaceous rocks (Moore, 1967, 1969; Lyle and others, 1977). The Ghost Rocks consists mostly of isoclinally folded shale and argillite, but pillowed greenstone and thin limestone beds are present locally. The Ghost Rocks may have been deposited on a continental slope, although this conclusion is tentative (Nilsen and Moore, 1979).

A fault separates the Ghost Rocks Formation from the Sitkalidak and Sitkinak Formations. Samples of both formations contain foraminifers of Eocene and Oligocene age (Lyle and others, 1977); however, Moore (1969) considered the Sitkinak to be Oligocene. The Sitkinak Formation contains an upper nonmarine part that is exposed only on Sitkinak Island. Moore (1969) and Nilsen and Moore (1979) distinguished the Sitkalidak from the marine part of the Sitkinak, exposed on Kodiak Island, on the basis of the relative abundance of conglomerate: the conglomeratic Sitkinak is stratigraphically higher than and in conformable contact with the Sitkalidak, in which conglomerate is rare. The environments of deposition of the marine parts of the two formations are nearly the same, as deduced from turbidite-lithofacies assemblages. Nilsen and Moore (1979) suggested that the Sitkalidak Formation represents a prograding deep-sea fan sequence that contains basin-plain to upper-slope deposits. However, microfossil assemblages, which show no signs of having been transported from a shallower environment, suggest that the rocks were deposited in a neritic environment (R. Boettcher, Anderson, Warren and Assoc., Inc., oral commun., 1978). The environment of deposition deduced from the sedimentary facies is at odds with that deduced from microfossil assemblages, and we presently prefer the sedimentologic interpretation that the strata were deposited in a bathyal environment.

The nonmarine part of the Sitkinak Formation on Sitkinak Island is in fault contact with the Sitkalidak Formation and consists of interbedded fluvial-channel conglomerate and interchannel shale and coal. Plant fossils date the nonmarine part as middle or late Oligocene (J. A. Wolfe, in Moore, 1969), however, they are now considered to be early Oligocene (J. A. Wolfe, oral commun., 1979). Moore (1969) extended the Sitkinak from Sitkinak Island to Chirikof and Kodiak Islands. Armentrout (1979), however, believes that the rocks assigned by Moore to the Sitkinak Formation on Chirikof and Kodiak Islands are of Eocene age and belong to the Sitkalidak Formation.

The Narrow Cape Formation crops out at two widely separated places. The northeastern outcrop, at Narrow Cape, is at the type section. There, early and middle Miocene shallow-water megafossils (Allison, 1978) are exposed in marine strata that overlie, with angular unconformity, steeply northwest-dipping strata of the Sitkalidak and Ghost Rocks Formations (Nilsen and Moore, 1979). The southern outcrop, on Sitkinak Island, consists of shallow water marine deposits of late Oligocene or early Miocene age (Allison, 1978; Nilsen and Moore, 1979). The strata rest conformably on the nonmarine part of the Sitkinak Formation and are preserved in two synclines.

Shallow-water marine strata of the Tugidak Formation of late Pliocene and early Pleistocene age (Allison, 1978) are exposed on Tugidak and Chirikof Islands, southwest of Kodiak Island. On Chirikof Island, Pliocene strata unconformably overlie strongly deformed Oligocene or older beds. The unconformity at the base of the Pliocene strata may pass between Tugidak and Sitkinak Islands because Tugidak Island is underlain by Pliocene strata, whereas Sitkinak Island is underlain by deformed Paleogene beds.

The third group of rocks exposed on Kodiak Island are plutonic rocks, which yield K/Ar dates in the range of 56 to 60 m.y. (Hill and Morris, 1977) and intrude the Upper Cretaceous (Maestrichtian) turbidites of the Kodiak Formation and Paleocene turbidites of the Ghost Rocks Formation (Moore, 1967). The plutonic rocks may have formed by anatexis of the country rock (Hudson and Plafker, 1977; Hudson and others, 1979).

A cross section through Kodiak Island illustrates the general tectonic style in the insular block (Fig. 7). Beds generally strike northeast parallel to the regional trend, and the dips of all features are dominantly northwest. This structure is interpreted to have formed by accretion in Mesozoic and early Cenozoic time. Deformation generally decreases toward the trench as does the age of the rock. Most units are fault-bounded making it difficult to estimate total sediment thickness, however, projecting a marine refraction measurement along strike suggests that sedimentary rock beneath the island is at least 3 km thick (Shor and von Huene, 1972).

In summary, Kodiak Island is a terrain exposing accreted upper Mesozoic and lower Cenozoic rock, predominantly rock of Cretaceous age. The belts of accreted rock parallel the Aleutian trench. The landward (northwest) boundary of the accreted complex includes a fault zone that is probably an extension of the Border Ranges fault (McKevett and Plafker, 1974), which is a fundamental

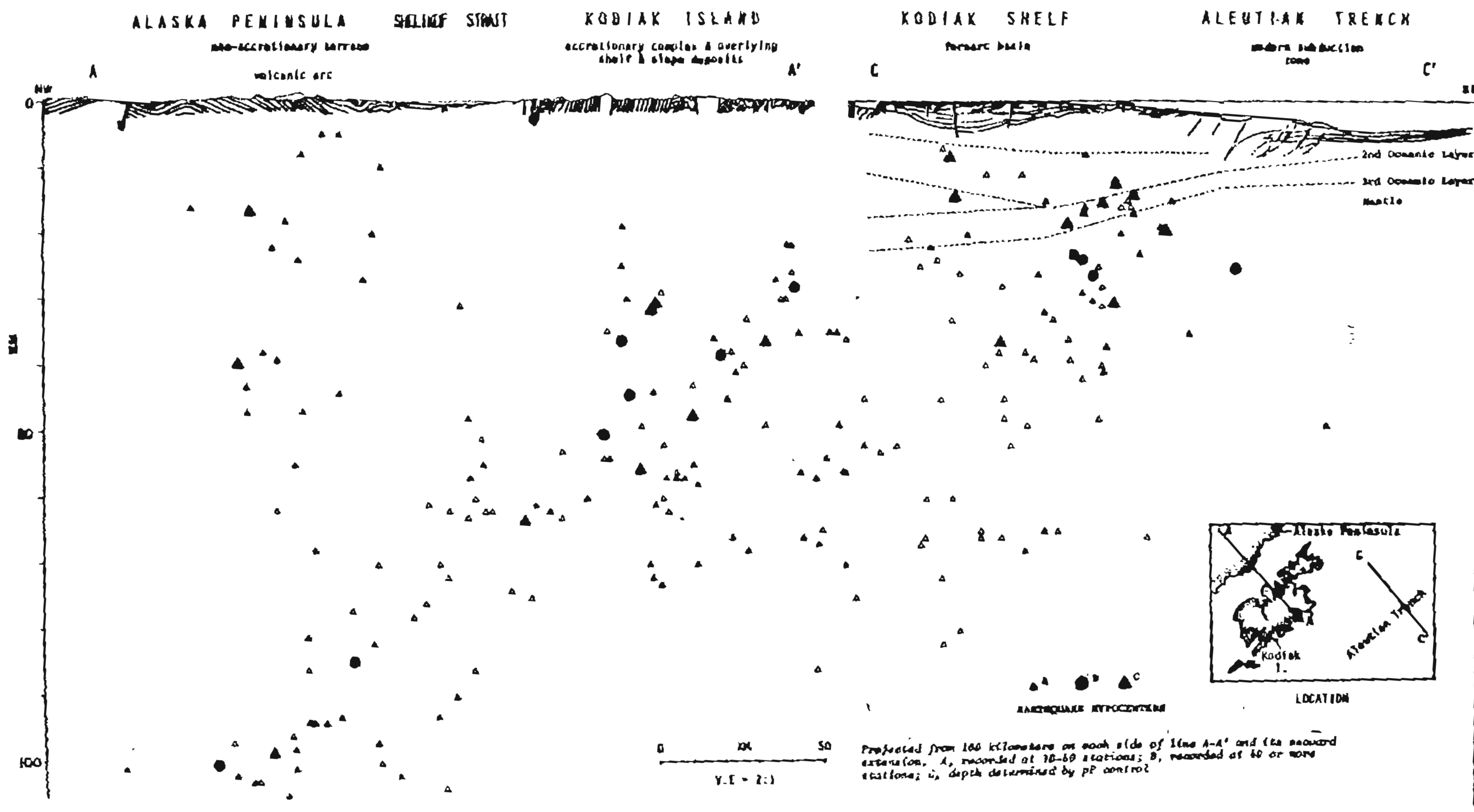

FIG. 7

Geologic section across Kodiak Island and the Kodiak margin showing structure from the Aleutian volcanic arc to the Aleutian Trench. Earthquake hypocenters shown in circles and triangles; crustal structure from seismic-refraction measurements shown by dashed lines. For further explanation of the cross section see von Huene and others, 1979.

tectonic boundary around the Gulf of Alaska. On Kodiak Island the fault is associated with the separation of less deformed sedimentary rock deposited in a shelf and slope environment that underlie the Alaska Peninsula and Shelikof Strait from the steeply dipping accreted rocks originally deposited in ocean basin, trench, and trench-slope environments on Kodiak Island. Kodiak Island was emergent in the Oligocene as shown by inclusion of pebbles of distinctive Mesozoic and early Tertiary rock in the nonmarine Sitkinak deposits on Sitkinak Island.

Seismicity and Crustal Structure

The Kodiak shelf lies within a single zone of aftershock activity from major earthquakes such as the 1964 Great Alaskan Earthquake (Sykes 1971, Hampton and others, 1979; Pulpan and Kienle, 1979). The adjoining aftershock zones of major earthquakes like the 1964 event do not overlap, and they appear to correspond with the descrete structural blocks bounded by transverse structural alignments mentioned in a previous section. If this is correct, the Kodiak shelf is within a single crustal structural unit and Tugidak Basin is near or on the transverse boundary separating the Kodiak and Shumagin structural units (Fisher and others, in press).

Earthquakes recorded by the worldwide network of seismometers have been the only available information concerning the seismicity of the Kodiak area until recently when a local network of seismometers was established there by the University of Alaska. A small amount of data from the local network is available in preliminary form for one 6.5 M earthquake in 1979 and its aftershocks (Pulpan and Kienle, 1979). Much was written concerning seismicity associated with the 1964 Alaskan Earthquake (see The Great Alaska Earthquake of 1964, Seismology and Geodesy, National Academy of Sciences, 1972), which illustrates the effects of major earthquakes in this region. However, epicenters recorded in periods between major earthquakes show the whole zone of seismicity better than the 1964 data alone (Fig. 7). Since 1967 the expanded network of worldwide seismometers has improved the precision of earthquke location in the Kodiak area, and a 9-year summary of epicenters for a segment off Kodiak Island is shown in a cross section (Fig. 7). This cross section shows a distribution of earthquakes that is similar to other such distributions on cross sections in which more precisely located epicenters from local instrument networks are displayed (Davies and House, 1979). The more precise epicenter distributions show a well-defined Benioff zone below a depth of 40 km, and above about 40 km earthquakes in the Benioff zone become diffuse. Epicenters in Figure 7 show similar distribution when only the most accurately located events are considered (filled triangles and circles, Fig. 7). Most of the stress was released in the upper zone above 40 km in the 1964 earthquake, and this is where future major earthquakes are anticipated (Davies and House, 1979).

Crustal structure of the Kodiak block is known from marine seismic refraction measurements (Shor and von Huene, 1972, Holmes and others, 1978, Fisher and Holmes, 1980, von Huene, 1979). Crust of continental thickness can be expected beneath Kodiak because it is essentially an extension of the Kenai Peninsula where crustal thickness was estimated to be 35 km (Hales and Asada, 1966). Along the Pacific shore of Kodiak Island, the crust is about 25 km thick, whereas 150 km seaward at the Aleutian Trench the crust is 13 km thick and has an oceanic structure (Fig. 7).

In summary, Kodiak Island is continental crust above a Benioff zone, and the Kodiak shelf, which includes the zone of diffuse seismicity, is transitional crust. Some earthquake foci appear well below the crust in the transition zone (Fig. 7), however, the depths are uncertain due to the imprecision of the depth measurement from teleseismic data. It should be noted, however, that few earthquake foci are located in the upper two seismic layers, which are mainly sedimentary rock.

The continent-to-ocean transition involves thickening of two upper seismic refraction velocity layers (Fig. 7). One with velocities ranging from 5.0 to 5.5 km/s, appears continuous with the second oceanic layer, as though the second layer continued far below the continent. Continuation of oceanic crust well beneath the continent is indicated just north of Kodiak by continuation of oceanic linear magnetic anomalies beneath the trench slope and shelf (von Huene, 1972, Schwab and others, 1980). However, beneath the Kodiak shelf it is uncertain whether crustal thickening involves only oceanic crust or whether the thickening involves mainly sediment. Sedimentary rock, which is probably metamorphosed, gives seismic velocity values of about 5 km/s in areas beneath the trench upper slope (von Huene, 1979). Therefore it is difficult to distinguish oceanic layer 2 from metamorphosed sedimentary rock by examination of velocity data in the thickened material.

The overlying seismic-refraction layer (with velocities of 4.5 km/s and less) probably consists only of sedimentary rock. Thickness ranges from less than 1 km on the oceanic crust to a maximum of 9 km beneath the shelf (Shor and von Huene, 1972). This sediment mass is assumed to have been thickened by tectonic and sedimentary processes. Seismic-reflection techniques are able to delineate only the structure in the upper part of this sediment mass (Fig. 7). Thus the regional geology and tectonic history are the main basis from which to infer the character of the lower part. The Kodiak shelf from seismological and refraction data appears to be underlain by a thick sediment section above the transition from continental to oceanic crust. The uppermost sedimentary units are well stratified and gently deformed. The underlying layers are inferred sedimentary rock with seismic velocities of 3 to 5 km/s. In most places a sudden increase of seismic velocity occurs between the upper and lower layers (Fisher and Holmes, 1980). The transition from oceanic to continental crust is marked at depth by thickened sediment and dipping oceanic crust that is associated with a diffuse zone of seismicity, probably the extension of a Benioff zone. The seismicity is typical of convergent margins and is related to thrusting of oceanic crust beneath the continent. This thrusting is generally considered to be linked with the thickening of the sediment by tectonic repetition and by forming sediment traps and forearc basins such as those beneath the Kodiak shelf.

Offshore Geology

The three offshore Neogene basins within the area proposed for leasing are Tugidak, Albatross, and Stevenson basins (Fig. 4). The latter two basins are separated by the Dangerous Cape high (Fisher and von Huene, 1980).

Tugidak Basin

Tugidak basin is described by Fisher (1979) as a forearc basin in lower Miocene or pre-Miocene rock that was filled with gently folded strata of late Miocene and younger age. The basin lies on the southeast flank of a basement ridge, called the Kenai-Kodiak ridge, that may be a buried extension of Kodiak Island to the southwest. A shelf-edge ridge, named Tugidak anticline bounds the basin on the southeast (Figs. 8,9). The northeast and southwest sides of the basin are formed by the Trinity Islands on the northeast and by the flank of the low structural ridge along which Chirikof Island emerges.

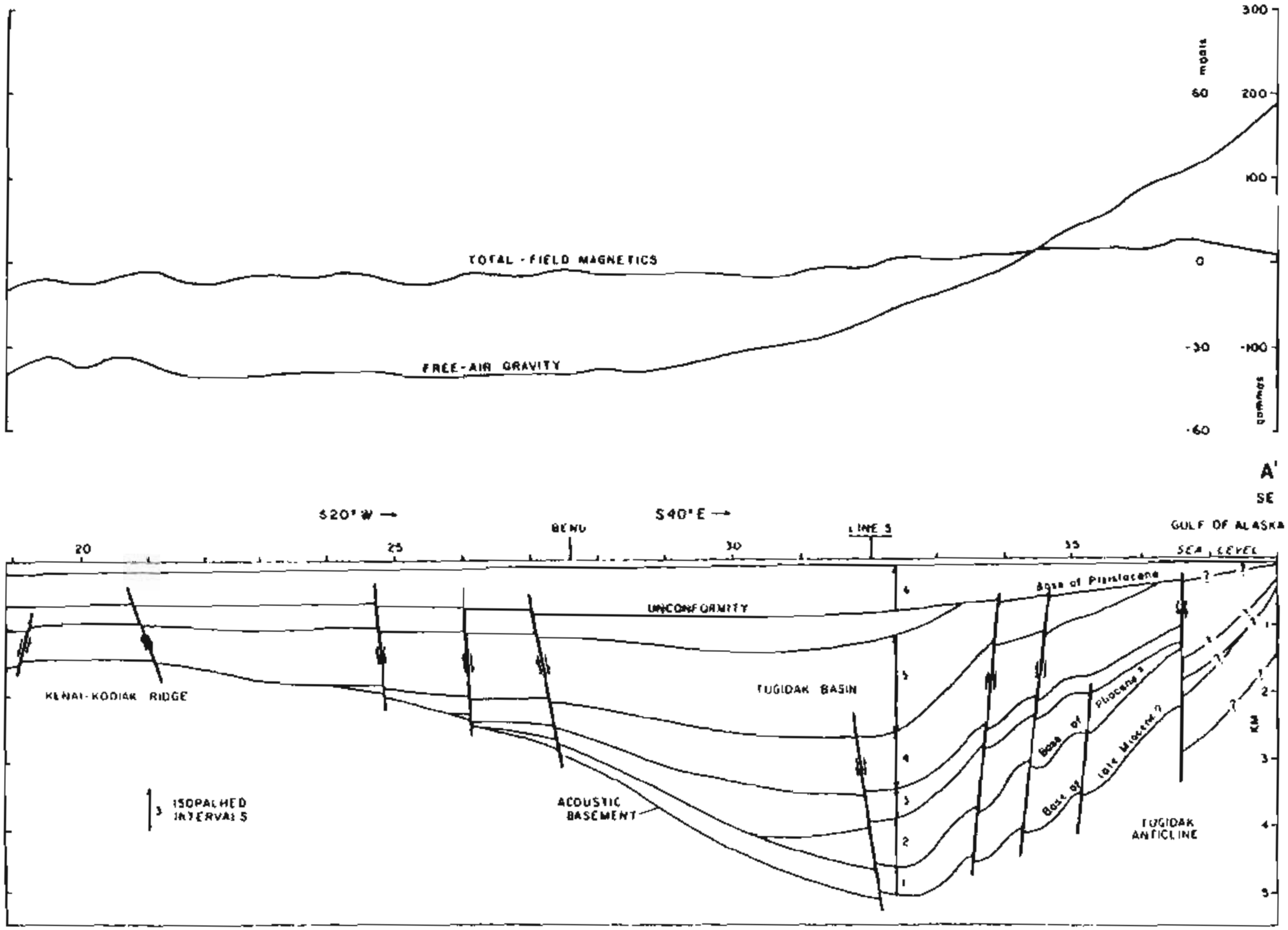

FIG. 8

Cross section of Tugidak Basin based on unmigrated CDP seismic-reflection data. Note delineation of isopached intervals which are shown in Figure 10 (from Fisher, 1979).

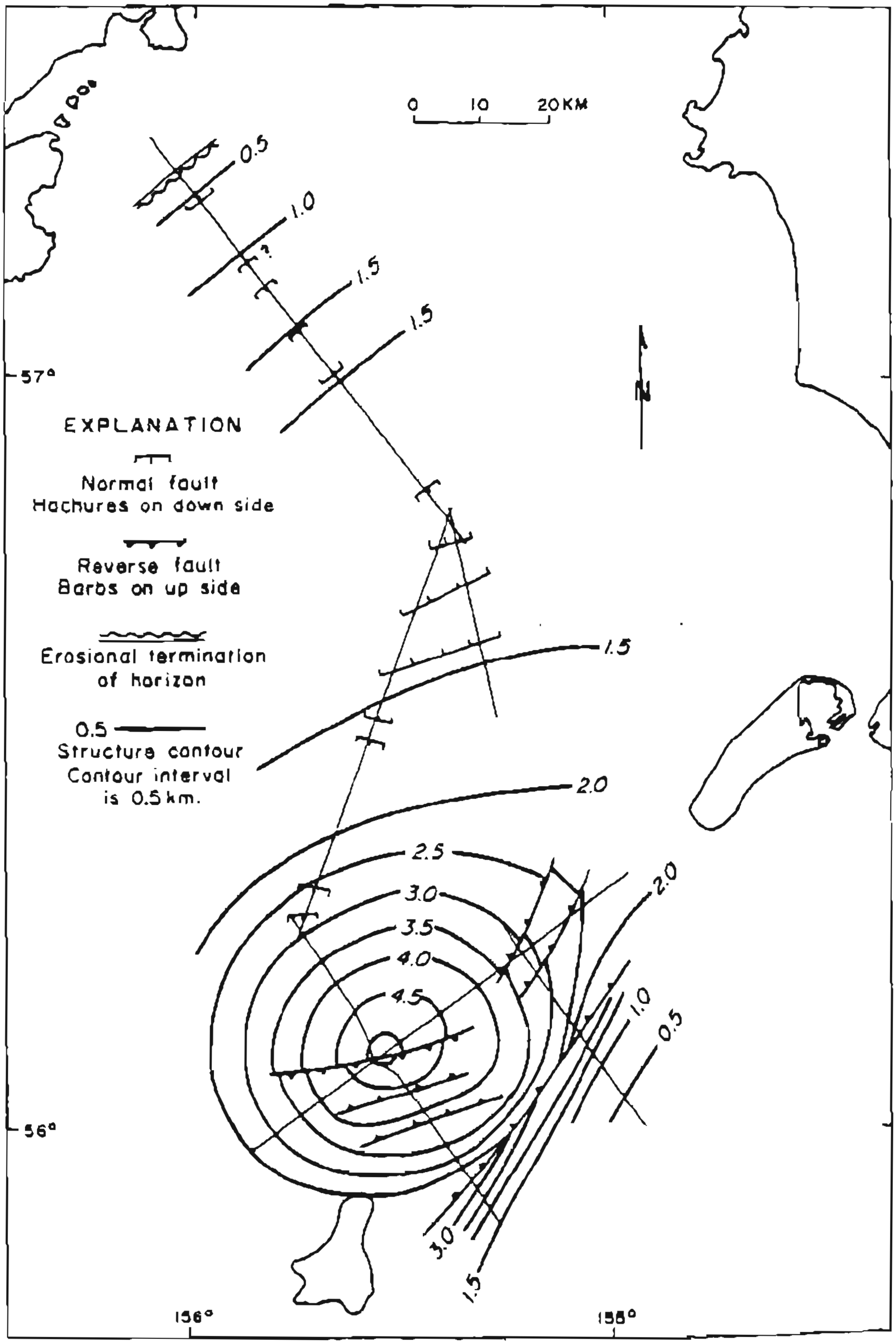

FIG. 9
Structure contours drawn on acoustic basement. Strikes of faults are uncertain (from Fisher, 1979).

The ages of strata in Tugidak basin are estimated by comparing the sequence of unconformities in the seismic records with the sequence of tectonic events on the surrounding islands. If the estimated ages are correct vertical tectonism was rapid in the seaward part of the basin along Tugidak anticline and considerably slower along the Kenai-Kodiak ridge. Uplift of the anticline and subsidence of the basin may have been most rapid in the Pliocene (Fig. 8).

The configuration of Tugidak basin is shown by contours of depth to the acoustic basement (Fig. 9). The deepest part of the basin is nearly circular and 5 km deep. The strikes of faults are uncertain because of the wide spacing of the seismic lines that form the basis of the depth contours.

The present structure of strata within Tugidak basin is broadly synclinal. Although the center of the basin is about 120 km northwest of the Aleutian Trench, compressional structures are only present near the seaward margin of the basin. The transition from landward-dipping to seaward-dipping faults is abrupt, and extensional faults (seaward dipping) continue to the Alaska Peninsula.

On the flank of the Tugidak anticline, minor folding and reverse faulting increase with depth. Along the Kenai-Kodiak ridge some of the normal faults have increasing vertical offset with depth, suggesting faulting during basin filling. The flank of Kenai-Kodiak ridge is cut by small channels, as shown by high-resolution seismic records. This basement high may have been subaerial because vigorous erosion is implied.

Free-air gravity and total-field magnetic anomalies show little expression of the variable thickness of basin fill; for example, there is no gravity low associated with the 5 km of strata in the basin. The Tugidak uplift coincides with a relatively steep gravity gradient, but magnetic data show no corresponding effects due to the uplift. The rocks in the core of Tugidak uplift appear to be denser than the strata filling Tugidak basin, but they are no more magnetic.

A history of basin development can be constructed from the estimated ages of three horizons and a series of isopach maps (Fig. 10). In the first map, the strata in interval 1 (the isopach intervals are shown by numbered intervals in Figure 8) thicken seaward, and the basin is elongate transverse to the regional trend. Thus strata of this interval were deposited when the Tugidak anticline was unable to block seaward transport of sediment. In the second interval the trough is elongate parallel to the regional trend and filled with sediment that onlapped from the southwest. Tugidak anticline probably formed at the time of deposition of this interval because from this time on the basin was a trough. The depocenter of the third isopach interval has shifted both northeast and toward the Alaska Peninsula relative to the depocenters of underlying intervals. The landward component of motion was probably caused by growth of the Tugidak uplift. The depocenter of the fourth interval is northeast and seaward of the underlying depocenter. The seaward shift in the depocenter may indicate that sediment supply exceeded the rate of uplift, or it may indicate a relative uplift of the Kenai-Kodiak ridge and subsidence of the Tugidak uplift. The fifth position of the depocenter is farther to the northwest suggesting renewed growth of Tugidak uplift, or reduced sediment input. Growth of the uplift continued until the crest was eroded and the unconformity at the base of Pleistocene rocks was formed. The depocenter of the sixth and last interval, of Pleistocene and younger age, appears to be northwest of depocenters of the subjacent intervals, but the

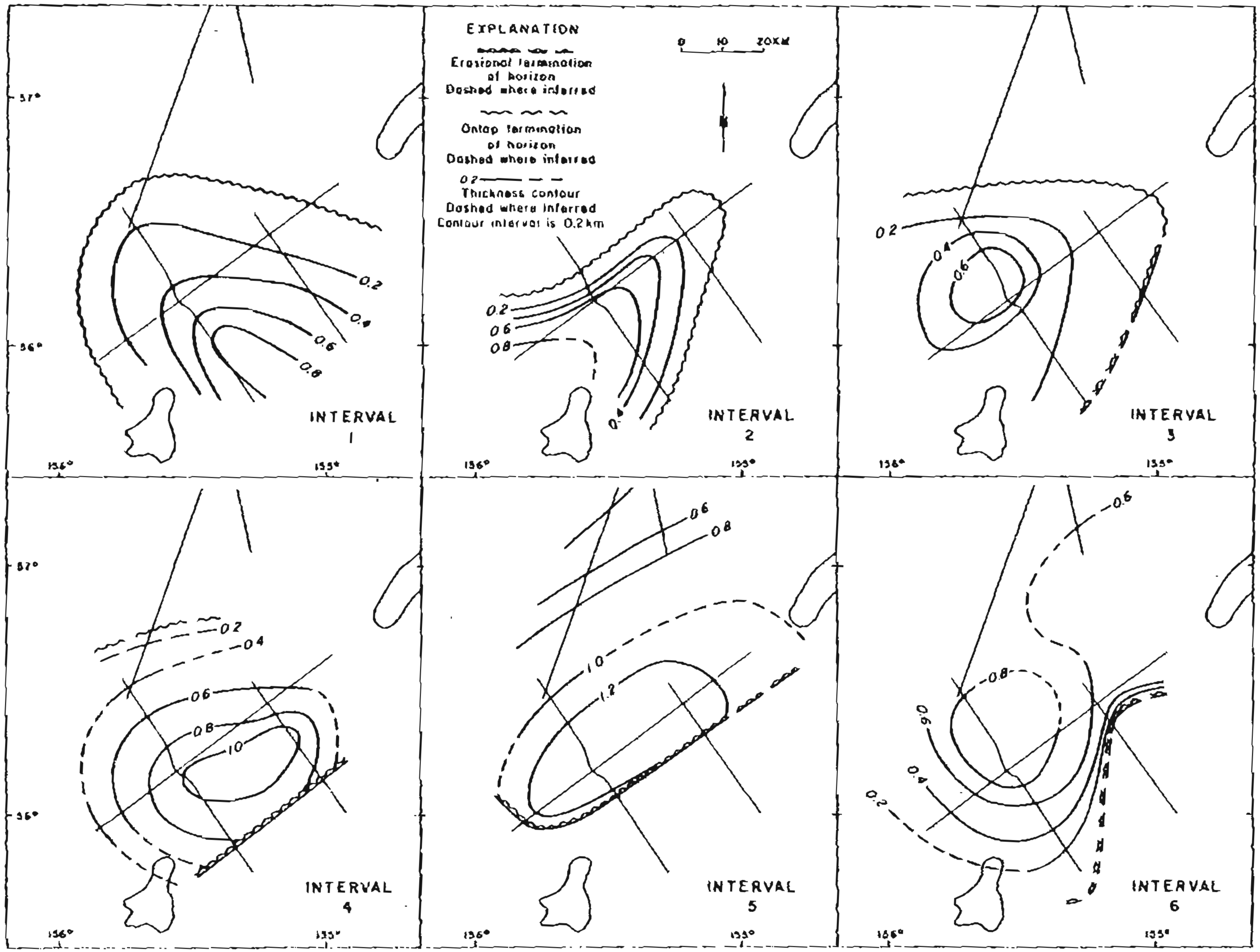

FIG. 10
Isopach maps of Tugidak basin using intervals indicated in Figure 8 (from Fisher, 1979).

control is less certain. The inferred shift of the depocenter implies continued uplift of the Tugidak anticline. Northwestward progradation of strata above the unconformity indicates a southeast source area; elevation of the Tugidak uplift and lowering of sea level may have created a seaward source area. Truncation of strata at the seafloor indicates uplift during the late Pleistocene or Holocene.

The tectonic development of Tugidak basin, as constructed from the analysis of seismic-reflection records, begins with an unconformity on lower Miocene(?) or older rock that was deformed into a seaward-opening trough. At least the landward part of the unconformity surface could have been subaerially eroded as suggested by erosional channels and by contrasting seismic character between rocks above and below the unconformity (Fisher, 1979). From the beginning of the Pliocene, Tugidak anticline impeded seaward transport of sediment. The Pliocene and Pleistocene migration of the basin depocenter describes a path that would generally be expected of an uplifting shelf-break anticline, but complex secondary effects are also observed.

Albatross Basin

Albatross basin underlies the southwestern part of the Kodiak Shelf and is a nearly circular depression that contains a maximum of 5 km of gently to moderately deformed basin fill. Sitkinak Island and the southern end of Kodiak Island are on the landward flank of the basin (Fig. 11). The southwest and southeast limit of the basin is Albatross Bank. The northwestern side of Albatross basin is the northeast end of the Dangerous Cape high.

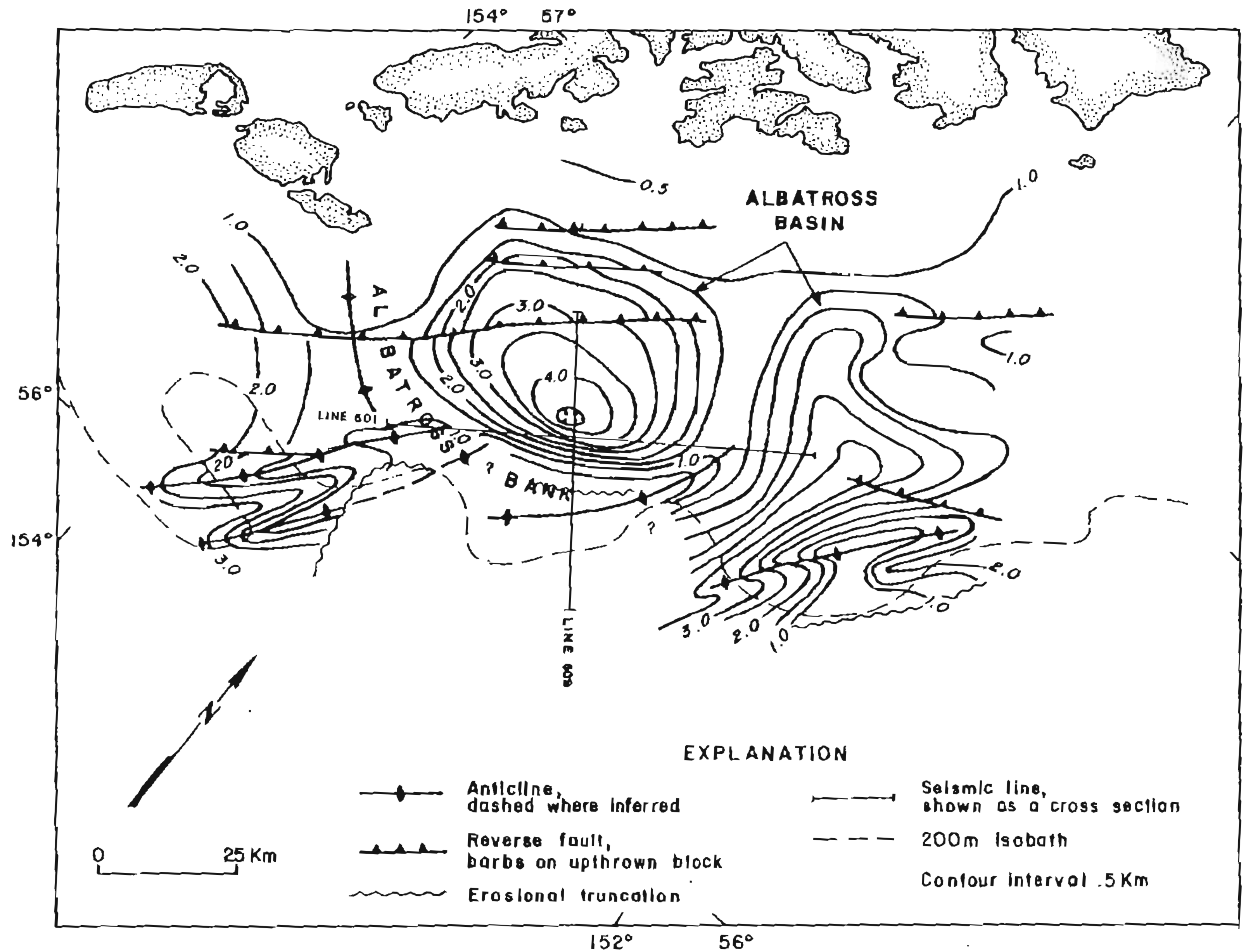

FIG. 11
Structure contours of horizon C in Albatross basin using a single velocity function as discussed in Fisher and von Huene (1980).

Around Albatross basin, Albatross Bank consists of at least four anticlines. The most prominent curves around the southeast and southwest sides of Albatross basin. The other anticlines strike northeast. The spacing of seismic lines is so coarse over the bank that not all of the anticlines are well defined. Albatross Bank is the most tectonically active area of the Kodiak shelf, as shown by deep erosion of strata turned up on the landward flank of the bank, by a concentration of earthquakes, by numerous slides and slumps, and by a pronounced bathymetric ridge (Hampton and Bouma, 1977). In the core of the bank, strata dip too steeply to be resolved by the seismic-reflection technique (Fig. 12). The axis of the bank is commonly broken by high-angle reverse faults as determined from scarps on the seafloor.

The structure of Albatross basin is shown in a seismic record in Figure 12. The bottom of the basin is difficult to follow in this record because of multiple reflections; however, it is located by interpretation of the grid of seismic lines obtained over the basin. Reflections that define an upper and a lower sequence of strata are emphasized by lines drawn on the record. The lower sequence is between horizons B and D; strata in this sequence thicken seaward. The upper sequence overlies horizon B and thickens landward. The change in the direction of thickening indicates that the basin depocenter migrated landward when uplift of Albatross Bank began. Absolute uplift of Albatross Bank is suggested by a bathyal assemblage of Miocene foraminifers in rocks dredged from the bank (von Huene, 1972), and benthic foraminifers in Pliocene rocks that were deeply buried and subsequently uplifted to present shelf depth (McClellan and others, 1980a).

Before uplift of Albatross Bank began, the floor of the basin had a seaward dip, as indicated by the northwest direction in which the lower

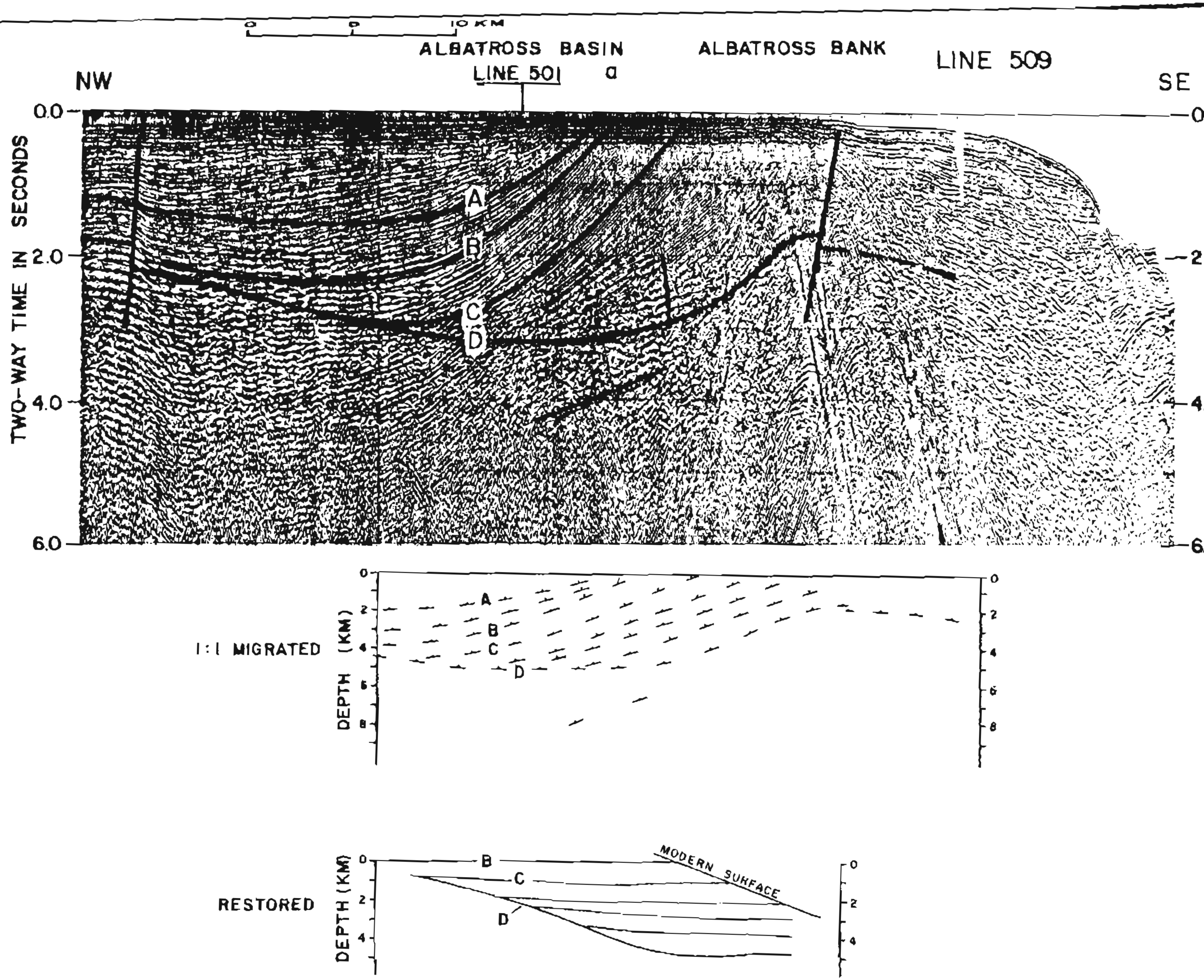

FIG. 12 Seismic record 509 (location given in Figure 11) showing the nature of horizon C which is contoured in Figure 11. Migrated depth section is without vertical exaggeration. Flattening horizon B at sea level gives a minimum depth and slope prior to development of Albatross Bank.

sequence of strata laps onto the basin floor (Fig. 12). The configuration of the basin before uplift can be estimated from the seismic data by a two-step reconstruction: (1) migration of the seismic record; and (2) rotation and flattening of horizon B at sea level. A minimum dip of the basin floor results because horizon B may have dipped seaward, whereas in step 2 that the horizon is assumed to be flat when Albatross Bank began to grow. Similarly, a minimum depth to the bottom of the basin results because horizon B may have been below sea level, whereas in step 2 it has been assumed the horizon was at sea level. The construction of the migrated section is described in Fisher and von Huene (1980). The migrated section confirms that strata below horizon B thicken gradually seaward and form a lower sequence that laps landward onto the basement. The lower sequence was probably deposited before Albatross Bank formed, because in this sequence the strata have nearly constant thickness, even up the flank of the anticline, whereas strata in the upper sequence thin rapidly seaward on the migrated section. Hence deposition of the upper sequence postdates the beginning of uplift.

The second step in the reconstruction—rotation, flattening, and alignment of horizon B with sea level—results in the restored section in Figure 12. The restored section shows the minimum seaward dip of basin fill and floor just before uplift of Albatross Bank began. The minimum dip of the floor of the basin was about 20° under the landward part of the basin. Sediment is difficult to trap on a 20° slope, so the section may have been rotated seaward after deposition and prior to uplift of the Albatross Bank anticline.

A minimum uplift of 3 km has occurred along Albatross Bank. The minimum uplift, measured at the southeast end of Horizon D, is determined from the difference between the 5-km depth to the horizon on the restored section and the 2-km depth to the horizon on the migrated section.

Reverse faults and anticlinal folding at Albatross Bank indicate compressive deformation there, but it decreases landward from the structurally active bank. Near the landward margin of the basin are three faults (Fig. 11). The vertical exaggeration of the seismic sections makes the direction of dip of the faults difficult to determine; the faults, however, dip steeply and the landward side has moved up relative to the seaward side. These faults are within the fault zone proposed by von Huene et al (1972) that parallels the regional structural trend from Hinchinbrook Entrance to Sitkinak Island. Where this zone crops out along the shore of Kodiak Island, the faults are nearly vertical and dip both landward and seaward.

The east-trending part of Albatross Bank began to rise earlier than the northeast-trending part, because strata in the former are angularly discordant across horizon C, whereas no discordance or thinning is evident in the latter. Abundant coherent reflections below horizon C are present only in Albatross basin. Strata that produce the coherent reflections pinch out on the southwest and northeast sides of the basin, and terminate at the sea floor near the crest of the bank.

The northeast flank of Albatross basin is not sharply defined because the main anticline of Albatross Bank merges with a low ridge that is transverse to the shelf (Fig. 11). Strata do not thin across the transverse high, hence the high began to form after most of the strata between horizons B and C were deposited. The high separates the main part of the Albatross basin from a subsidiary syncline that nearly crosses the shelf and is part of Albatross basin. The northeast flank of the syncline rises toward the Dangerous Cape high and forms the northeast flank of Albatross basin.

Dangerous Cape High

The Dangerous Cape high is northeast of Albatross basin and is characterized by shallow burial of horizon C and by structure that is distinct in style from the structure in other areas of Kodiak shelf. The seaward end of the high is an anticline at the shelf break with less relief on horizon C than Albatross Bank. The northeast and southwest boundaries of the Dangerous Cape high are transitional and are located where acoustic basement begins to descend into adjacent basins (Fig. 13). Horizon C is best observed along the Dangerous Cape high because the horizon is commonly less than 1 km deep and nearly flat in many places. Locally, intrabasement reflections are evident where they diverge in dip from horizon C, but these reflections cannot be followed throughout the seismic grid (Fig. 14).

The shelf-break structure consists of tightly folded anticlines in the southwest half of the high and a broad low anticline in the northeast half (Figs. 13 and 14). Hence, the shelf-break structure changes from the high-relief fold along Albatross basin to the broad, deeply buried shelf-break structures in the northeast part of the Dangerous Cape high. High-relief structures are again present at the shelf break near Stevenson basin.

A unique structural complex, called the central-shelf uplift, lies midway between Kodiak Island and the shelf edge (Fig. 13). It consists of numerous steep reverse faults and anticlines, and is in marked contrast to the simple structure in basins that flank the high. Some strata thicken uniformly through the central-shelf structure; a major part of the faulting, therefore, postdates partial burial of horizon C.

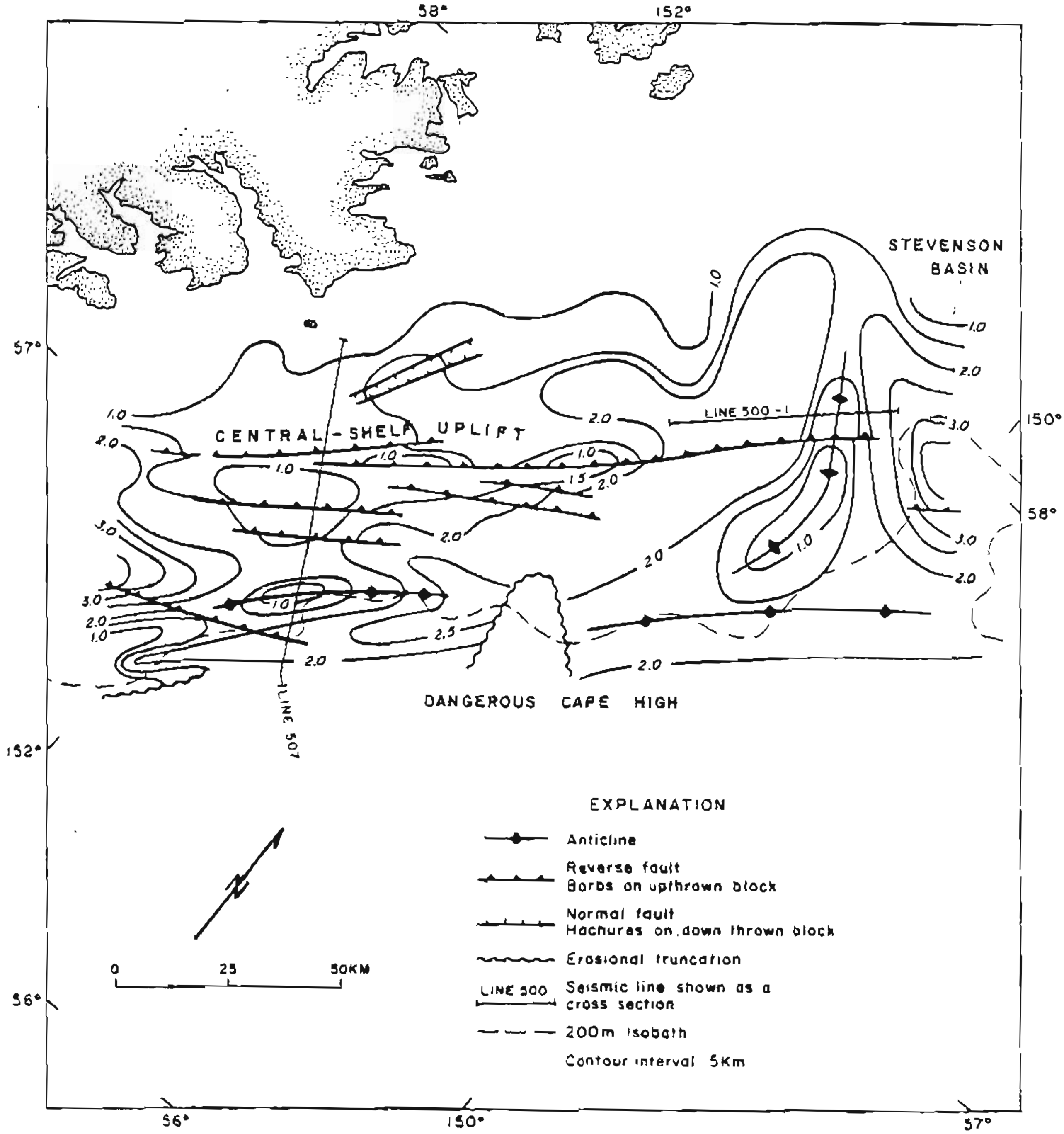

FIG. 13

Structure controus of horizon C in the area of the Dangerous Cape high.

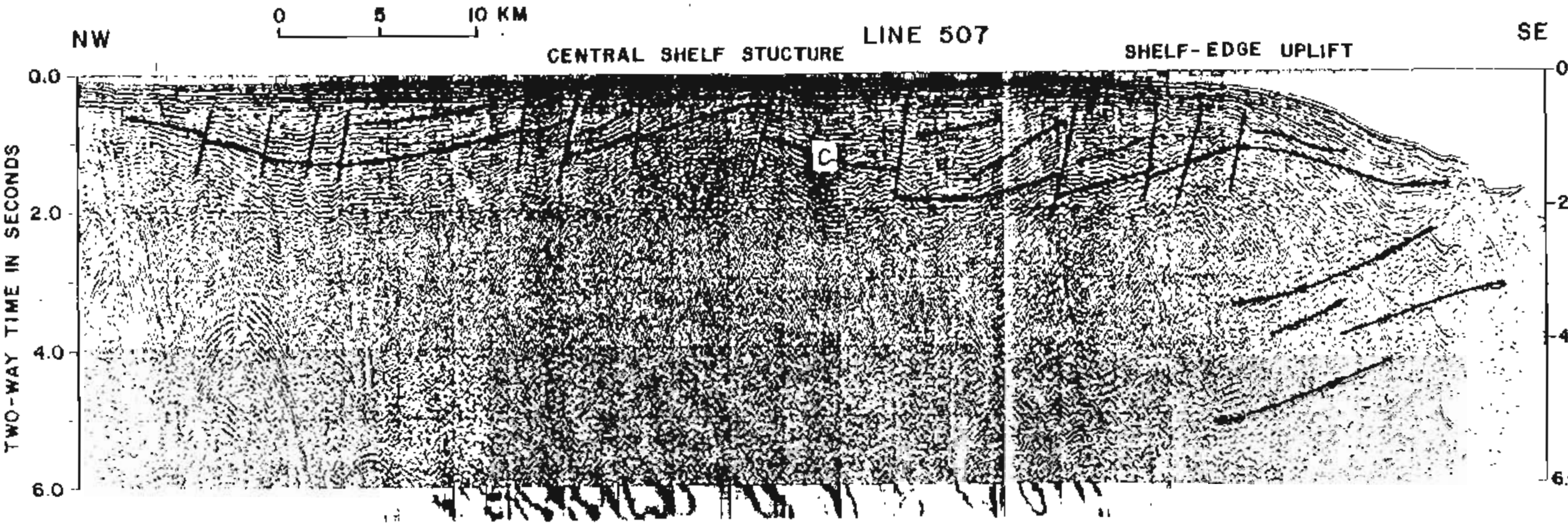

FIG. 14

Seismic record 507 through the Dangerous Cape high; location given in Figure 13.

Stevenson Basin

Stevenson basin is northeast of the Dangerous Cape high (Fig. 15) and is bounded by it on the southwest. The northeastern boundary of the basin is beyond the northeast end of the seismic coverage available for this report.

The structure of Stevenson basin is similar to that of Albatross basin. The fill in Stevenson basin is trapped by a shelf-break structure, and is gently to moderately deformed. Slumps are prominent along the seaward flank of the shelf break (Hampton and Bouma, 1977), perhaps attesting to recent uplift of the structure. The shelf-break structure seaward of Stevenson basin, unlike the structures that collectively form Albatross Bank, consists of one broad anticline. Portlock Bank is an anticline transverse to the shelf that separates Stevenson basin into southwestern and northeastern parts. The southwest part of Stevenson basin is filled by sediment 3.5 km thick that is composed of two sequences. The upper sequence fills a channel that cut into the lower sequence and the sediment that now fills the channel came from the high-standing area of the Dangerous Cape high.

Strata in the lower sequence in Stevenson basin dip landward, and their updip ends terminate at an unconformity that separates the two sequences. Sediment in the lower sequence came from the Dangerous Cape high, as did strata in the upper sequence. Strata of the lower sequence thin gradually up the flank and across the crest of Portlock anticline, showing that the anticline began to grow after deposition of part of the lower sequence in Stevenson basin; thus, uplift of Portlock anticline appears to have begun at about the same time as uplift of the shelf break anticline.

The lower sequence is relatively thin in southwestern Stevenson basin but thickens northeast of the crest of Portlock anticline. In northeastern

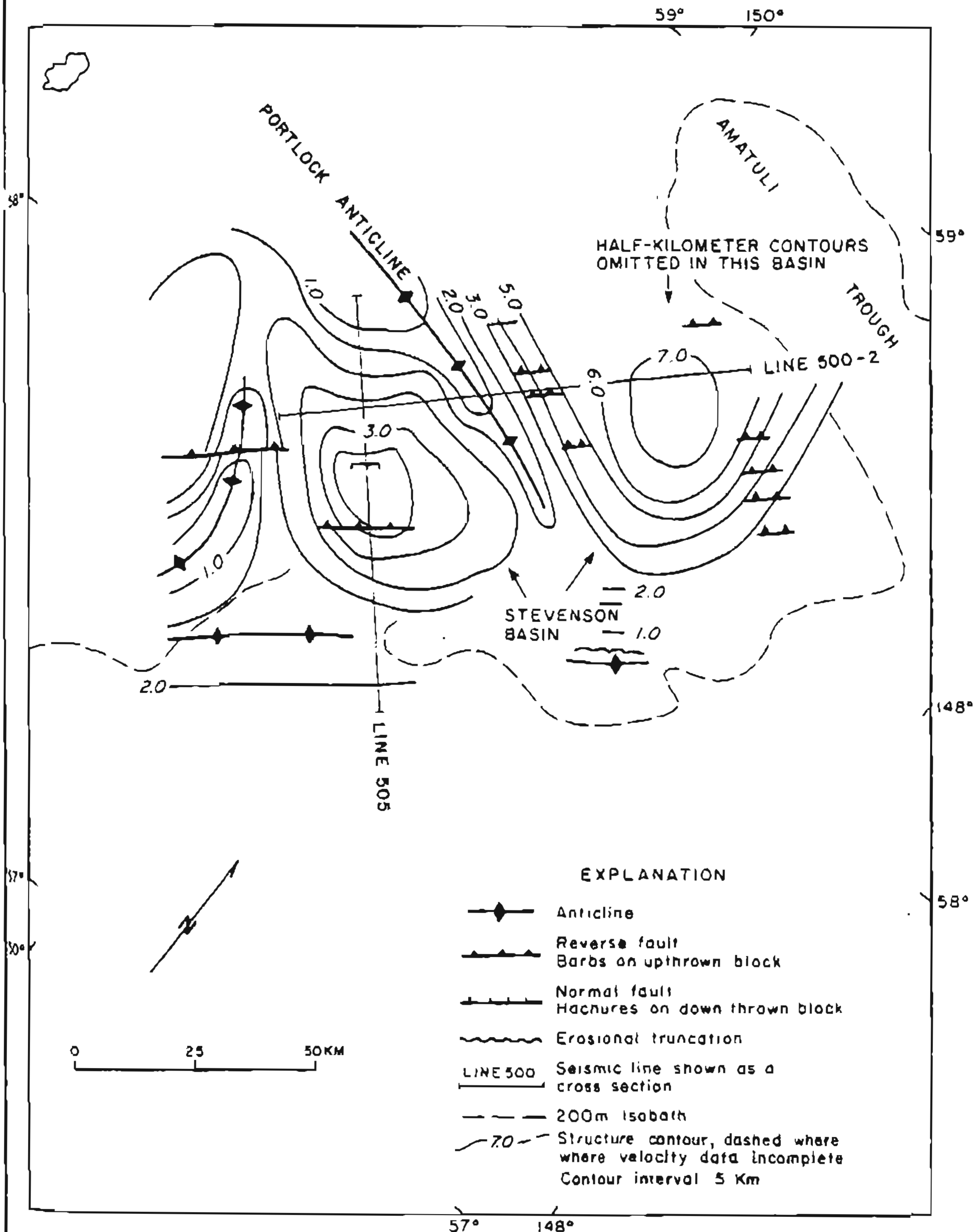

FIG. 15

Structure contours of horizon C in the Stevenson basin area.

Stevenson basin the upper sequence overlies an unconformity and may have come from Cook Inlet. Portlock anticline may have separated the source areas for the upper sequences in the two subbasins. The northeastern subbasin may contain as much as 5 to 7 km of gently deformed strata, though velocity data are poor for depths greater than 5 km.

Faults are numerous in Stevenson basin and have vertical displacements of less than 200 m. The coarse seismic grid over the basin precludes determining the strike of the faults, but the faults probably conform to the general northeast-striking structural grain of the shelf, as shown in a map of shallow features (von Huene and others, in press).

Ages of Strata Under the Shelf

A few dart core samples suggest the geologic age of seismic horizons; the ages from proprietary stratigraphic drilling are not available to us until the time limitations on these data expire. Therefore, the ages of some seismic horizons have been estimated by comparing onshore and offshore stratigraphy (Fisher and von Huene, 1980). The age of strata beneath the shelf is suggested by an analogy with onshore stratigraphy. Paleogene strata exposed on the islands dip steeply, and strata older than middle Oligocene are indurated, whereas Neogene strata have moderate dips and are less indurated than the older strata. This stratigraphy and structure is analogous to that between strata above and below horizon C; strata above horizon C dip gently to moderately, and the rare reflections below that horizon suggest that the strata dip more steeply than can be resolved with the seismic technique. Thus, it can be inferred that strata above horizon D in Albatross basin, and above horizon C elsewhere, are probably no older than Neogene.

More specific ages are estimated from a comparison of onshore and offshore unconformities of possible regional extent. Onshore unconformities are at the bases of lower Miocene, Pliocene, and Pleistocene strata. The weakness in this comparison is that the onshore unconformities are exposed locally in widely separated areas; therefore, whether an unconformity has regional extent is unknown. For this analysis we assume that onshore unconformities had regional extent. The unconformity at the base of Pleistocene strata is exposed on Chirikof and the Trinity Islands. A horizon in seismic data obtained over Tugidak basin may be the offshore continuation of the Pleistocene unconformity (Fisther, 1979). Under the Kodiak shelf, the shallowest unconformity is horizon A which is present at the base of the submarine canyon in Stevenson basin. Another horizon correlated with horizon A on the basis of similar structural and stratigraphic positions, is at the base of channels in strata in the Dangerous Cape high and truncates strata on the flanks of anticlines near Albatross basin.

The next-lower onshore unconformity is at the base of Pliocene strata, which are exposed on Chirikof and Tugidak Islands. At Chirikof Island, gently dipping Pliocene shelf deposits unconformably overlie deformed Paleogene sedimentary rock. The next lower unconformity offshore is horizon C; strata above this unconformity may be Pliocene in age. However, horizon B records the time of uplift of Albatross Bank, and the large size of this structure suggests that it formed during a regional tectonic event. The emergence of the Alaska Peninsula, the strata above horizon C are older than Pliocene, as inferred from the correlation of unconformities, and horizon C could be of late Miocene age.

Microfossils from the upturned strata in Albatross Bank are predominantly Pliocene and younger, and several cores of middle to late Miocene age were recovered from near the edge of the shelf (McClellan and others, 1980a). Landward-dipping stratta dredged on the upper slope, seaward of Albatross Bank, also yielded middle to late Miocene microfossils (McClellan and others, 1980b). Fisher and von Huene (1980) conclude that most of the fill in Albatross basin is probably of late Miocene through Quaternary age.

Structure of Aleutian Trench

The origin of horizon C and of overlying unconformities might be understood better if the unconformities could be traced beyond the shelf edge to their seaward end. Unconformities are seen in seismic records across the slope, but they are difficult to correlate with unconformities under the shelf, because few seismic horizons can be traced through the complex structure at the shelf edge. In a few seismic records that cross the slope, local unconformities are evident (von Huene, 1979). Unconformities at the base of downslope deposits can be traced with varying confidence from the shelf break to near the toe of the slope (Fisher and von Huene, 1980). Beneath the upper part of the slope, unconformities which seem to correlate with horizon C truncate some structural highs and are conformable with strata in some structural lows, suggesting vigorous erosion.

The geology of the modern Aleutian Trench can be used as one possible analog for reconstruction of a Cenozoic history of the Kodiak Shelf, although past trenches may have differed from present trenches. Many authors have interpreted the Kodiak Formation as consisting of ancient trench deposits and the Paleogene rocks on Kodiak island as consisting of trench-slope deposits (G. W. Moore, 1967; J. C. Moore, 1974; Nilson and Moore, 1979; Budnick, 1974).

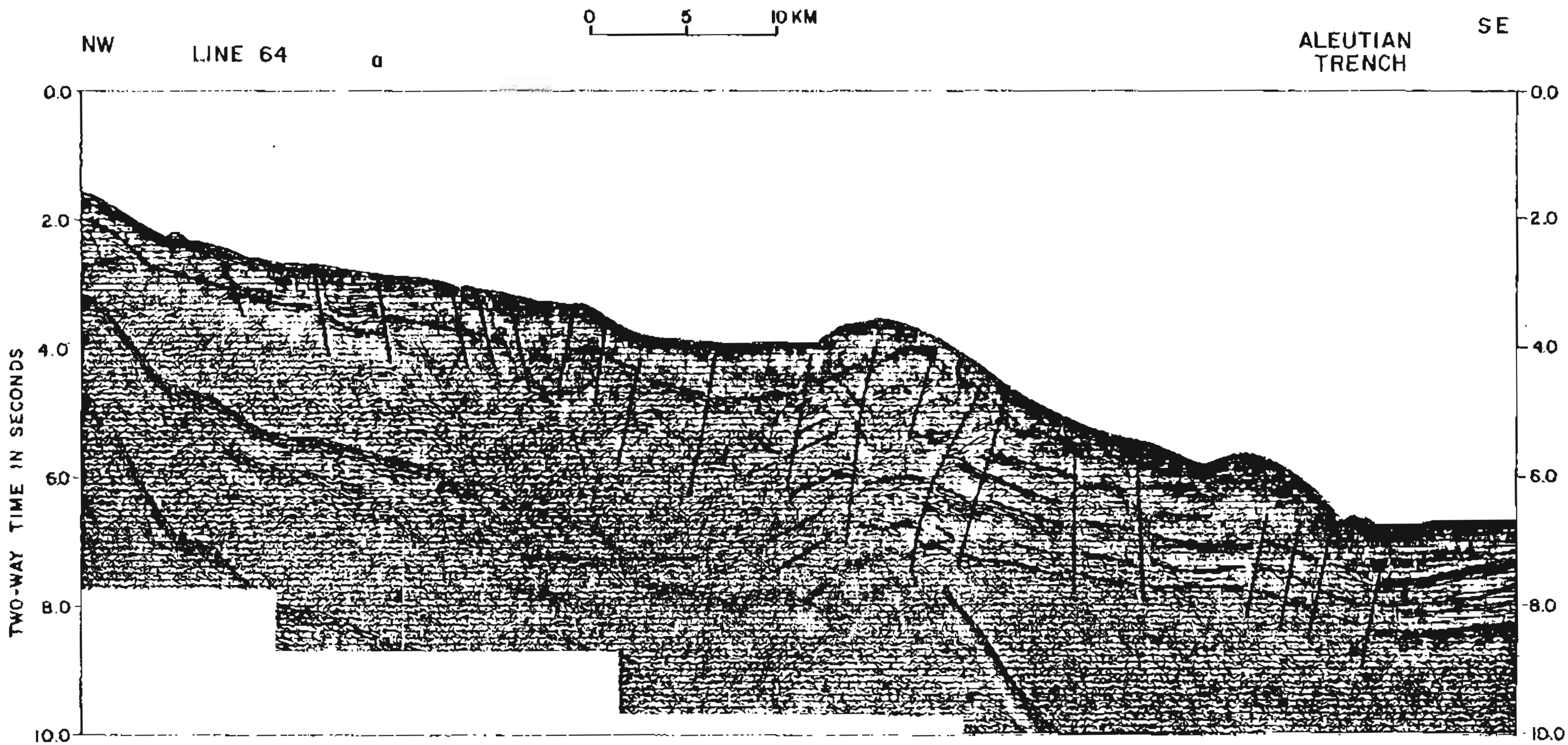

FIG. 16

Seismic record 64 from the edge of the shelf near Stevenson basin to the Aleutian Trench showing the major disconformity between reflections paralleling the slope and underlying areas from which coherent reflections are rare.

The Aleutian Trench off Kodiak is a checkmark-shaped basin formed by a bowing down of the ocean crust where it begins to plunge beneath the continent. Above the igneous crust, DSDP drilling encountered a thin basal sequence of pelagic shale and a 10 m bed of earliest Miocene chalk (Kulm, von Huene, and others, 1973). The middle Miocene section consists of deep ocean turbidite sand and silt probably interbedded with hemipelagic silt. The turbidites generally increase in volume up section probably reflecting the increasing proximity to land of the drillsite as the Pacific plate converged with the North American plate and the increasing glaciation around the Gulf of Alaska. In the Aleutian Trench this nearly 1000 m thick oceanic sediment is covered by up to 800 m of late Pleistocene sediment ponded in the trench. A DSDP drill hole in trench fill encountered mostly clayey silt and silt turbidites with surprisingly little sand (Kulm, von Huene and others, 1973). The absence of sand at the drillsite was explained by channeling the sand in a longitudinal turbidity current channel along the trench axis (Piper and others, 1973). In general, the Neogene oceanic section and trench fill are composed of silt with some channel sand; the composition of the section is probably influenced by Neogene glaciations around the Gulf of Alaska.

Where the trench section meets the trench landward slope there is a zone of tectonic deformation with various structural styles (von Huene and others, 1979). Since the structural styles are difficult to resolve with seismic-reflection techniques they are known only in a general way. The best resolved is a style where the trench deposits continue as a coherent layer above the igneous ocean crust landward for as much as 40 km (Fig. 5). Deformation of the coherent layer along steep reverse faults is relatively minor (less than 500 m) and these faults extend into the igenous basement rather than flattening parallel to it (von Huene, 1979). Another structural style consists of large thrust faults that dip seaward as well as landward (Seely, 1977). A third style is similar to that proposed for the Kodiak margin by Dickinson and Seely (1979); this style consists of landward-dipping thrust faults that sole out along the top of the igenous oceanic crust. Whatever the style, most of the tectonic imprint that can be seen in seismic records is developed under the trench lower slope, because under the trench upper slope tectonism seems to decrease significantly in intensity. Under the upper slope a blanket of downslope deposits from 0.5 to 1.0 km thick are only gently deformed, and along most seismic lines across the upper slope not much structure is visible below the slope deposits. In places a marked angular unconformity truncates the section beneath the slope deposits, and the general dip of the reflections is landward, much like the structure at Albatross Bank, but not as steep. In seismic lines parallel to the strike of the upper slope, the structure is more often visible. In these records the structure consists of broad folds in thick coherent sequences of strata (von Huene, 1979). Therefore, a large part of the section, which was presumably deformed and accreted during subduction, appears to have broad continuity (on a scale of 20-40 km) rather than being chaotically deformed, except perhaps in narrow zones. From the differences in tectonic style of the presumed modern and Pleistocene subduction complex, no single tectonic model can be applied with much confidence, particularly on the scale of a single hydrocarbon prospect. If the structure beneath the trench upper slope is analogous to the structure of acoustic basement beneath the forearc basin, then coherent sections of landward-dipping strata of unknown lithology could occur there. Since the seismic velocities in the strata below the downslope deposits are between

3 and 5 km/s (von Huene, 1979) and are similar to velocities in strata below the forearc basin and on Kodiak Island, strata under the basins may have a lithology similar to the Paleogene section exposed on the island (Fisher and Holmes, 1980).

TECTONIC HISTORY OF THE KODIAK SHELF AREA

The tectonic history of the Kodiak Shelf has been addressed by various authors (G.W. Moore, 1975; Moore and Connelly, 1976; Nilsen and Bouma, 1977; Moore and Bolm, 1977; Nilsen and Moore, 1979; Fisher and Holmes, 1980; Fisher and von Huene, 1980). Opinions diverge, especially for the pre-Neogene, and many conclusions are inferential and not constrained by direct data. The history given here is a guide rather than an extensive discussion, and parts of it will probably change once the results from drilling become known. The Kodiak Shelf may be underlain by Cretaceous through Quaternary rock; hence, we will deal with this period of time.

The Upper Cretaceous rocks on Kodiak Island are turbidites deposited in a basin-plain and slope environment in a linear basin, perhaps a trough adjacent to the Alaskan margin (Nilsen and Moore, 1979). Sediment transport was relatively unidirectional to the southwest, parallel to the regional trend. About 60 m.y. ago these rocks were intruded by plutons which may or may not have reached the surface as volcanoes. The Paleocene Ghost Rocks Formation, which does not easily fit a facies progression, was nonetheless most likely deposited along the Alaskan margin.

Beginning in the Eocene (Fig. 17A) the northwest part of Kodiak Island may have been above sea level and may have supplied sediment for Eocene slope, flattening parallel to it (von Huene, 1979). Another structural style consists of large thrust faults that dip seaward as well as landward (Seely, 1977). A third style is similar to that proposed for the Kodiak margin by Dickinson and Seely (1979); this style consists of landward-dipping thrust faults that sole out along the top of the igenous oceanic crust. Whatever the style, most of the tectonic imprint that can be seen in seismic records is developed under the trench lower slope, because under the trench upper slope tectonism seems to decrease significantly in intensity. Under the upper slope a blanket of downslope deposits from 0.5 to 1.0 km thick are only gently deformed, and along most seismic lines across the upper slope not much structure is visible below the slope deposits. In places a marked angular unconformity truncates the section beneath the slope deposits, and the general dip of the reflections is landward, much like the structure at Albatross Bank, but not as steep. In seismic lines parallel to the strike of the upper slope, the structure is more often visible. In these records the structure consists of broad folds in thick coherent sequences of strata (von Huene, 1979). Therefore, a large part of the section, which was presumably deformed and accreted during subduction, appears to have broad continuity (on a scale of 20-40 km) rather than being chaotically deformed, except perhaps in narrow zones. From the differences in tectonic style of the presumed modern and Pleistocene subduction complex, no single tectonic model can be applied with much confidence, particularly on the scale of a single hydrocarbon prospect. If the structure beneath the trench upper slope is analogous to the structure of acoustic basement beneath the forearc basin, then coherent sections of landward-dipping strata of unknown lithology could occur there. Since the seismic velocities in the strata below the downslope deposits are between

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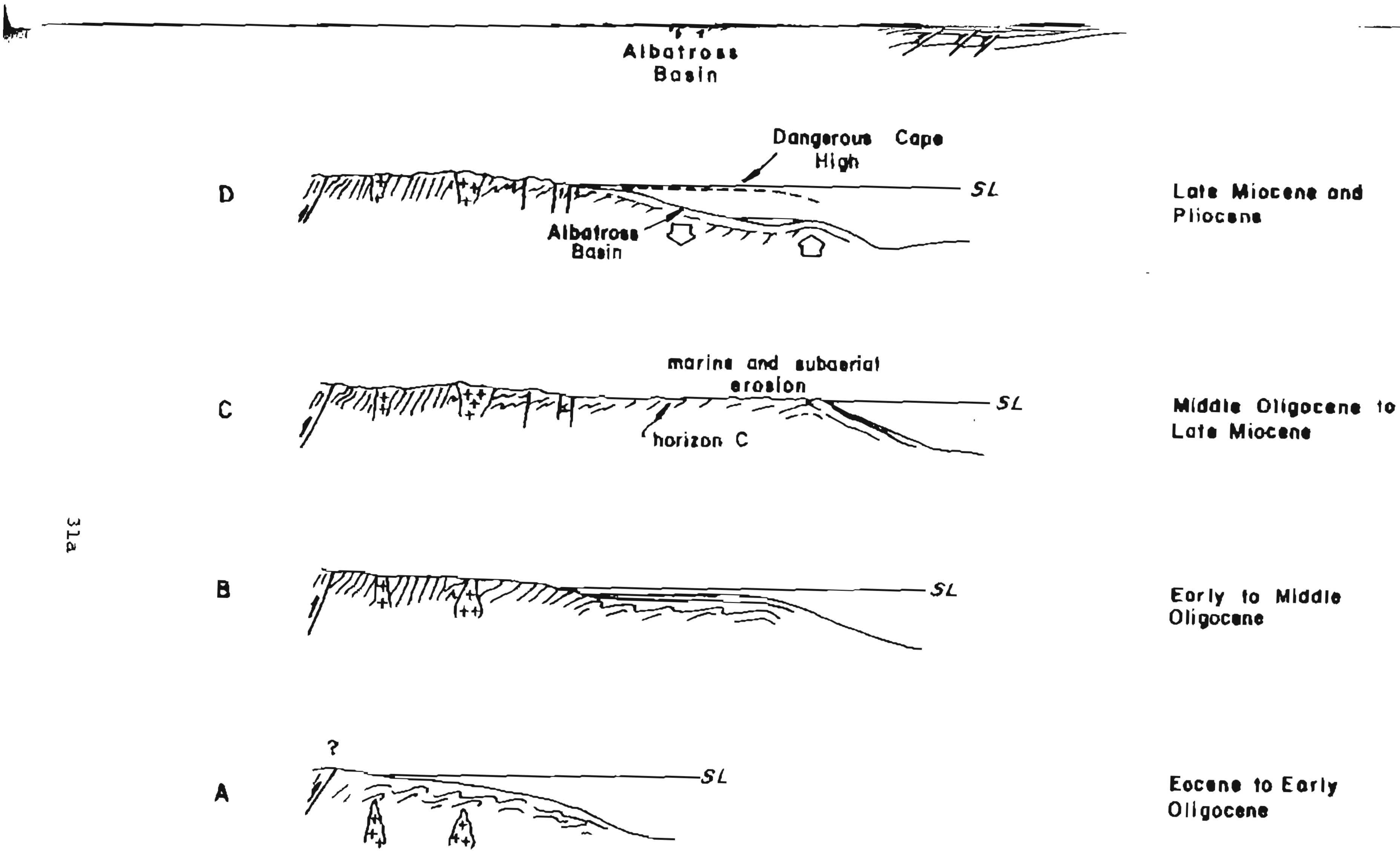

FIG. 17

Diagrammatic sketches summarizing a possible tectonic history of the Kodiak Shelf.

deep-sea fan, and shelf deposits (Sitkalidak Formation). Nilsen and Moore (1979) suggest that an elongate sediment prism developed during periods of subduction in which the Eocene slope and fan deposits were trapped. Between the uplifted source terrain and the slope, a shelf basin may have covered the Kodiak formation.

Beginning in the early Oligocene (Fig. 17B), uplift and erosion of Kodiak Island continued. The island was eroded deeply enough to expose the radiolarian chert along the northwest part of the island and to expose rock from the 60 m.y. old plutons (G.W. Moore, personal communication). During this period a magmatic arc on the Alaska Peninsula provided volcanic debris to the forearc area.

In the late Oligocene (Fig. 17B), the shore was near Sitkinak Island, and the shore may have extended northeastward along the present coast of Kodiak Island. Thus, a shelf may have existed at that time in the area of the present one. If a magmatic arc existed on the Alaska Peninsula its activity was probably infrequent.

In late Oligocene to early Miocene time (Fig. 17C) the insular areas were still above sea level, but the shore probably receded northwest, at least near Sitkinak Island and Narrow Cape where strata were deposited over older rocks (G.W. Moore, 1969). This may have been accompanied by subsidence of the landward part of the shelf, but the seaward part may have begun to shoal in the latter part of this period in order to become subaerial during the middle and late Miocene.

By the middle Miocene extensive parts of the shelf may have been subaerial. In a similar geologic setting along the Japan Trench, a Neogene subareal erosion surface under the shelf was recently found (von Huene, Nasu, and others, 1978). During this period the unconformity subsided beneath Albatross and probably Stevenson basins, whereas the Dangerous Cape high remained at shallow depth.

During the late Miocene and Pliocene (Fig. 17D), most of the shelf subsided, and many of the last remnants of the offshore subaerial terrain submerged. The uplift of Albatross Bank and Tugidak anticline was initiated, and they probably continued to rise through the Pliocene when parts of them became subaerial. Large channels crossed the shelf perhaps in response to increased glaciation during the Pliocene. In the Pleistocene the channels in Stevenson basin were blocked and Tugidak basin was eroded perhaps coincident with a low stand of sea level.

This geologic history contains two speculative points important to an evaluation of the petroleum potential of the Kodiak Shelf. First, some areas may be exposed and eroded, and transgressive sequences above the erosional unconformity may contain favorable reservoir rocks. Second, erosion of an uplifted block may also result in truncation of structure such that hydrocarbon traps are destroyed.

Exploration of the Kodiak Shelf is in an initial stage, and little direct data exist concerning the source and reservoir potential of rocks beneath the shelf because they are essentially unsampled. Therefore, knowledge of the source and reservoir characteristics is based on inference from the adjacent exposed areas and on other analogs. At present, we have no test of the strength of particular inferences. A recent comprehensive summary of the petroleum geology of the Kodiak Shelf (Fisher, in press) forms the basis for the following discussion.

Source Rock

Organic geochemical data have been obtained for rocks exposed on Kodiak Island, for a few surface samples from strata that crop out near Albatross Bank, and for samples from DSDP drill holes on the trench slope. Few of these rocks contain sufficient organic carbon to make them source rocks for petroleum. On average, samples from Paleogene rocks contain less than the 0.5 wt. percent organic carbon that is considered the minimum needed for source rocks. Samples from the nonmarine part of the Oligocene Sitkinak Formation, the Pliocene Tugidak Formation, and Pliocene to Pleistocene rocks from the trench lower slope contain about 0.6 wt. percent. The indigenous organic matter is characteristically herbaceous and coaly, and since the hydrogen content of such material is low, the amount of organic carbon needed to generate oil in these rocks may be close to 1.0 wt. percent. If herbaceous and coaly kerogen are also the dominant type of organic matter offshore, gas and gas condensate may be the most abundant hydrocarbon generated under the Kodiak Shelf.

Eocene through middle Miocene rocks from Kodiak Island are thermally mature, whereas samples of the fill in Albatross Basin and the Pliocene Tugidak Formation are thermally immature. These are probably minimum levels of maturity for rocks offshore that are buried by as much as 5 to 7 km of sediment younger than middle Miocene.

The distribution of temperatures through geologic time in convergent margins depends on complex geologic processes; thus along the Kodiak margin temperatures may have been affected not only by subduction of normal oceanic crust, but also by possible subduction of the Kula Ridge in the middle Tertiary (Grow and Atwater, 1970; DeLong and others, 1978) and by anatectic plutons that intruded the Kodiak margin during the Paleocene, and that may have formed when subduction did not occur (Hudson and others, 1979). In the Middleton Island well, northeast of the Kodiak Shelf, the thermal gradient appears to be as great as or greater than that off northern Japan where gas has been discovered (von Huene, Nasu, and others, 1978). Rock samples from Kodiak Island and Albatross Bank suggest that strata in these areas have potential to generate only gas or condensate from rocks of middle Miocene age and older; however, strata under the shelf may have better source rock characteristics.

Reservoir Rock

Rock of pre-Pliocene age on Kodiak Island generally have poor reservoir characteristics. Lower and middle Miocene rocks have the best quality, but even these rocks have only fair permeability and poor porosity. The poor reservoir characteristics are caused by diagenetic changes, probably because the rocks contain volcanic lithic fragments and plagioclase feldspar,which are chemically unstable. The general diagenetic trends of rocks under Kodiak Shelf is not known except by comparison to onshore rocks.

Offshore the seismic velocities of rocks above horizon C is considerably lower that the velocity of onshore rock (Shor and von Huene, 1972; Holmes and others, 1978; Fisher and Holmes, 1980; Fisher and von Huene, in press); the rocks below horizon C, however, have approximately the same velocities as onshore rocks. If equivalent velocity indicates equivalent compaction and diagenesis of rock, the best potential reservoirs are probably above horizon C.

Structural Traps

Basins under the Kodiak Shelf contain few structural traps because most of the basin fill is only gently folded. The most favorable structural traps are Tugidak anticline, Albatross Bank, and Portlock Bank. Along the landward flank of Albatross Band and Tugidak uplift most strata are truncated at the seafloor or at an unconformity within 1 km of the seafloor; hydrocarbons in the truncated basin fill, therefore, could have escaped. Traps may exist in the older rocks that presumably core Tugidak uplift and Albatross Bank. Portlock Bank is uplifted by a large anticline that is not eroded and hydrocarbons would tend to migrate up both flanks of the anticline from the two parts of Stevenson Basin. Other structures that may be hydrocarbon traps are a transverse anticline that divides Albatross basin, structures in the central-shelf uplift of the Dangerous Cape high, and a transverse anticline near the boundary between the Dangerous Cape and Stevenson basin. We have insufficient data to evaluate the closure of these structures.

From the geologic history of the Kodiak Shelf, we believe that stratigraphic traps could be associated with horizon C; such traps could be in coarse deposits that are inferred to directly overlie horizon C. These deposits are thought to have been deposited during a marine transgression, and as eroded areas subsided they may have been covered initially by a sequence containing beach sand, and overlying muds could form a seal.

Summary

The potential of finding commercial quantities of liquid hydrocarbons does not appear very encouraging on the basis of samples from Kodiak Island. Only Paleogene rocks are thermally mature, but these rocks contain low amounts of herbaceous and coaly kerogen that would produce mostly gas, and would probably be found in structures with poor reservoir rocks. This conclusion must be tempered because it is not known how similar the onshore and offshore rocks are.

The area considered in this appraisal (Fig. 1) includes most of the Kodiak shelf province (water depths from 0 to 200 m), portions of the Kodiak slope province (200 to 2500 m), and a small area with water depths greater than 2500 meters. Resource appraisals have been made for the Kodiak shelf and slope; not enough data exist, however, to apportion the potential resources of the Kodiak slope into specific areas and to provide a separate estimate for the portion of the slope that is included in the sale area. The sale area could contain about 50 percent of the resource potential of the Kodiak slope province. The economically recoverable resources in that portion of the sale area where the water depths are greater than 2500 meters are estimated to be negligible.

The estimates are assessments of undiscovered, recoverable oil and gas. These quantities are considered recoverable at current cost and price relationships and at current technology, assuming additional short-term technological growth. The assessments are probability estimates of least quantities associated with given probabilities of occurrence. They are shown as specific probability levels (Table 1) and as complete cumulative probability distributions (Fig. 18).

Estimates in each case are stated in two ways. First, the conditional estimates are those quantities that may be present, assuming that commercial quantities do exist. Second, the unconditional estimates are those quantities that may be present when the risk that no hydrocarbons actually exist is included. The probability of finding commercial quantities of hydrocarbons in frontier areas such as the proposed Kodiak sale area is uncertain. A marginal probability is estimated to express this risk and is used to convert the conditional distributions to unconditional distributions. In this case the chance of finding oil in commercial quantities is considered to be 23 percent for the shelf area and 14 percent for the slope. For nonassociated gas in these provinces, the chance of finding commercial quantities is 31 percent for the shelf and 16 percent for the slope.

The basin assessment procedures were based upon subjective probability techniques and they incorporate geologic judgments and analyses of the petroleum characteristics of the basin. The analytical procedures included:

1. A review and interpretation of geological and geophysical data.
2. The application of arbitrary hydrocarbon yields derived from various United States hydrocarbon-producing basins.
3. Comparison with other petroleum provinces.

On the basis of regional geology and reflection seismic data, the Kodiak sale area appears to have a sufficient sedimentary section for the generation of hydrocarbons. Reflection seismic data also indicate folding, faulting, and unconformities, which could provide suitable traps for hydrocarbons. The existence of suitable source beds, the maturation of the source beds, and the presence of adequate reservoir beds are not well known. These unknown factors are the principle risks for finding recoverable hydrocarbons in the proposeed Kodiak sale area.

ESTIMATED UNDISCOVERED RECOVERABLE OIL AND GAS RESOURCES

TABLE 1

KODIAK SHELF (0-200 meters)

	95% Probability	5% Probability	Statistical Mean	Marginal Probability
billions of barrels)				
onditional	0.20	2.21	0.87	1.00
nconditional	0.0	1.18	0.20	0.23
./dissolved gas (TCF)				
onditional	0.36	3.82	1.51	1.00
nconditional	0.0	2.05	0.35	0.23
ssoc. gas (TCF)				
onditional	1.48	8.83	4.19	1.00
nconditional	0.0	6.18	1.30	0.31
gated gas (TCF)				
onditional[1]	2.50	10.87	5.70[2]	1.00
nconditional	0.0	6.71	1.65[2]	0.47

KODIAK SLOPE (200-2500 meters)[3]

	95% Probability	5% Probability	Statistical Mean	Marginal Probability
billions of barrels)				
onditional	0.73	3.91	1.92	1.00
nconditional	0.0	2.03	0.27	0.14
./dissolved gas (TCF)				
onditional	0.89	4.81	2.36	1.00
nconditional	0.0	2.50	0.33	0.14
ssoc. gas (TCF)				
onditional	1.13	5.72	2.87	1.00
nconditional	0.0	3.23	0.46	0.16
ated gas (TCF)				
onditional	2.71	8.90	5.23[2]	1.00
nconditional	0.0	4.11	0.79[2]	0.28

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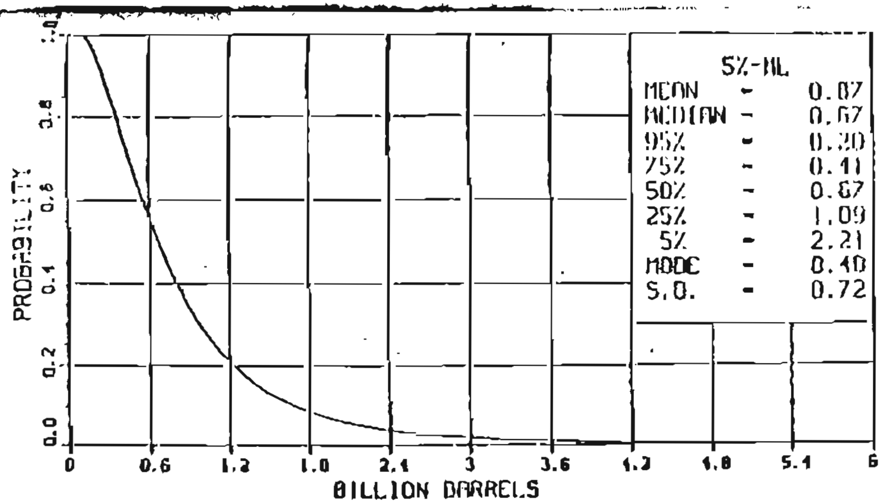
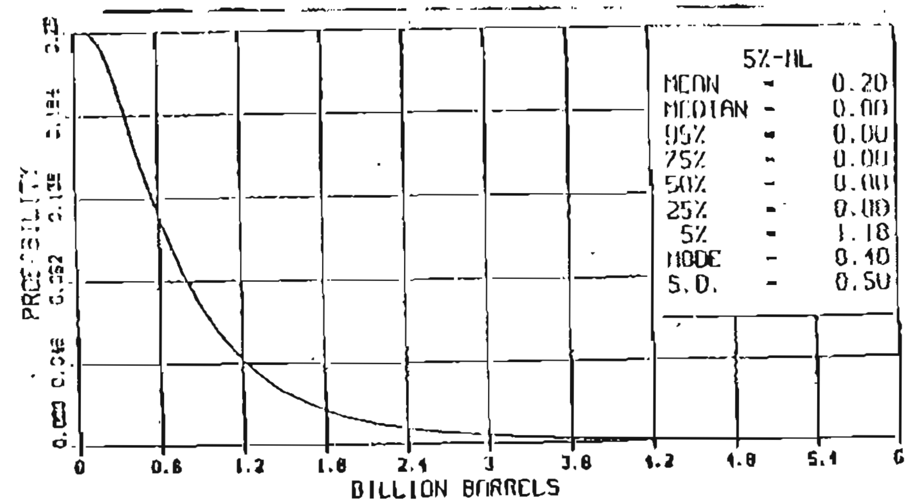
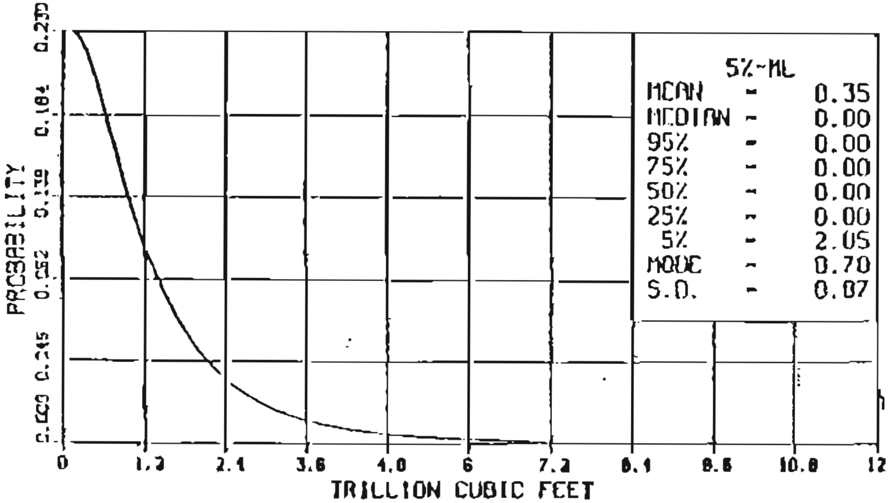
ndtional on: there is both assoc. and non-assoc. gas present.
ese are exact means whereas the Monte Carlo aggregated means on the graphs may ightly differ due to simulation.
timates are for the total Kodiak slope province. The proposed sale area cludes about 50 percent of the potential hydrocarbons under the slope.





KODIAK SHELF (0-200M) ASS.-DIS. GAS UNCOND.



KODIAK SHELF (0-200M) ASS.-DIS. GAS COND.

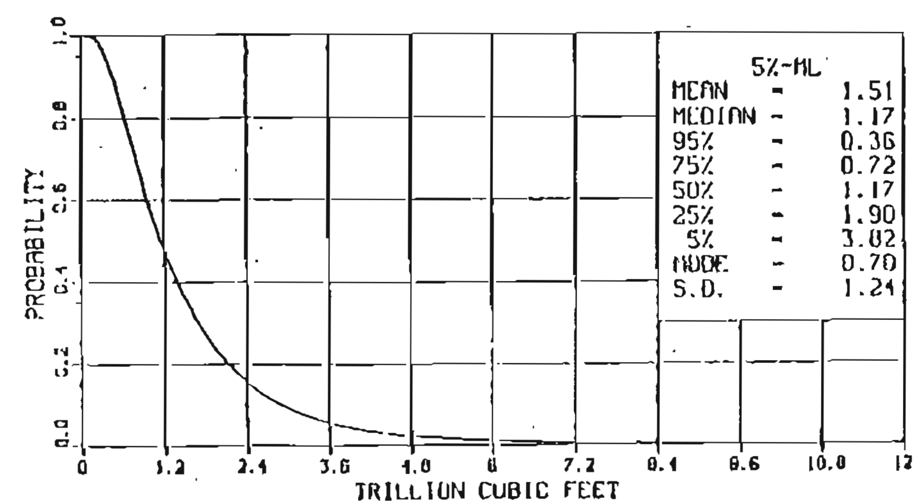
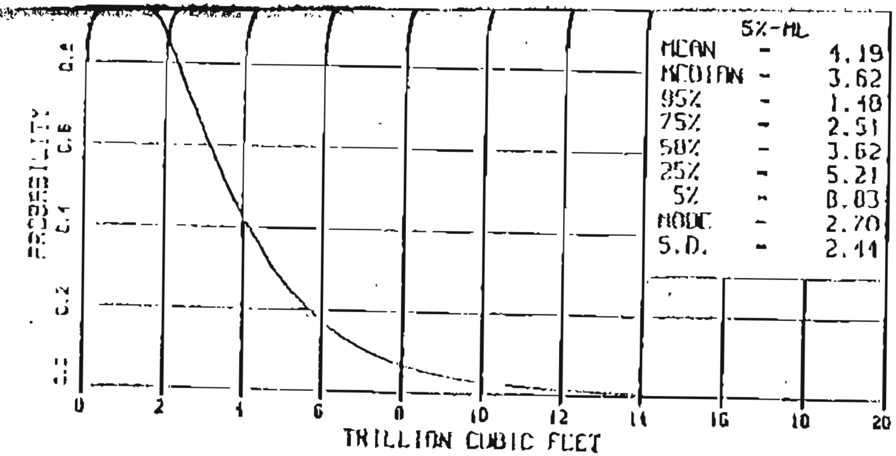
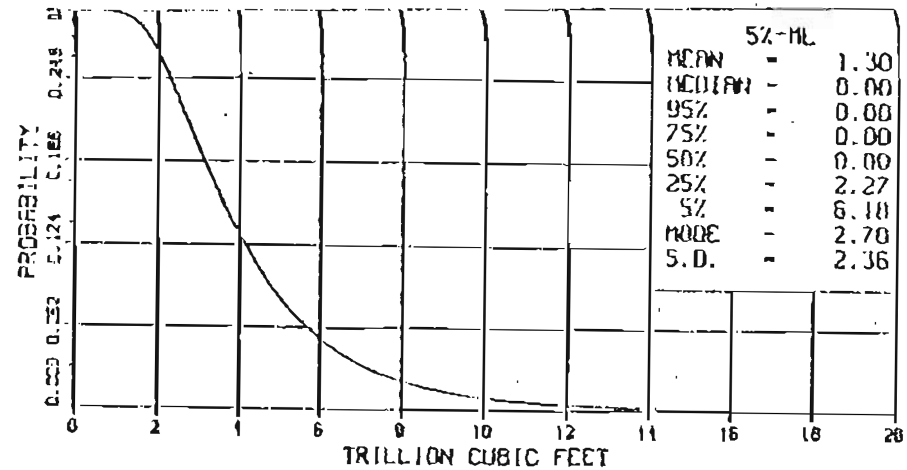
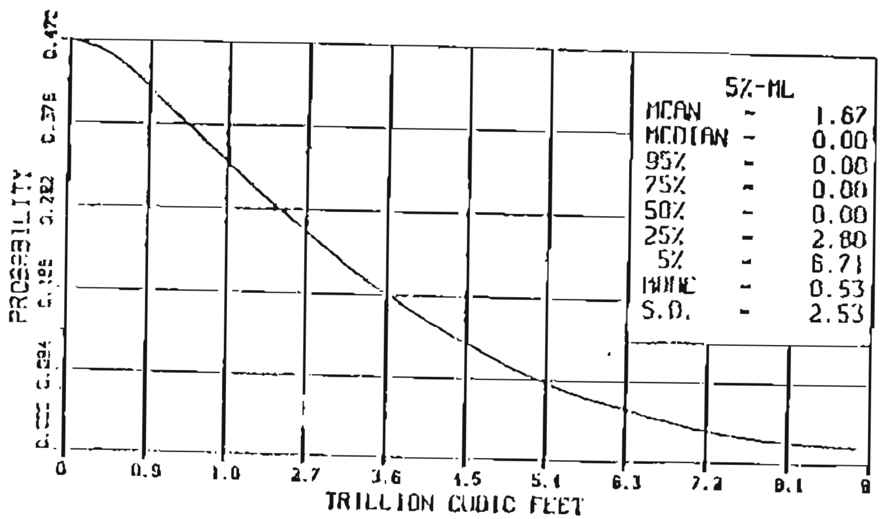


Fig. 18A. Estimates of undiscovered recoverable oil and gas under Kodiak shelf.





KODIAK SHELF (0-200M) TOTAL GAS UNCOND.



KODIAK SHELF (0-200M) TOTAL GAS COND.

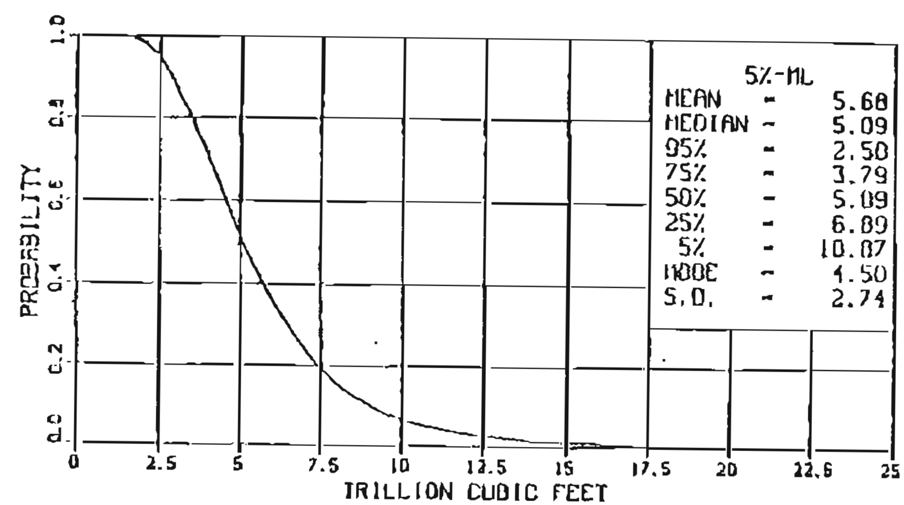


Fig. 18A, continued

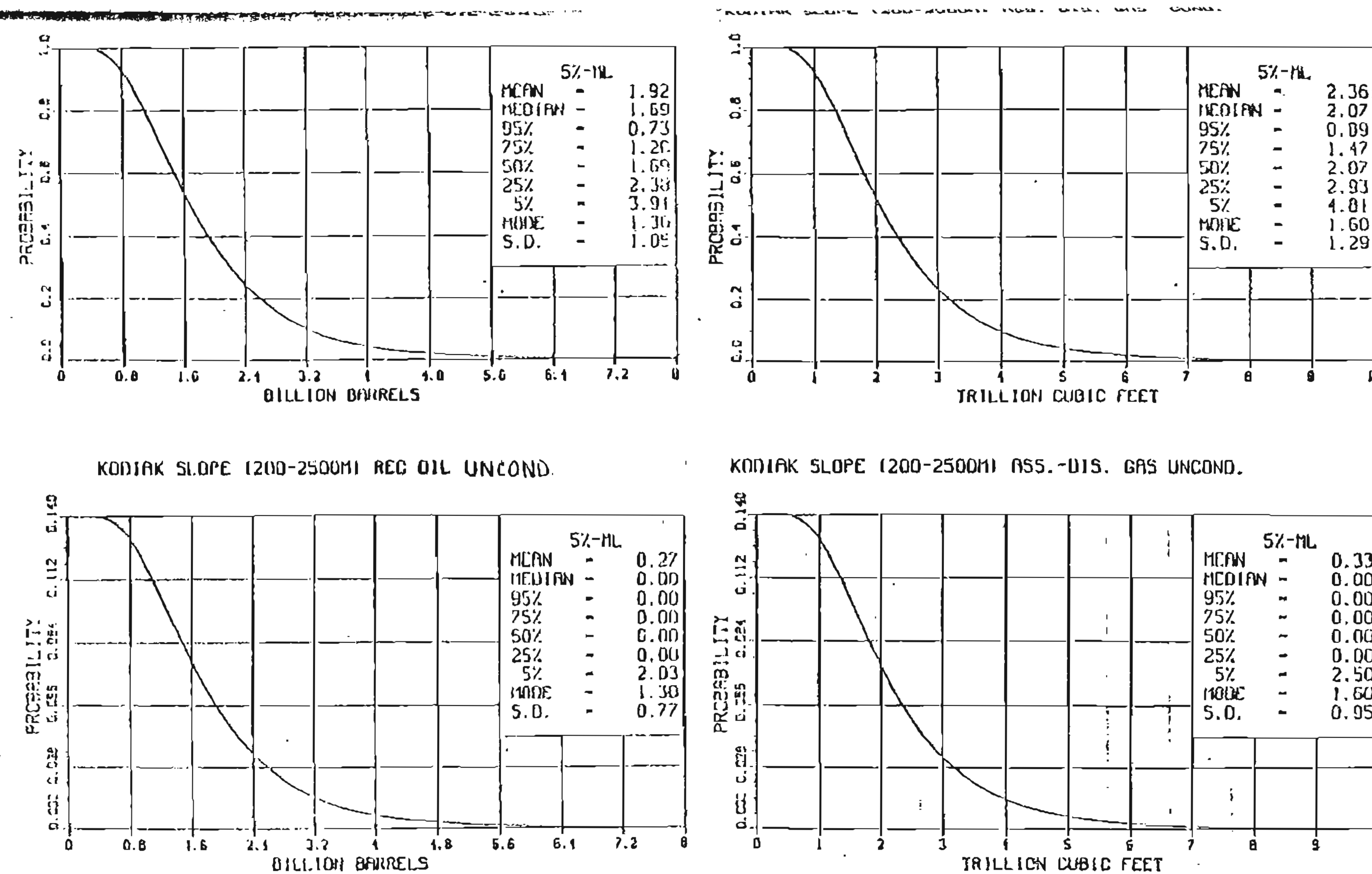
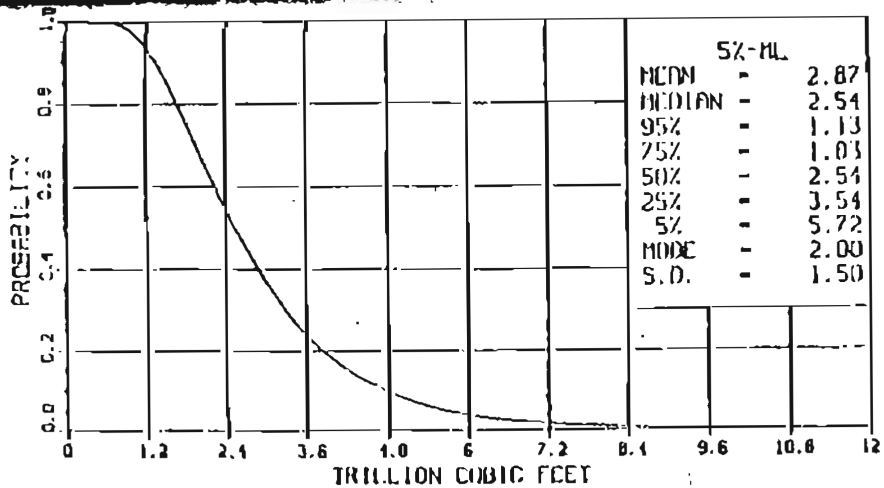
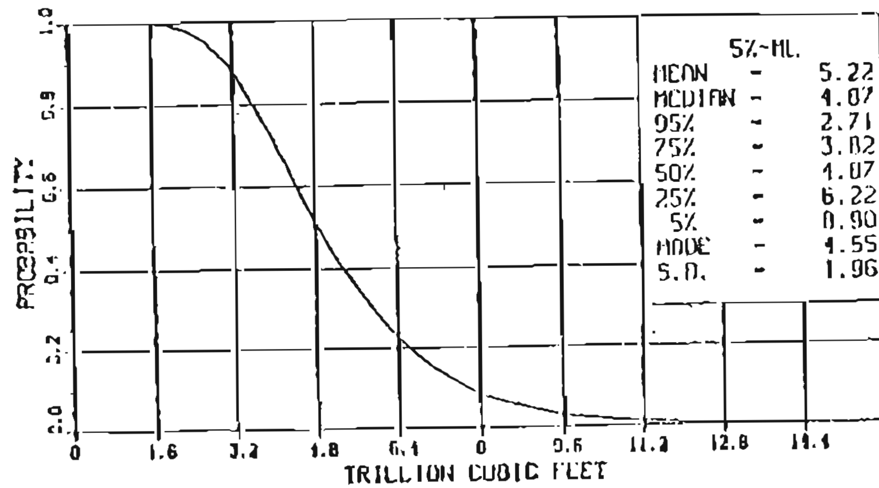
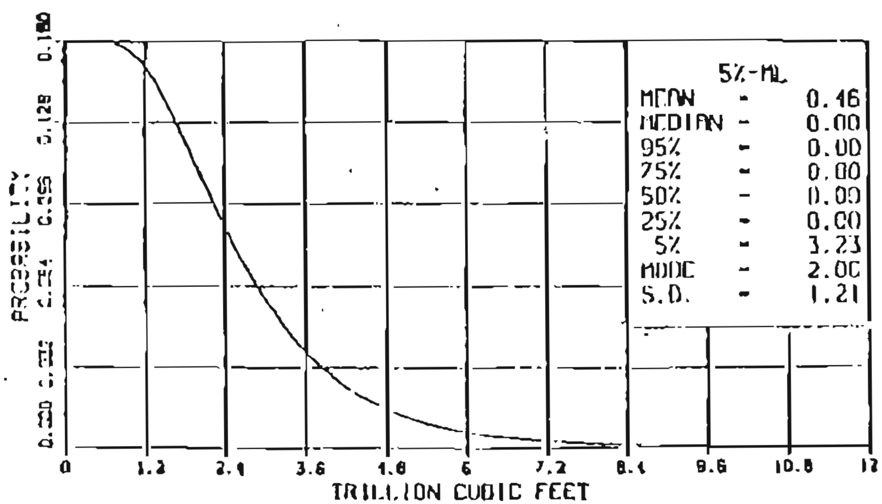


Fig. 18B. Estimates of undiscovered recoverable oil and gas under Kodiak slope. Estimates are for the total Kodiak slope province. The proposed sale area includes about 50 percent of the potential hydrocarbons under the slope.





KODIAK SLOPE (200-2500M) REC NON-AS50C GAS UNCOND.



KODIAK SLOPE (200-2500M) TOTAL GAS UNCOND.

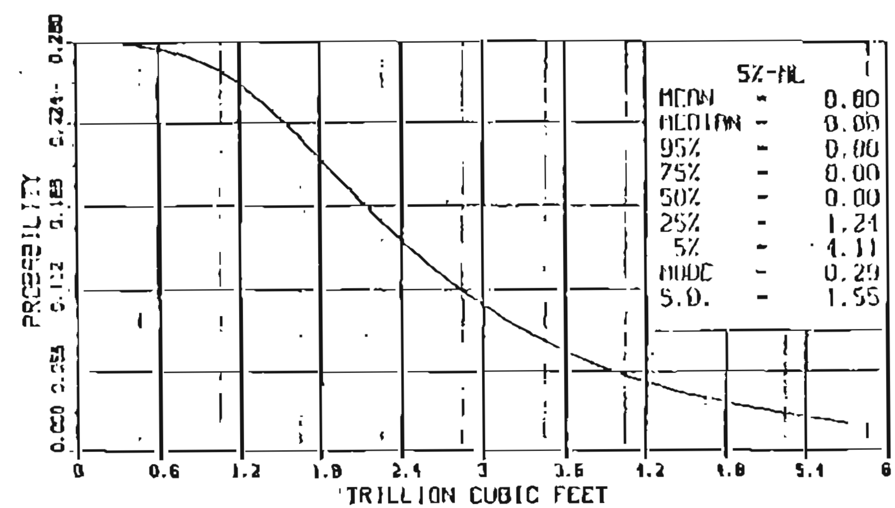


Fig. 18B continued

ENVIRONMENTAL GEOLOGY

General Considerations

Major geoenvironmental studies on Kodiak Shelf have been conducted since 1976 by the U.S. Geological Survey (geology and geophysics) and the University of Alaska (seismology), as part of the BLM/NOAA Outer Continental Shelf Environmental Assessment Program. Geological and geophysical data were gathered aboard the research vessels SEA SOUNDER and S.P. LEE. Seismic reflection surveys were run along 8200 km of trackline, using combinations of 30- to 60- kilojoule sparker, 800-joule boomer, and 3.5- and 12-kilohertz high-resolution systems, and limited side-scanning sonar and underwater photography were done. Sediment samples were gathered at 158 stations (Bouma and Hampton,1976, 1978; Hampton and Bouma, 1979). High-resoultion records contracted in 1976 and 1977 by the U.S. Geological Survey Conservation Division over about 10,000 km of trackline were also used.

Seismicity has been studied using the long-term historic record and data gathered by a network of 24 short-period, vertical component seismograph stations on the Alaska Peninsula, around lower lower Cook Inlet, and on the Kodiak islands. The detection threshold within the network is appoximately magnitude 2, but is as low as magnitude 1 in some portions (Pulpan and Kienle, 1979).

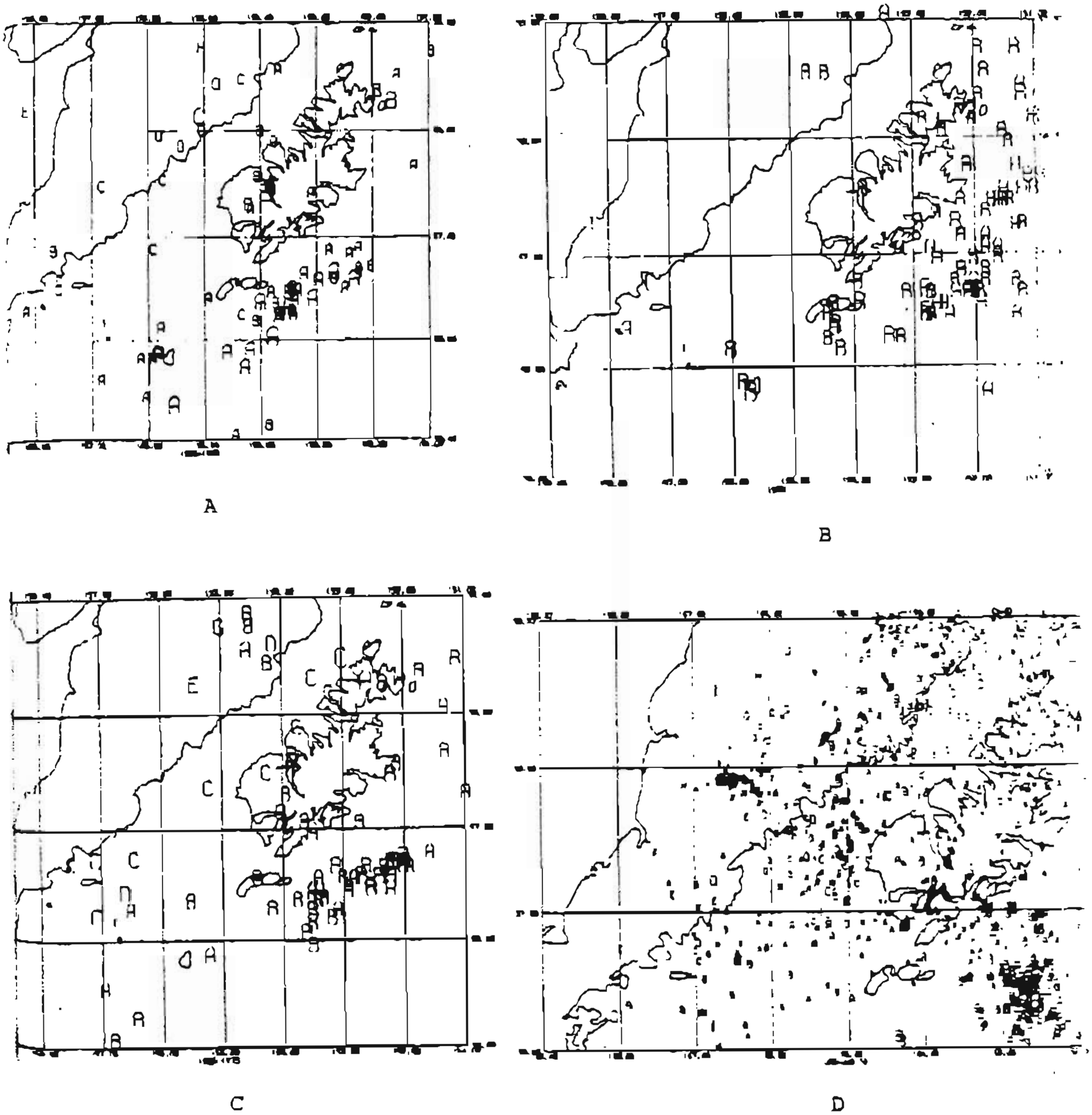
Seismicity

The Gulf of Alaska-Aleutian Island area is one of the most seismically active on Earth, accounting for about 7 percent of the annual worldwide release of seismic energy. Most of this energy release is associated with great earthquakes (larger than magnitude 7.8). Since recording of large earthquakes began in 1902, at least 95 potentially destructive events (M>6) have occurred in the vicinity of the Kodiak Shelf.

Great earthquakes in the Gulf of Alaska-Aleutian Island area may occur in a spatial-temporal series. Aftershock zones are nonoverlapping and define segments of lithosphere that experience separate episodes of major seismic activity (Sykes, 1971). Certain segments that have recently been inactive are identified as seismic gaps, judged most likely for the next great earthquakes. Estimates of recurrence intervals within segments range from 800 years based on long-term geological evidence (Plafker and Rubin, 1967) to 30 years based on the historic record (Sykes, 1971). The Shumagin seismic gap, as delineated by Pulpan and Kienle (1979), may extend to within a few kilometers of the southwest boundary of sale area 61 on the Kodiak Shelf.

The last great earthquake to affect the Kodiak Shelf was the 1964 event of magnitude 8.5. The epicenter was in Prince William Sound, 500 km to the northeast, but rupture extended along the shelf to Kodiak Island, and aftershocks covered the entire shelf. Seafloor uplift of 15 m occurred in the central Gulf of Alaska (Malloy and Merrill, 1972) and 7 m on the Kodiak Shelf (von Huene and others, 1972).

The historic record shows a cluster of seismic events near the mouth of Kiliuda Trough and nearby on southern and middle Albatross Banks (Fig. 19). The southwestern boundary of this zone is about at the same location as one of the transverse tectonic segments described by Fisher and others (1980) and also near the southwestern extent of aftershocks from the 1964 Alaska earthquake. Other shallow seismicity on the shelf is diffuse and shows no linear trends or alignment along known faults (Pulpan and Kienle, 1979).



19 Epicenters in the vicinity of Kodiak Shelf. a) magnitudes $M_B>4$ from 1954-1963, b) magnitudes $M_B>5$ in the 1964 Alaska earthquake, c) magnitudes $M_B>5$ from 1965-1975, d) January-June 1978. Letter code represents hypocentral depth range (A: 0-25 km, B: 25-50 km, etc.). Data compiled by H. Pulpan, University of Alaska.

Shallow Structures

Shallow folds and faults on the Kodiak Shelf trend approximately N45°E, parallel to the Aleutian Trench, except for a few local divergences (Fig. 20). Structures occur in zones, indicating areal variation in the intensity of related environmental concerns on the shelf.

A major fault zone extends along the southeast coast of Kodiak Island, both on and offshore (Capps, 1937; Moore, 1967; von Huene and others, 1972), and continues some 600 km to Montague Island in the eastern Gulf. Fault lengths range up to at least 60 km on the Kodiak Shelf (Fig. 20), and perhaps up to 140 km (Thrasher, 1979). Faults in this zone are steep and have both landward and seaward dips.

A less extensive zone of faults, with associated large folds, occurs near the shelf break along southern and middle Albatross Banks. A similar structural style exists near the shelf break on Portlock Bank, close to the boundary of our areal coverage, but faults die out and folds become broad and subdued on the intervening area of northern Albatross Bank.

A transverse zone of folds trends across Portlock Bank. These folds are part of a series of structures that may form one of the transverse tectonic boundaries described by Fisher and others (1980).

Several lines of evidence suggest that the major zones of shallow structures are actively forming and related to modern tectonism. Von Huene and others (1972) compared bathymetric records before and after the 1964 Alaska earthquake and determined that perhaps to 7 m of uplift occurred on middle Albatross Bank. Fault offset in 1964 was documented on and adjacent to Montague Island (Malloy and Merrill, 1972) at the northeast extent of the zone that trends along the coast of Kodiak Island. Indirect evidence, such as

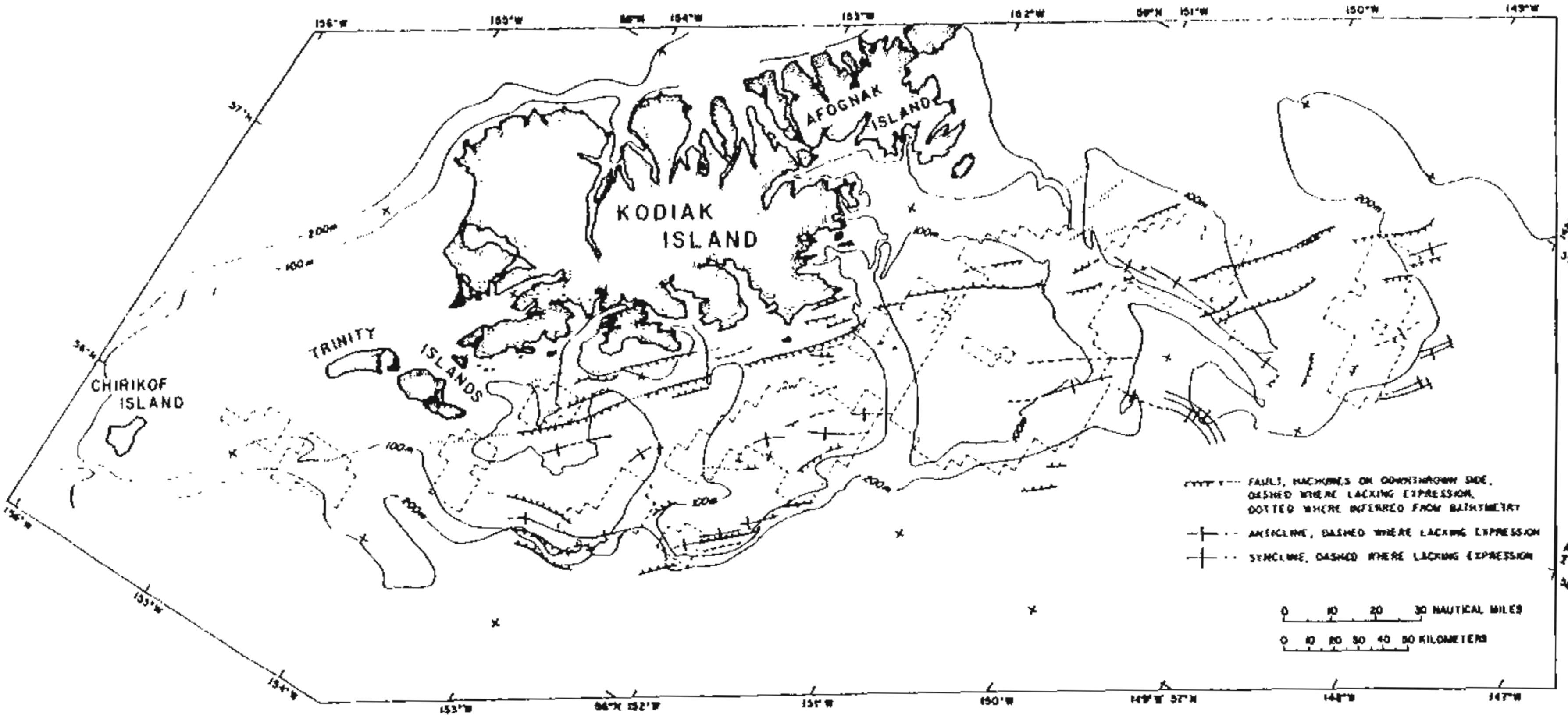


FIG. 20

Shallow folds and faults. Compiled by R. von Huene and D. Varchal (U.S. Geological Survey Open-file report, in press). No data southwest of Sitkalidak Island.

sharp bathymetric expression of fault scarps and occurrence of aftershocks, suggests offset on Kodiak Shelf itself.

Folds along the shelf break commonly deform the seafloor, indicating recent deformation. They have been breached by erosion in several places, exposing semilithified to lithified Pleistocene and older rocks (McClellan and others, 1980).

Physiography and Bathymetry

The physiography of the Kodiak Shelf consists of a series of flat banks, generally 50 to 100 m deep, cut by transverse troughs, up to 200 m deep (Fig. 21). The main elements of the physiography have a structural or erosional origin.

A significant second-order physiographic feature is a discontinuous series of arches along the shelf break. These arches are the seafloor expression of anticlines described previously and have a relief of up to 60 m. They extend along the banks and across the troughs, forming a discontinuous sill along the edge of the shelf. The arches are best developed from southern to middle Albatross Bank, including Kiliuda and Chiniak Troughs, but are poorly developed to absent on northern Albatross Bank. The arch across the mouth of Stevenson Trough is breached by two erosional channels. Arches are well developed on Portlock Bank and across the middle of Amatuli Trough, far from the shelf edge. Low areas cut transversely across the middle of Albatross and Portlock Banks, interrupting the arch.

No such arch exists in Sitkinak Trough, which also differs from other troughs in that it is deep and only indents the shelf edge, rather than extending across the shelf. The walls of this trough are relatively steep.

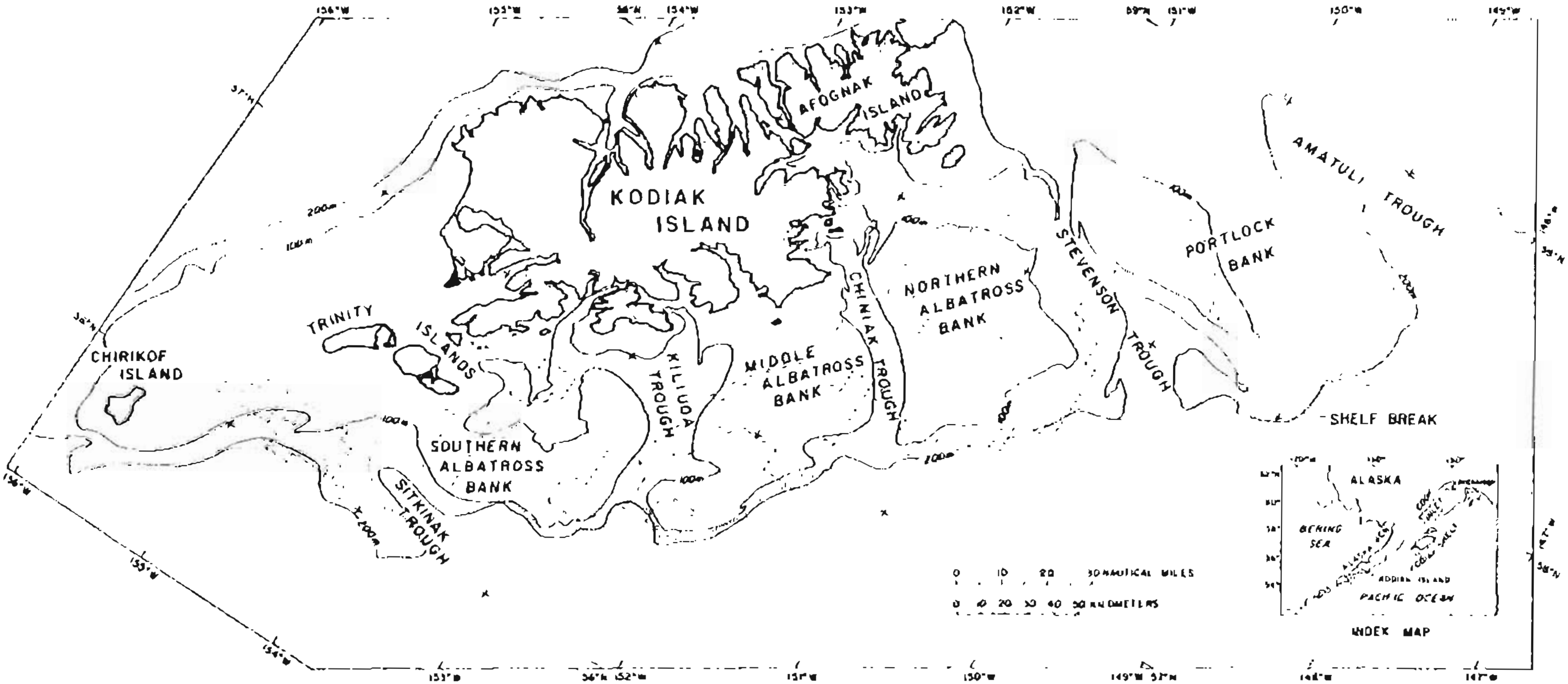


FIG. 21

Major physiographic features.

Young anticlines growing seaward of the main shelf break are forming a new break off Kiliuda Trough and southwest middle Albatross Bank, and off Portlock Bank. The shelf break is therefore a discontinuous, in echelon feature in these areas.

Other second-order physiographic features that have environmental significance are bedrock ridges, fault scarps, and sand waves. Ridges occur where steeply inclined bedrock crops out at the seafloor and has experienced differential erosion. Maximum relief of these features is about 5 m.

Fields of large sand waves appear at three locations, in Stevenson Trough, on northern Albatross Bank, and between Chirikof and Trinity Islands (Fig. 22). Wave heights reach 15 m, and wave lengths reach 300 m. Smaller sand waves, on the order of a meter high, also have been noted on side-scanning sonar records.

Abrupt scarps are abundant in the zones of faults described previously, and occur locally in other places over the shelf. Maximum offset is about 10 m, but varies significantly along the length of a fault.

The slope of the seafloor is low over much of the Kodiak Shelf, being nearly flat on most parts of the banks, and rarely exceeding 5 percent on the flanks of troughs. A notable exception is Sitkinak Trough, where gradients reach 20 percent. The upper continental slope is also relatively steep, with gradients of 10 to 40 percent being typical.

Stratigraphy, Facies, and Surficial Sediment

Surficial unconsolidated sediment on Kodiak Shelf consists of various proportions of terrigenous, volcanic, and biogenic debris (Gershanovich, 1968; Bouma and Hampton, 1976, 1978, 1979). A generalized thickness map of unconsolidated sediment is shown in Figure 23. Unconsolidated sediment forms

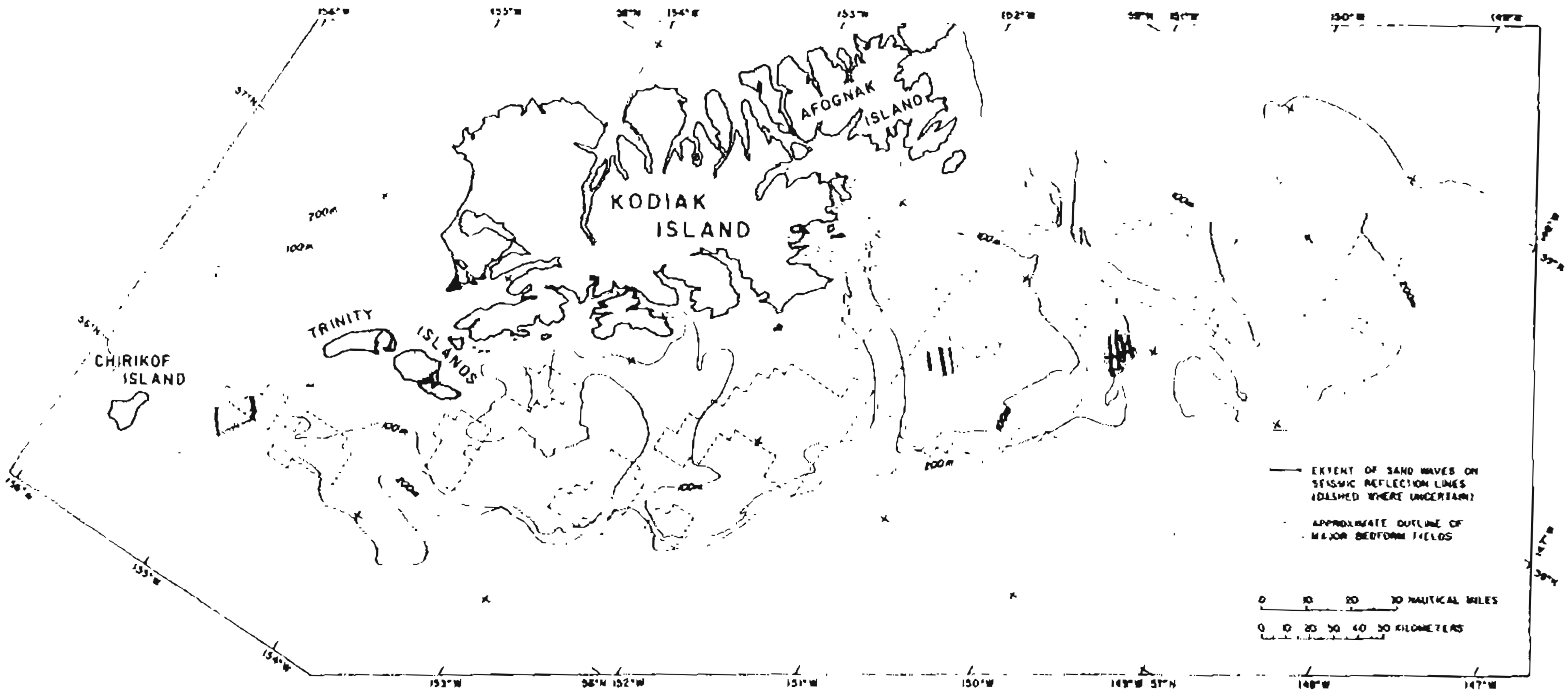


FIG. 22

Locations of large sand waves and major sand wave fields.

a thin veneer over much of the shelf, typically less than 100 ms of acoustic penetration measured as two-way travel time. (Note that 1 ms two-way travel time = 1 m thickness for acoustic velocity of 2000 m/s.) Local closed basins have up to 200 ms of fill, and sediment thickness in Sitkinak Trough exceeds 400 ms.

Sedimentary bedrock crops out over broad areas of the shelf. It is well stratified and folded. Where covered with unconsolidated material, a marked structural discordance typically occurs, and it is the depth to this unconformity surface that is given in Figure 23.

A variety of sediment types exists on the shelf. Distribution of sediment types is related to physiography and also to stratigraphic units that have been defined on the basis of seismic-reflection signature (Fig. 24 and Table 2; Thrasher, 1979). On the banks, typical unconsolidated sediment is coarse-grained (gravelly to bouldery sand), with the main compositional components being terrigenous debris and megafaunal shells. Silt- and clay-size material are present in minor amounts, and the composition of this fraction is volcanic ash, with siliceous microfossils, clay minerals, and other terrigenous material present in small amounts. This sediment type correlates with Thrasher's (1979) stratigraphic unit Qgf, which is the most widespread unconsolidated facies on the shelf and is interpreted to be of glacial-fluvial and glacial-marine origin. It also correlates with stratigraphic unit Qgm, which occurs along the margins of the mouths of the troughs. These deposits are speculated to be lateral and terminal moraines. Typical Qgm sediment is somewhat muddier and lower in megafaunal shells than typical Qgf, although a sharp distinction cannot be made.

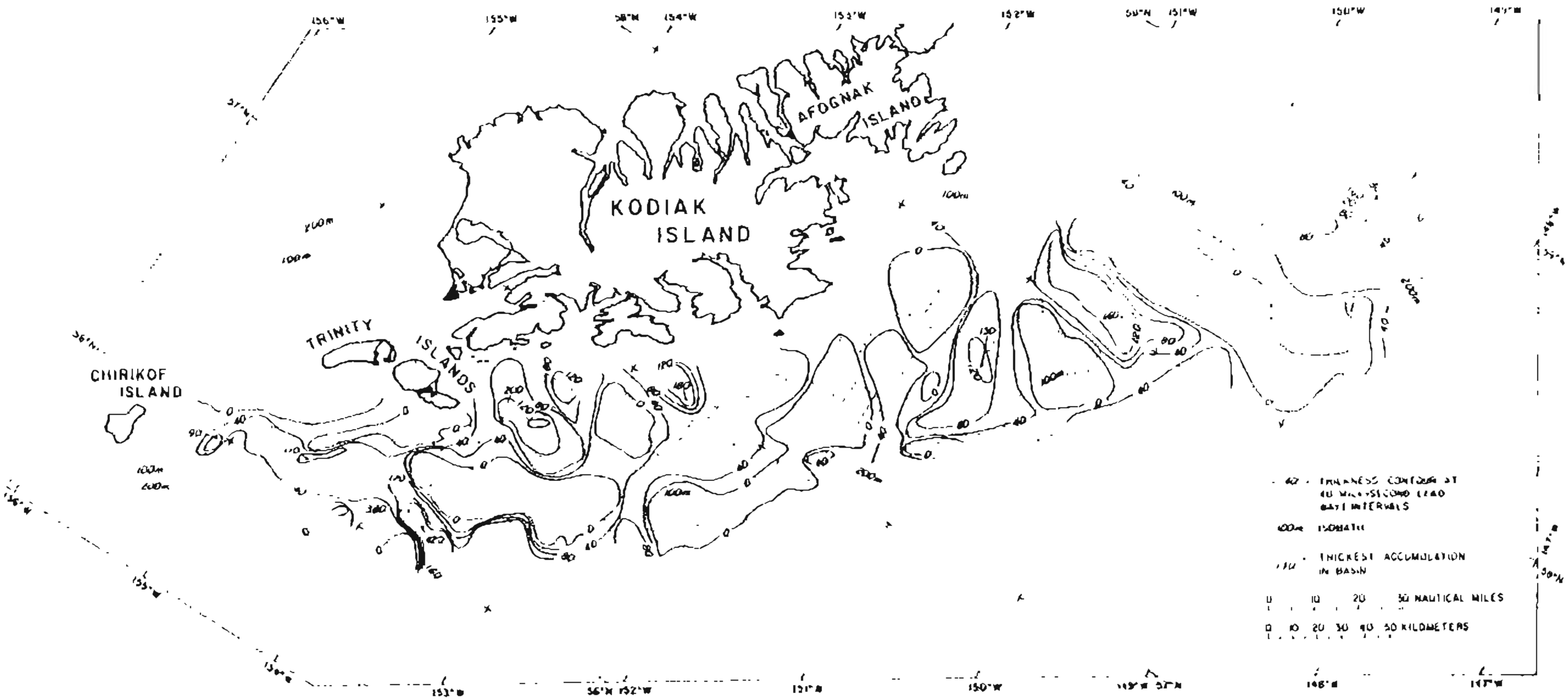


FIG. 23

Generalized thickness map of surficial unconsolidated sedimentary units.

Typical sediment flooring the troughs, corresponding to Thrasher's stratigraphic unit Qs, is finer grained and of different composition than typical sediment on the banks. Moreover, sediment type varies from trough to trough. Sitkinak Trough contains muddy sand, with some coarse debris, that is composed of terrigenous material and moderate amounts of volcanic ash. Amatuli Trough apparently contains similar sediment although only two samples have been collected. Kiliuda Trough has mud and sandy mud composed of terrigenous minerals, volcanic ash, and with large amounts of siliceous microfossils in the sand fraction. Chiniak Trough contains sandy muds composed mostly of volcanic ash. Stevenson Trough contains terrigenous sand, with moderate amounts of mud and volcanic ash.

Volcanic ash, derived from the 1912 eruption of Katmai volcano on the Alaska Peninsula, is an important constituent of surficial sediment (Hampton and others, 1979). In general, the ash distribution on the seafloor of Kodiak Shelf shows high concentrations in Chiniak Trough and in shallow depressions on the banks. Low concentrations exist on flat parts of the banks.

Clay minerals are present in small to moderate quantities in all surficial sediment types. Composition of the clay was analyzed by Hein and others (1979), and two major sources were identified: the Copper River about 400 km away in the eastern Gulf of Alaska and local bedrock outcrops on Kodiak Shelf itself. Clay-mineral suites from these two sources are mixed over most of the shelf, but the Copper River suite seems to collect on flat parts of the banks. Bedrock-derived clays collect around outcrops and in nearby shallow depressions on the banks. Mixtures from the two sources are found in the trans-shelf troughs. Microscopic analysis shows that some Katmai ash has been altered to clay, but most is surprisingly fresh.

Bedrock samples, taken as dart cores from areas of seafloor outcrop, are composed of semilithified to lithified siltstone and fine-grained sandstone. Outcrops occur in the crestal regions of large anticlines, and microfaunal age determinations are as old as middle or late Miocene (McClellan and others, 1980). Grab samples of poorly sorted mixtures of terrigenous and megafaunal shell debris were obtained at some areas designated as bedrock outcrop on Figure 24. This implies a thin cover of unconsolidated material, especially in valleys between bedrock ridges.

The sedimentary processes and history of the Kodiak Shelf can be deduced from the available data. The sedimentary bedrock probably was eroded during Pleistocene time. The coarse-grained unconsolidated sediment that covers the bedrock, to judge from sediment texture and the inferred regional history, was deposited by Pleistocene glacial processes (Karlstrom, 1964; University of Alaska, 1974). Thrasher (1979) has delineated glacial ground, lateral, and end moraine deposits. The glacial deposits were reworked during the Holocene transgression.

The influx of modern sediment is low, because no large rivers drain onto Kodiak Shelf. The Copper River and local submarine outcrops provide minor epiclastic material. Occasional strong volcanic eruptions such as the Katmai event in 1912 are a relatively major source of sediment (volcanic ash), although the absolute amount is minor. Biogenic sources provide some siliceous and carbonate shell debris.

The present-day sedimentary setting is therfore one of reworking of predominantly pre-Holocene deposits. Currents impinge on the seafloor from the southwestward-flowing Alaska current and from large storm waves. Fine sediment is winnowed from the surficial deposits on the banks, and its fate is determined by the pattern of ocean currents and by the physiography. A minor

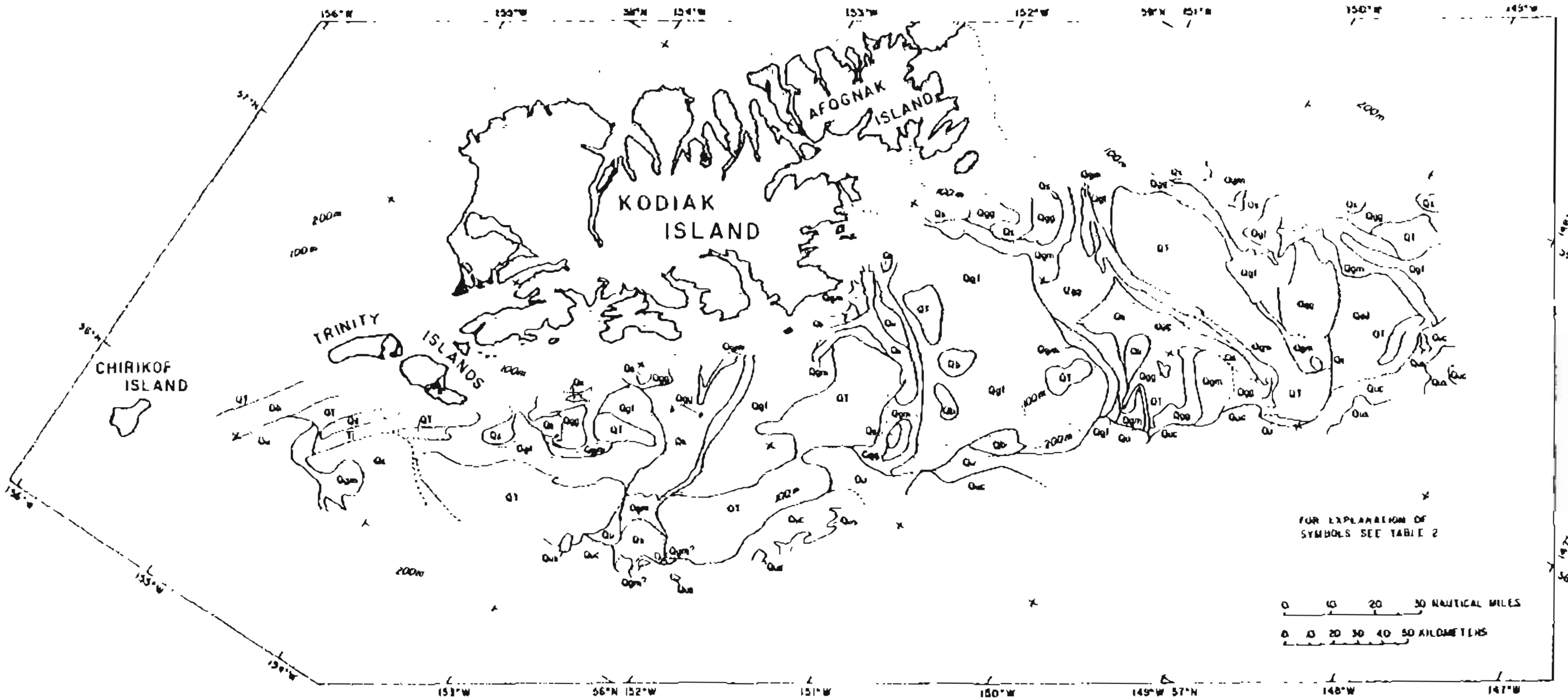


FIG. 24

Surficial sedimentary units (from Thrasher, 1979). See TABLE 2 for description.

Table 2. Description of sedimentary units (From Thrasher, 1979. Refer to Fig. 24).

Qs: Holocene Soft Sediments. Shallow basins of Holocene sediments that exhibit well-defined, continuous, horizontal reflectors.

Qb: Holocene Bedforms and Sand-Fields. Mapable regions of bedforms and, where possible, the massive sand unit with which they correlate.

Qu: Holocene and Pleistocene Undifferentiated Deposits. Exhibit well-developed, non-horizontal, parallel layering, with occasional indications of internal layering.

Qgm: Pleistocene Glacial Lateral and Terminal Moraines. Fairly linear deposits generally located along the sides and across the mouths of sea valleys. Very little or no acoustic internal structure.

Qgg: Pleistocene Glacial Ground Moraine. Hummocky upper surface; no internal structure.

Qgf: Pleistocene Glacial-Fluvial and Glacial-Marine Deposits. Thick deposits exhibiting some discontinuous, non-parrallel, non-horizontal reflectors.

QT: Plio-Pleistocene Sedimentary Rocks. Gently depping, truncated sedimentary rocks that exhibit well-developed parallel internal reflecotrs.

T: Tertiary Sedimentary Rocks. No seismically determinable internal structure. Observed only in small outcrops along the landward edge of the mapped area.

Quc: Quaternary Undifferentiated Continental slope Deposits. Large seismic vertical exaggeration and steep slopes seaward of the continental shelf edge preclude accurate mapping on the continental slope.

Qus: Quaternary Undifferentiated Sediment Basins on the Upper Continental Slope. Exhibit well-defined, near-horizontal, continuous reflectors.

amount is redeposited on the banks in broad shallow depressions where thin surficial layers of ash- and clay-rich material have been sampled. A much greater amount is deposited in troughs. Kiliuda and Chiniak Troughs in particular are floored by fine-grained ash-rich sediment. The negative relief of the troughs and the sills across their mouths have created quiet depositional settings. Sitkinak Trough contains thick accumulations of terrigenous silty sediment that may be derived mainly as first-cycle input from Shelikof Strait, plus some reworked Kodiak Shelf debris.

The sedimentary environment in Stevenson Trough is distinct from the others. The presence of clean sand that has been molded into large predominantly seaward-facing sand waves suggests strong bottom currents. The sill across the trough has been breached. Modified glacial sediment on the sill is similar to that on the adjacent banks, whereas within a breach and on the adjacent continental slope it is more similar to sediment within the trough. Transport appears to have occurred out of the trough and onto the continental slope. But it is uncertain whether this occurs significantly at present or if it took place mainly during the Holocene transgession.

Gas-Charged Sediment

Hydrocarbon gases, methane (C_1), ethane (C_2), ethene ($C_{2:1}$), propane (C_3) and propene ($C_{3:1}$) are common in near-surface sediment of Kodiak Shelf. Of these gases, C_1 is the only one of quantitative importance. Concentrations of C_1 range from about 5×10^{-1} to 1.2×10^5 µL/L of interstitial water, whereas concentrations of the other hydrocarbons rarely exceed 1 µL/L. Gas-charged cores have been recovered from three main areas on Kodiak Shelf: (1) Kiliuda Trough, (2) Chiniak Trough, and (3) Sitkinak Trough. In all cases, the composition of gases indicates that they were derived from shallow biological processes, rather than a deep thermogenic source.

A variety of acoustic anomaly types is found in seismic-reflection records on Kodiak Shelf perhaps indicating the presence of bubble-phase gas in the sediment (e.g., Schubel, 1974; Whelan and others, 1976; Holmes and Cline, 1977). Major anomaly areas are: (1) along the length of Chiniak Trough and nearby on northern Albatross Bank, (2) on middle Albatross Bank near Kiliuda Trough, and (3) within the recurved area of Kiliuda Trough and nearby on southern Albatross Bank (Fig. 25). Gas-charged cores have been collected from some locations of acoustic anomalies, although the correspondence between gas-charged cores and acoustic anomalies is not one-to-one. A gas seep has been detected in the anomaly zone on middle Albatross Bank, along the extension of a mapped fault.

Sediment Slides

Sediment slides in the area of Kodiak Shelf have been identified in seismic-reflection profiles, and the distribution of slides is shown in Figure 9. Indications of slides are rare on the Kodiak Shelf, whereas they are abundant on the adjacent continental slope. The two possible slides identified on the shelf are in Stevenson Trough and appear as small hummocks on the seafloor. Self and Malmood (1977) report slides on the flanks of unidentified troughs southwest of Kodiak Island and south of Sitkinak Island, but exact locations are not given. Steep slopes occur in this area.

The distribution of large slides is uneven along the upper continental slope. They are abundant off southern and middle Albatross Bank and off Portlock Bank but have not been found off northern Albatross Bank. (The slides identified off northern Albatross Bank in Figure 26 are small. Small slides occur in other areas also.) The occurrence of large slides shows a relation to structural and tectonic elements of the region. Near-surface folds and faults are actively growing, with consequent slope steepening, and

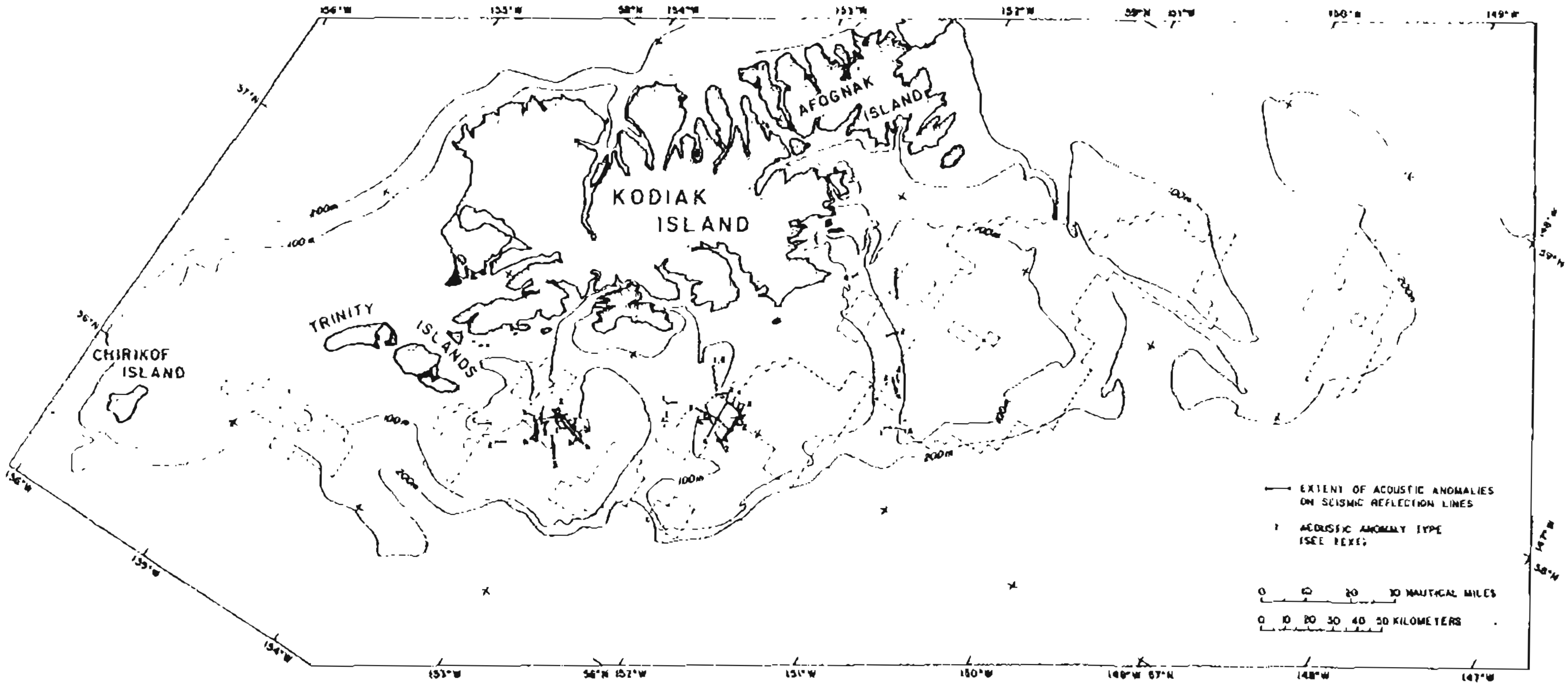


FIG. 25

Locations of acoustic anomalies. See text for description of anomaly types.

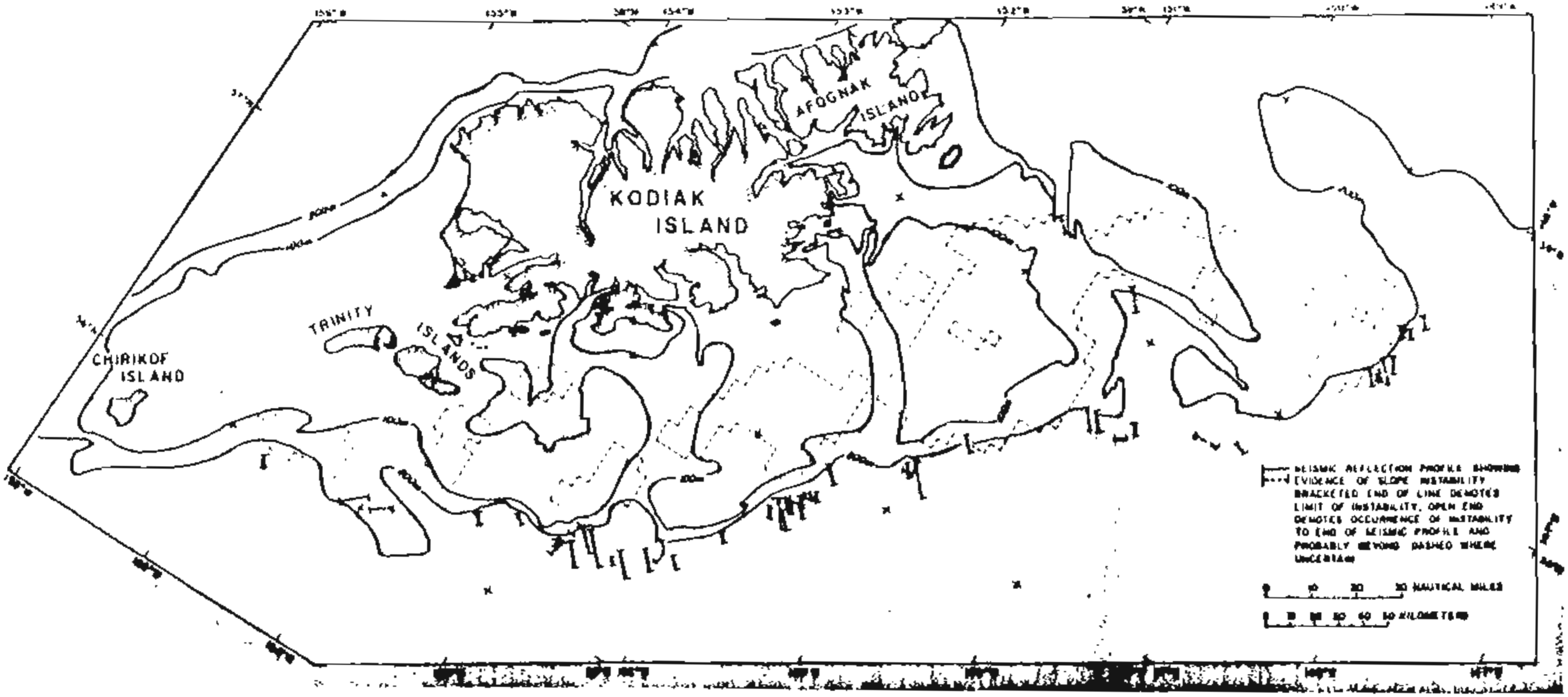


FIG. 26

Locations of sediment slides.

the shelf-break arch is well developed. Earthquake epicenters are concentrated near the large slides adjacent to southern and middle Albatross Banks (Fig. 19). In contrast, gentle folding, low seafloor inclinations, and a subdued shelf-break arch characterize the area where large slides are absent, and epicenters are sparse.

The large slumps are controlled by tectonic processes such as active growth of structures along the shelf break. A quantitative evaluation by Hampton and others (1978) of two specific large slumps indicates that steep slopes, removal of lateral ground support by faulting, and earthquake accelerations are the most likely environmental factors to activate these slumps. Magnitudes of several of these factors are less in the area off northern Albatross Bank, implying a variation of the intensity of tectonism along the shelf break. Future generation of large slumps can be expected on the upper continental slope in the areas of intense tectonism.

The scarcity of slides on Kodiak Shelf probably is accounted for by the presence of relatively coherent sediment on sloping portions of the seafloor and the low seafloor slopes in general. This is in strong contrast to the nearby northeastern Gulf of Alaska where large slumps occur on slopes of less than 1° in fine-grained, underconsolidated sediment derived from coastal glaciers and the Copper River (Carlson and Molnia, 1977; Molnia and others, 1977). The weakest sediment on Kodiak Shelf, which commonly shows evidence of being gas-charged and is exposed to strong earthquake forces, is not prone to sliding. This sediment is present mainly on flat seafloor, but is also stable in most relatively steep areas such as Sitkinak Trough. Other forms of sediment instability such as liquefaction and consolidation subsidence are possible in the soft sediment, but indications of these phenomena can be subtle and have not been detected.

Environmental Assessment

Geologic processes pose several environmental conditions of concern to resource development on the Kodiak Shelf. Some processes may affect the operation and safety of offshore engineering activities. For example, seismic events may severely disrupt petroleum exploration and production operations on drilling platforms. Other geologic processes in turn may be affected by resource development, with deleterious environmental consequences. For example, incorporation of spilled contaminants into bottom sediment may affect benthic life.

Environmental geologic concerns on Kodiak Shelf are broadly related to tectonic and sedimentary processes. Most processes affect broad areas, and their origin or occurrence at a specific location can have both local and widespread consequences.

Seismic-Tectonic Effects

The tectonic setting of the Kodiak Shelf creates potential environmental hazards. Seismicity and structural deformation are spatially variable across the region, posing different sets of concerns from place to place. As discussed on a previous page, zonation of seismicity has been postulated, with identification of a seismic gap near Kodiak Shelf where the potential for a major earthquake is great. Folding and faulting are more severe along sections of the shelf break and near Kodiak Island than in other places, and postulated transverse tectonic boundaries may indicate other areas of concentrated deformation.

The minimum recurrence interval of 30 years for a major earthquake could be exceeded by the lifetime of an oil-producing province, because the last major event to affect Kodiak Shelf was in 1964. So, although earthquakes cannot be predicted with confidence, seismic hazards are a valid concern for offshore development. Strong ground shaking, fault rupture, sediment displacement, and tectonic deformation of the seafloor have all occurred on or adjacent to the Kodiak Shelf and can be expected in the future.

Kodiak Shelf might be affected seismically from major events in either of two regional zones; that involved with the 1964 Alaska earthquake or that identified as the Shumagin seismic gap. The 1964 earthquake had aftershocks across the entire Kodiak Shelf, and seafloor deformation or ground shaking of the magnitude associated with this event could affect operation of bottom-founded installations such as drilling platforms. A major event in the Shumagin seismic gap may not have epicenters located on Kodiak Shelf, if present theory is correct (Sykes, 1971; Pulpan and Kienle, 1979), but significant ground shaking could be generated at least in the southwest part of the area.

Another area of seismic concern is near the mouth of Kiliuda Trough and adjacent sections of southern and middle Albatross Banks, where several moderate earthquakes have occurred (Fig. 19). This area displays a much higher rate of strain release than elsewhere on Kodiak Shelf, and seismic-reflection records show evidence of folding, faulting, seafloor deformation, and sediment sliding (Pulpan and Kienle, 1979; Hampton and others, 1979). The shelf-break area of Portlock Bank shows similar structural features, suggesting similar tectonic behavior, but the historic record shows no concentration of seismic activity there.

The area along the shelf break on northern Albatross Bank appears from structural and seismic evidence to be less active and therefore less prone to local tectonic hazards than the two adjacent zones of strong deformation discussed above. Regional seismicity could still produce significant ground shaking there, of course.

Displacement of the seafloor can result from movement along shallow faults, causing damage to installations that span them. Present-day seismicity does not indicate any clear linear seismic trends that define active faults (Pulpan and Kienle, 1979). But, offset in 1964 along faults within the zone extending along and offshore from Kodiak Island has been documented in places and inferred in others (Malloy and Merrill, 1972; von Huene, 1972) raising special concern for proper routing of pipeline corridors across the zone. Another significant fault zone exists along the shelf break of southern and middle Albatross Bank, and other individual examples have been noted across the shelf. Faulting and tectonic deformation of the seafloor can generate tsunamis, which can devastate coastal areas as happened on Kodiak Island in 1964 (Kachadoorian and Plafker, 1967).

Sediment

The sedimentary environment of Kodiak Shelf has many unusual features of practical significance. Semilithified to lithified bedrock is exposed over large areas, and a diverse suite of unconsolidated sediment is present including coarse-grained material, clean sand, and normal terrigenous mud. Furthermore, input of modern sediment is small, and ocean currents impinging on the seafloor can be strong in places but are insignificant in others. Broad areas are being reworked, whereas others serve as quiet repositories for winnowed debris.

Although geotechnical data are lacking, sedimentary bedrock appears to provide strong foundation material at the seafloor over broad expanses of Kodiak Shelf. Resistance to trenching and pile driving might be significant, and problems of emplacement of engineering structures might be encountered on bedrock ridges due to rough topography.

Accumulations of unconsolidated sediment on Kodiak Shelf are generally thin, and in many places firm bedrock is within reach of subbottom structural foundations. The banks appear overall to be composed of strong stable material, and foundation problems should be minimal. Boulders in unconsolidated debris might interfere with drilling and setting of casings, however.

The localized concentrations of fine sediment in some of the troughs might have engineering importance, although the deposits typically are only a few tens of meters thick. Accumulations in Chiniak and Kiliuda Troughs might be composed of volcanic ash grains and siliceous microfaunal tests throughout much of their thickness. The ash particles are plate- to rod-shaped and some are highly vesicular. Siliceous shells are hollow and fragile. Individual grains are therefore weak, and the deposits have high void ratios. Grain crushing and rearrangement during loading might result in substantial consolidation. Also, liquefaction, with associated strength loss and subsidence, is a possibility during earthquakes. Similar problems might be encountered with the fine-grained sediment in Sitkinak Trough, but the higher percentage of terrigenous material suggests greater stability. The large thickness of unconsolidated sediment in Sitkinak Trough might necessitate different foundation design than in areas of less fine sediment accumulation. The sandy material in Stevenson Trough appears to be a type of material that would be stable under loading, but its engineering properties have not been studied in detail.

The volcanic ash recovered in sediment samples is relatively fresh, as has also been reported for buried ash deposits in the Gulf of Alaska (Scheidegger and Kulm, 1975). So, the sediment stability problems commonly encountered in terrestrial ash deposits that have been altered to clay are unlikely to be met on Kodiak Shelf.

The surficial deposits of volcanic ash that were sampled on the banks are only a few centimeters thick and of no engineering importance.

Strong currents are indicated where large bedforms occur (Fig. 22), although the degree of modern activity compared to times of lower sea level is uncertain. Scour of sediment can cause loss of support and differential settlement at the base of seafloor installations (Posey, 1971; Wilson and Abel, 1973; Palmer, 1976). Also, fluttering due to resonance set up by vortex shedding can occur where pipelines have become suspended as a result of scour. This has been documented in nearby Cook Inlet (Goepfert, 1969).

Slope instability does not appear to be a major problem on the shelf, having been reported only from a few areas (Fig. 26; see also Self and Malmood, 1977). The high degree of stability is related to the restricted occurrence of soft sediment mainly on flat areas of seafloor, whereas slopes are underlain by coarse-grained material. Sitkinak Trough is a notable exception, but no large slides have been specifically located there. Because of a low influx of modern sediment onto the shelf, large accumulations of unstable underconsolidated sediment like those in the nearby northeastern Gulf of Alaska do not occur (see Carlson and Molnia, 1977).

Locations of gas-charged sediment have been identified on Kodiak Shelf, and environmental problems are possible. Most gas appears to be generated by shallow microbial decay, although the gas seep on middle Albatross Bank may indicate a deeper thermogenic source there.

Slope instability, low strength, and overpressuring have been found associated with gas-charged sediment (Whelan and others, 1976; Nelson and others, 1978). Direct evidence that similar problems exist on Kodiak Shelf is sparse; the gas seep on middle Albatross Bank suggests overpressuring. Gas-related craters, subsidence, or slope instability have not been noticed (see, for example, Nelson and others, 1979). But, although large blowouts and failures may not have been initiated by natural environmental forces, engineering activities may serve to trigger them, and special attention is warranted in the specified areas.

Man-induced pollution of Kodiak Shelf waters can have magnified effects at certain places on the seafloor. Sediment particles can serve as carriers of contaminants, and localized concentration and storage are determined by the current patterns and hydraulic sorting processes that control sediment dispersal pathways and the locations of depositional sites. The distribution of benthic fauna should vary spatially with sediment type (although supporting biological data are lacking), so specific faunal populations might be less affected than others by a contamination event. For example, the localized occurrence of Katmai ash in some troughs and in bank depressions implies that these sites are presently repositories for fine-grained sediment. Pollutants that become incorporated into bottom sediment should be swept from other areas into them, and local fauna would be affected. Also, it is likely that sediment transport across the shelf break is localized where physiographic barriers are absent or have been breached, which would cause disturbance of local populations after a pollution event.

TECHNOLOGY, INFRASRUCTURE, AND TIME FRAME NEEDED FOR EXPLORATION AND DEVELOPMENT

Technology

Technology for successful drilling and production in northern offshore environments has been developed in Cook Inlet and the North Sea. Jack-up drilling platforms would probably be used in shallow water for exploratory drilling. Drill ships and large semi-submersible vessels would be used for exploration in deeper waters. Large semi-submersibles have proven to be superior to drill ships for continued operation in severe storms in the Lower Cook Inlet. Production platforms similar to those in the North Sea can be used, and satellite subsea completions may be used. Sea ice is not a problem over the Kodiak Shelf, but is present at times in some of the bays. Seasonal ice formation on ships and platforms from freezing spray can sometimes be a problem.

As has been frequently indicated by North Sea experience, what is a marginal or uneconomic field one day may the next day be declared commercial due to changing circumstances. Oil and gas prices may change, new technology may be developed, or discoveries near the uneconomic field may provide a pipeline or lines to shore. Small gas volumes may initially be re-injected. Offshore loading of oil may occur early in the life of some fields.

Exploration bases will probably be at the towns of Kodiak and Seward. Both have deep harbors and public and private docks capable of handling large ships. The old Kodiak Naval Station, now operated by the Coast Guard, has some docks in various stages of neglect. Approaches to Seward are many fathoms deep and channels into Kodiak are up to 25 feet deep.

The airport at Kodiak can handle aircraft of Boeing 707 size and the Seward airport can accommodate Lockheed C-130s. There is room at both airports for helicopter support operations. Getting to the Kodiak Shelf is easier than getting to most places in Alaska. Wien Air Alaska operates daily Boeing 737 flights between Anchorage and Kodiak and several flights a week between Kodiak and Seattle. Western Airlines flies Boeing 727s between Kodiak and Seattle. The Alaska Ferry System serves both Kodiak and Seward. Kodiak town is 1,258 nautical miles from Seattle and about 4,000 miles from Yokohama.

Infrastructure

In the event that oil and gas in commercial quantities are found on the Kodiak Shelf, the route to market probably would be via tanker ship to the U.S. West Coast. Production from platforms and subsea completions would be gathered by pipeline to a central location on Kodiak or Afognak Islands. A large discovery of gas would justify construction of an LNG plant ashore. Kazakof and Izhut Bays on Afognak Island have sites that may be suitable for oil and gas processing and shipping facilities if a significant discovery is made in the northern end of the area. A more southerly find would favor a shore site in Kaiugnak Bay, Three Saints Bay, Kiliuda Bay, Ugak Bay, or Chiniak Bay, all on Kodiak Island. Factors to consider in site selection are a large enough reasonably flat area ashore, deep water wide enough to accommodate turning tankers, protection from storm winds and seas, land site high enough above the ocean to be reasonably safe from tsunamis, and last but not least, a favorable political situation.

No shortage of drilling equipment or supplies is anticipated. Based on the cyclical pattern of exploratory rig construction, the present tightening supply of rigs will be alleviated after 1982, approaching the time of this sale. Platform construction capacity should at that time also be adequate on the U.S. West Coast and in the Orient.

average duration of gusts in excess of 55 knots about eight hours per storm. Waves 60 feet high have been reported in fall and winter storms. Cloudiness is considerable; fogs are most frequent in June and July and sometimes close the Kodiak airport in summer.

The weather is generally comparable to that of the northern North Sea at similar latitudes, where successful petroleum production is now underway. Adverse weather, sea conditions, distance from supply bases, plus the Kodiak Shelf's potential for earthquake activity, will cause delays and increase costs. Additional delays of unknown duration may occur from court orders delaying and prohibiting certain actions because of objections which may be raised by special-interest groups.

Time Frame

The time frame is developed from the following resources, which are conditional on hydrcarbons being present in the call area, which will be outlined in the Call for Nominations. The estimates for the call area in the slope province (200-2500 meters) are about 50 percent of the potential hydrocarbons under the entire slope.

Water Depth	Confidence Level		
0-200 meters	95% Probability	5% Probability	Statistical Mean
Oil, billion bbls.	0.20	2.21	0.87
Assoc. Gas, TCF	0.36	3.82	1.51
Non-Assoc. Gas, TCF	1.48	8.83	4.19
200-2500 meters			
Oil, billion bbls.	0.36	1.96	0.96
Assoc. Gas, TCF	0.44	2.40	1.18
Non-Assoc. Gas, TCF	0.56	2.86	1.44

Exploratory drilling may begin in the year after the sale. With exploratory successes, production platforms would begin to be installed by the fifth

By the time of production from the area, pipelines may be operating from the U.S. West Coast to refineries in the midwestern United States. Production from Prudhoe Bay will be declining by the time, freeing some refinery capacity on the West Coast.

Approximately 80 percent of the exploration manpower would come from outside Alaska. For construction and production, approximately 80 percent of the workers would come from personnel residing in Alaska.

Weather

The weather of the Kodiak Shelf is cold, windy, foggy and wet. At Kodiak town the mean annual temperature is 41° F. The normal monthly temperature is below 32° F December through February, and 50° F or above July through September. During the summer, the mean air temperature closely approximates the mean sea surface temperature, rising above it during August but falling below again in September. In winter the mean maximum air temperature is about the same as the water surface temperature. The maximum and minimum temperatures for Kodiak town are 86° F and -12° F.

Precipitation is abundant throughout the year ranging between 40 and 80 inches with an average of 56 inches. Snow falls in all months except July and August with mean annual snowfall of 90 inches and a range from 16 to 178 inches. Precipitation is often difficult to measure because of strong winds; it is going horizontal instead of down. Drifting and blowing snow occasionally close the airport at Kodiak for a winter day.

The average wind speed at Kodiak town is 20 knots. Williwaw winds have been reported in excess of 120 knots by the Coast Guard. Gusts of over 50 knots have occurred in every month of the year and are most frequent in the winter. An average of eight storms each year bring winds in excess of 55 year after the leases are issued, and peak oil production may be attained in the tenth year. Development drilling would cease after the twelfth year, and individual fields would have approximately 30-year lives, with all platforms likely to have been removed by the 40th year after production begins. It is estimated that the minimum economic field will have 100 million barrels of oil or 0.6 trillion cubic feet of gas, recoverable, for the 0-200 meter water depths, and will have 300 million barrels of oil or 1.8 trillion cubic feet of gas, recoverable, for the deeper waters of 200-2500 meters. Only two fields, worldwide, are presently rated commercial in such deeper waters, and neither are located in severe climates. The oil industry is presently in the relatively early stages of deepwater oil and gas developments.

It is assumed that the average field size will be double the minimum economic field size, and that one well may be supported by any of the following resource amount:

0-200 meters	Recoverable
Oil	7.5 million bbl.
Non-Assoc. Gas	45 billion CF.

200-2500 meters	Recoverable
Oil	12 million bbl.
Non-Assoc. Gas	72 billion CF.

On this basis, discoveries would develop as follows:

Water Depth 0-200 meters	Oil Resource Case 95% Probability	5% Probability	Statistical Mean
Number of fields	1	11	4
Wells (oil and service)	36	396	144
Peak production, MBD	63	690	270
Gas-Oil ratio	1750	1750	1750
Peak assoc. gas, MMCFD	110	1200	480

200-2500 meters	Oil Resources Case 95%	5%	Mean
Numbers of fields	1	3	2
Wells (oil and service)	44	235	115
Peak production, MBD	115	615	300
Gas-Oil ratio	1225	1225	1225
Peak assoc. gas, MMCFD	140	750	365

0-200 meters	Non-Assoc. Gas Case 95%	5%	Mean
Number of fields	1	7	4
Wells	15	87	41
Peak production, MMCFD	245	1475	700

200-2500 meters	Non-Assoc. Gas Case 95%	5%	Mean
Number of fields	0	1	0
Wells	0	19	0
Peak production, MMCFD	0	480	0

Oil production platforms would have from 24 to 48 oil wells, each, and 12 to 24 service wells, each. Gas production platforms would have 10 to 24 wells, each. In deep water, only one marginal gas field may be discovered.

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