UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SUMMARY GEOLOGIC REPORT FOR PETROLEUM LEASE SALE #100, KODIAK SHELF, ALASKA

by

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U.S. GEOLOGIC SURVEY
OPEN-FILE REPORT 84-24

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SUMMARY

Refined biostratigraphy of rocks around and under Kodiak shelf and the paleomagnetism of Paleocene rocks on Kodiak island are the main new data published since the last resource report for the Kodiak shelf. The new biostratigraphic data indicate that a major Miocene hiatus underlies the shelf. Rocks beneath this hiatus are primarily of Eocene age, although lower Oligocene rocks could be present locally. Deep (5 to 7 km) shelf basins are filled with Pliocene and younger deposits. The Miocene hiatus has regional extent and is the limit of effective penetration of seismic energy, in that only rare reflections are returned by the rocks below the hiatus.

Paleomagnetic data provide constraints on the Paleogene history of rocks under Kodiak island. These data suggest that Paleocene rocks exposed on the island originated as far as 25° south of the expected position of Kodiak island, relative to the Paleocene paleopole for North America. These data support the concept that during the Cenozoic a part of southern Alaska traveled rapidly north and collided with the rest of Alaska.

Organic-geochemical data are available only from onshore rocks, which lie essentially along the regional structural grain. We have no direct evidence for the properties of rocks offshore. However, if the offshore rocks are like those onshore, then regional geology and geochemical data suggest that the potential is low for finding major oil deposits under Kodiak shelf, because these data do not reveal the presence of adequate source rocks for liquid hydrocarbons. In addition, Paleogene rocks onshore generally have poor reservoir quality; adequate reservoirs, however, may be present in the Pliocene and younger fill within shelf basins. Numerous traps for hydrocarbons are present beneath the shelf.

INTRODUCTION

The shelf area adjacent to Kodiak Island and the Kenai Penensula lies within a convergent margin (Figure 1) that has been affected by episodic Cenozoic subduction at the Aleutian trench. In fact, the main geologic features evident in seismic-reflection data from this area result from the latest phase of subduction that began in the latest Miocene. Until recently, the pre-latest Miocene events that affected the Kodiak shelf were obscured by complex onshore geology. However, recent studies involving the detailed stratigraphy and paleomagnetism of Paleogene rocks have begun to illuminate the early Cenozoic geologic history of this margin. Other recent studies, involving near-surface and regional geology, show that Kodiak shelf is subject to geologic hazards associated with great earthquakes that are generated along and above the well-defined Benioff zone. This report is a summary of these recent studies, which are work done since the last resource report for the Kodiak area by von Huene and others (1980). The main topics affected by new results since that report are the geologic history, biostratigraphy, and petroleum geology of the Kodiak shelf. We consider first the geologic framework of the region of this shelf area and then the structure, stratigraphy, and history of the offshore area. These topics are followed by a description of the petroleum geology and the geologic hazards.

CHAPTER 1 - GEOLOGIC SETTING

Onshore Geology

The Border Ranges fault (Figure 1) forms the landward limit of rocks that figure in the petroleum potential of the Kodiak shelf. This feature was active as a reverse or thrust fault during the latest Cretaceous. It separates rocks as old as middle and late Paleozoic on the northwest, within the Cook-Shelikof basin, from Late Cretaceous and younger melange and deformed turbidites that lie southeast of the fault. The contrast in geology across this fault is so striking that it is used as the boundary between geologic terranes -- the Peninsula terrane extends northwestward from the fault, and the Chugach terrane extends southeastward (Jones and others, 1981). The age of formation of this fault is determined from the latest Cretaceous age of deformation of Mesozoic rocks within the Cook-Shelikof basin (Peninsula terrane) and from the latest Cretaceous and earliest Paleocene age of deformation of Maestrichtian and early Paleocene melange and turbidites (Chugach terrane) in the fault's lower plate (Fisher and von Huene, in press). This deformation was contemporaneous with an active magmatic arc.

The Border Ranges fault is marked along much of its 2400-km length by regional magnetic anomalies and by gravity anomalies, in which the gravity field decreases abruptly by 40 to 60 mGal across the fault. Simplified modeling of these potential-field data suggest that about 10 km of relatively low-density rocks, probably accreted turbidites, lie along the fault's southeast side.

The detailed geology of Cenozoic strata exposed on the Kodiak Islands has been described by Moore (1967, 1969), Lyle and others (1977), Nilsen and Moore (1979), Moore and Allwardt (1980), Byrne(1982), and Moore and others (1983). Rocks exposed on the Kodiak islands crop out in northeast-trending belts and include Mesozoic, turbidites, melange, and hemipelagic deposits; lower and middle Cenozoic turbidites; and middle and upper Cenozoic fluvial and marine-shelf rocks (Figure 2). The oldest Cenozoic rocks are early Paleocene turbidites and greenstone (the Ghost Rocks Formation), which are faulted to the northwest against a broad belt of Upper Cretaceous turbidite and hemipelagic deposits (the Kodiak Formation). The Ghost Rocks Formation contains a melange and is more complexly deformed than older and younger rocks that are in contact with the formation (Byrne, 1982).

In fault contact on the southeast side of the Ghost Rocks Formation are Eocene turbidites (the Sitkalidak Formation), which also crop out on Sitkinak Island. Possibly autochthonous microfossils suggest that some of these turbidites were deposited at neritic depths (Lyle and others, 1977); analysis of turbidite-facies assemblages, however, suggests that these turbidites were deposited at bathyal depths (Nilsen and Moore, 1979). Rocks in this formation are cemented firmly by abundant zeolites. According to Moore and Allwardt (1980), on Sitkinak Island this formation comprises two units: one is strongly deformed and is interpreted by them to be offscrapped trench fill; the other unit is less deformed than the first and may contain slope-basin fill.

On Sitkinak Island, the Sitkinak Formation (Oligocene) consists of fluvial rocks in fault contact with the Sitkalidak Formation. These nonmarine rocks contain plant fossils that were thought to be middle or late Oligocene age (J.A. Wolfe, in Moore, 1969), but are now considered to be early Oligocene (J.A. Wolfe, oral commum., 1979). The Sitkinak Formation was once thought to extend to the northeast of the Sitkinak Island (Moore 1967, 1969), but in their proposed revision of stratigraphic nomenclature, Armentrout (1979) and Moore and Allwardt (1980) suggest that this formation be restricted to the rocks on Sitkinak Island. Rocks elsewhere that were considered part of the Sitkinak Formation (Moore, 1969) are now assigned to the Eocene Sitkalidak Formation.

Unconformably overlying the nonmarine Sitkinak Formation is a marine siltstone of late Oligocene and early Miocene age (Allison and Marincovich, 1981). These rocks were initially assigned to the Miocene Narrow Cape Formation; megafossils indicate, however, that the siltstone on Sitkinak Island is older than the oldest rocks included in the type Narrow Cape (Allison and Marincovich, 1981). Several authors have suggested that the siltstone of Sitkinak Island be included in a different formation than the Narrow Cape.

The Narrow Cape Formation crops out only at its type section at Narrow Cape, on Kodiak Island. The Narrow Cape consists of lower and middle Miocene deposits, on the basis of megafossils (Allison, 1978). Rocks of the Narrow Cape unconformably overlie the steeply northwest-dipping Ghost Rocks and Sitkalidak Formations, and the Miocene rocks grade upward from inner to outer neritic deposits.

The Tugidak Formation is exposed on Tugidak and Chirikof Islands, southwest of Kodiak Island, and this formation consists of shelf strata of late Pliocene and early Pleistocene age (Allison, 1978). On Chirikof Island, the formation unconformably overlies Paleogene turbidites.

Offshore Stratigraphy

Samples of offshore rocks are available from only a few scattered locations; thus we must infer the age and lithology of offshore rocks indirectly. Paleogene rocks, probably coeval with the Sitkinak and Sitkalidak Formations exposed on Kodiak and Sitkinak Islands, are thought to underlie strata of Pliocene and younger age beneath the Kodiak Shelf. The Paleogene age of these rocks is based on the results of drilling nearby areas of the shelf and on seismic-refraction velocities. Three COST (Continental Offshore Stratigraphic Test) wells were drilled into the rocks under Kodiak shelf. Although information from these wells is still not public, the deepest rocks penetrated in these wells are reportedly of Eocene age (Herrera, 1978). To the northeast of the Kodiak shelf, Paleogene rocks were dredged from the continental slope near the Aleutian Trench (Plafker and others, 1979; Keller and others, in press). In addition, a well was drilled on Middleton Island (Figure 1) by Tenneco Oil Company, and this well penetrated 2300 m of Paleogene rocks. The oldest rocks penetrated were assigned to the early Eocene by Rau and others (1977); Keller and others (in press), however, assign these rocks to the late middle Eocene. Although the paleobathymetry of the oldest rocks could not be resolved by Keller and others, latest Eocene and Oligocene rocks were deposited in lower to middle bathyal depths. The

Oligocene section in this well is represented by a poorly fossiliferous unit; most of Oligocene time, however, is represented by a hiatus. Furthermore, only a thin unit of late Oligocene and early Miocene age is present: most of Miocene time is also represented by a hiatus.

In addition to well data, seismic-refraction velocities recorded over the Kodiak shelf also suggest that Paleogene rocks underlie the shelf, on the basis of a sharp discontinuity between velocities above and those below a regional unconformity (Holmes and others, 1978; Fisher and Holmes, 1980). Velocities above this unconformity range from 2.0 to 2.5 km/sec, and velocities below range from 3.5 to 4.5 km/sec. The deep velocities compare well with velocities of 3.5 to 4.2 km/sec measured near onshore outcrops of the Eocene strata exposed on Kodiak Island.

The sharp discontinuity between shallow and deep refraction velocities occurs throughout the shelf and corresponds, in seismic traveltime, to a strong reflection at the base of reflective strata (horizon C of Fisher and von Huene, 1980). Well and dart-core data suggest strongly that this reflection stems from the base of rocks of Pliocene and younger age. In the Middleton Island well thin latest Oligocene or early Miocene, lower to middle bathyal rocks are disconformably overlain by latest Miocene to Pleistocene rocks. In addition, the Pliocene age of rocks above the offshore unconformity is confirmed by the results of dart cores obtained along Albatross Bank, a shelf-edge structure that caused the exposure at the seafloor of the deepest rocks that fill Albatross Basin. Initial work on microfossils from these cores suggested that the deepest rocks in the basin were possibly as old as middle Miocene (McClellan and others, 1982). Re-evaluation of these data indicates that the rocks in the deepest part of this basin are no older than Pliocene (Keller and others, in press). The offshore basin-filling rocks, then, are coeval with the Tugidak Formation exposed onshore. These offshore strata onlap to the northwest across the shelf; hence, the onshore Tugidak Formation contains only the upper part of the transgressive Pliocene and younger sequence.

In summary, the Kodiak shelf is probably underlain at depth by Eocene and possibly by lower Oligocene rocks that were deposited on a continental slope. By analogy to the rocks exposed on Kodiak Island, we expect the offshore Paleogene rocks to be strongly deformed at least locally. A major period of erosion occured during the Miocene, and Pliocene and younger rocks were deposited in the basins that formed under the shelf. This Miocene unconformity has regional extent, and it is the limit of effective penetration of seismic-reflection data, inasmuch as only rare reflections are returned from below this horizon.

Offshore Structure

To help understand the genesis and history of rocks under the Kodiak shelf, we have begun studies of rocks under the lower continental slope that borders the Aleutian trench. Three grids of seismic-reflection data are currently being reprocessed in detail, including velocity analysis, restacking and migration (von Huene and others, 1983). From these grids of migrated data, we will investigate the three-dimensional configuration of rock units within the accretionary zone. Initial results are available from only one of these grids (Figure 1), which is located west of Kodiak Island. These migrated seismic lines show that the structure of the lower-slope rocks is highly variable: many faults and folds extend for only short distances parallel to the trench, and the structures change abruptly from simple homoclines to apressed folds. This variabliity is especially noticeable in the outer part of the accretionary zone. One laterally persistent geologic feature is the decollement that can be traced from a fault that breeches the seafloor near the toe of the slope to a subhorizontal surface that cuts across the slope rocks to lie along the top of a considerable thickness of slope and oceanic rocks (Figure 3). The decollement can be traced for 30 to 40 km landward from the trench, and the decollement separates subducting rocks from rocks that are being accreted to the front of the margin. In places, rocks as thick as 3 km are being subducted beneath the outermost part of the margin. These subducting rocks could be heated enough beneath the margin to produce hydrocarbons, making study of lower-slope processes important to understanding the petroleum potential of this margin.

The structure of the continental shelf around Kodiak Island includes three basins - Tugidak, Albatross, and Stevenson - separated by structural highs. Tugdak basin, southwest of Kodiak Island, is subcircular and contains as much as 5 km of undeformed to slightly deformed Pliocene and younger strata (Fisher, 1979; Fisher and von Huene, 1982; Figures 2 and 4, plate 1). The seaward limit of the basin is Tugidak uplift, which has uplifted the southeastern side of the basin by 2 to 3 km. The beginning of growth of the uplift is recorded by a change in the direction of thickening of Pliocene strata; rocks above one horizon thicken landward, whereas rocks below it thicken seaward.

Albatross basin is under the southwest part of Kodiak Shelf and contains as much as 5 km of strata that are as old as Pliocene (Fisher and von Huene, 1980; Figures 2 and 5, plate 1). These strata are undeformed to moderately deformed, and the degree of deformation increases southeastward from Kodiak Island to the shelf break. The shelf break is underlain by a large uplift that forms Albatross Bank, which began to grow in the Pliocene. As in the case of the Tugidak uplift, the beginning of growth of Albatross Bank is recorded by a change in direction of thickening of basin strata. Since the Pliocene, the uplift has risen by at least 3 km.

Albatross Bank curves around the southwest side of Albatross basin, from there the bank is recurved, striking to the west to connect with the Tugidak uplift. Albatross Bank also forms the southeast limit of Albatross basin as the bank curves around the basin, changing strike from east to northeast. The northeast part of Albatross basin is a syncline that strikes obliquely across the shelf and contains a maximum of 3 km of gently folded rocks.

The Dangerous Cape high adjoins Albatross basin on the northeast side. The high can be distinguished from Albatross basin by shallow depth (1 to 2 km) to the base of reflective strata (base of Pliocene rocks), by low relief of structures that underlie the shelf edge, and by the central-shelf uplift. This uplift lies midway between Kodiak Island and the shelf break and is longitudinally confined to the Dangerous Cape high. The uplift consists of numerous northeast-trending reverse faults and several anticlines (Figure 5). The density of compressive structures in the uplift is higher than the density of such structures in other areas of the shelf.

Stevenson basin lies northeast of the Dangerous Cape high and consists of two subbasins that are separated by the transverse Portlock anticline (Figures 2 and 7, plate 1). The southwestern subbasin is as deep as 3.5 km, and the northeastern subbasin may be as deep as 6 or 7 km; velocity data, however, are poor for depths greater than 5 km. Stevenson basin contains strata that are inferred to be as old as Pliocene. This basin also contains a large filled channel that was probably cut and then filled in response to Pleistocene eustacy. The basin fill is gently deformed, except around an anticline that underlies the shelf break and around the Portlock anticline. The latter anticline began to grow in the Pliocene, on the basis of the uniform thinning to the northeast of strata of that age that drape across the fold.

The geology of the shelf area that lies northeast of Stevenson basin is poorly known, mainly because of the paucity of seismic-reflection data collected there. The shelf basins already described have only subtle expression in gravity data (Fisher and others, 1983; Figure 8); thus, although we have obtained detailed gravity data over the poorly known area, these data are not a reliable guide to the presence of basins under the shelf. The absence of expression of the basins in gravity data is puzzling: despite the facts that the basins contain 5 to 7 km of young, low-velocity, and hence low-density, rocks and the basement is relatively high-density Eocene rocks, the basins cause only 10 mGal anomalies in gravity data.

Although no marked gravity low is present over the basins, subcircular gravity lows are present to the northeast of the basins, over areas underlain by shallow Upper Cretaceous deformed turbidites. These gravity lows are coincident with large circular lows in the geoid (compare Figures 8 and 9), as measured by satellite radar altimeters (J.G. Marsh, written commun., 1982). The relief of these geoid anomalies is as great as 3 m. The deficient mass that causes both types of lows lies at depth within the margin and must be of regional size. One possibility to account for the deficient mass is that these lows reflect a great thickness of partly subducted sedimentary rocks.

Multichannel seismic data collected near and over one of the geoid and gravity lows show deep reflections that come from rocks between 12 and 23 km deep (Fisher and others, 1983). The events are from reflectors that are broadly arched about a north-south axis. One possible cause for these events is that they are from the presently subducting Pacific plate or from a detached piece of that plate.

GEOLOGIC HISTORY

The earliest geologic events to affect the rocks under the region around Kodiak shelf were formation of the Upper Cretaceous melange and deformation of the Maestrichtian turbidites that make up most of the exposed rock on the Kodiak Islands. This deformation occurred during the Late Cretaceous along the Border Ranges fault, and the tectonism coincided in time with renewed magmatic-arc activity and with tilting of the Mesozoic rocks in the Cook-

Shelikof basin. This contemporaniety suggests that the rocks of the Peninsula and Chugach terranes were together during the Late Cretaceous, but none of the geologic data are specific about the paleogeography of the deformation.

Paleomagnetic data, however, suggest that the deformation occurred far to the south of the present latitude of the Kodiak shelf. In a regional study of paleomagnetic data from rocks in southern Alaska, Stone and others (1982) suggested that large areas of Alaska had undergone large-scale northward shifts in latitude. Although the concept that continental blocks had moved far was supported by onshore geologic investigations, the paleomagnetic data suggested that the assembly of Alaska occurred during the middle Cenozoic, whereas geologic constraints indicated an earlier, perhaps middle to Late Cretaceous, time for the assembly (Jones and others, 1982; Pavlis, 1982).

Paleomagnetic data from Paleocene rocks on Kodiak Island have been interpreted as showing that this northward motion did, indeed, occur during the Cenozoic (Moore and others, 1983; Plumley and others, 1983). These data, obtained from andesitic and basaltic volcanic rocks in the Paleocene Ghost Rocks Formation, suggest that during the Paleocene these rocks were 25° south of their expected Paleocene postion, in relation to the Paleocene paleopole for North America.

The paleomagnetic data were collected at two sites. The rock samples from both sites passed thermal cleaning and fold tests, and this suite of samples provides some of the best paleomagnetic data yet obtained from Alaska (Plumley and others, 1983). Despite the high quality of these data, the mean paleopoles from the sites disagree in declination by about 120°, which Plumley and others (1983) suggest is due to relative tectonic rotation of the two sample areas. Of greater consequence in tectonic reconstructions than the difference in declination is the 12° difference in inclination of the poles from the two sample areas. These authors attribute the inclination difference to the possibility that the time represented by the lava flows may have been too short to average out the effects of secular variation. The difference in declination precludes the determination of paleolongitude; the average inclination of the two sites, however, suggests that these rocks came from about 42° north latitude in the Paleocene.

Moore and others (1983) used these paleomagnetic data to reconstruct the Paleogene geologic history of the Kodiak Islands area. This history is still obscure enough that these authors gave three alternative possibilities for the northward movement of the volcanic rocks. In their opinion, the Chugach terrane did not travel alone but was affixed to the Peninsula terrane and possibly to Wrangellia, forming a continental fragment of considerable size. In one model, this fragment moved north by transform motion along the west coast of North America. In the other two models, the continental fragment moved north with the Kula plate. According to these two models, during the Paleocene the Kula-Pacific ridge was subducted beneath the slope of the continental fragment, which slope was made up of the rocks now exposed on the Kodiak Islands. An active magmatic arc along the Alaska-Aleutian Range batholith suggests that subduction did occur at this time. Subduction of the ridge caused a pulse of high heat flow in the fore-arc area that resulted in the formation of magma, as mid-ocean-ridge basalt mixed with the slope rocks to form volcanic and plutonic rocks. Radiometric dates on the magmatic rocks and paleontologic dates on rocks associated with the lavas suggests that these rocks were emplaced and cooled by 63 m.y.; hence, the ridge subduction occurred during the latest Cretaceous or earliest Paleocene. Moore and others (1983) further speculate that the Kula-Pacific ridge then underwent an reorganization, so that the continental fragment would remain on the Kula plate for its journey north. In essence, the ridge, once subducted, had to cease spreading, and a new ridge arm had to form south of the continental fragment. Oceanic crust produced at this new arm then resisted subduction, forcing the continental fragment to move north. According to this proposed reconstruction, the continental fragment moved rapidly to the north during the Eocene and collided with the main part of Alaska by the end of the Eocene. The Eocene rocks of the Sitkalidak Formation were deposited during the fragment's northward journey and collision, and the rocks were derived from the Peninsula and Chugach terranes. To Moore and others, the absence of magmatism in Alaska during the time of most rapid northward motion suggests that the relative motion between the fragment and the Alaskan mainland was accommodated not by subduction, but instead by distributed major crustal shortening and fragmentation. Shortly after the proposed collision, arc magmatism resumed along the Alaska-Aleutian Range batholith.

The deep-water Eocene deposits were uplifted during the Oligocene, and the fluvial and shallow-marine rocks on Sitkinak Island were deposited. These deposits provide the first indication that the area of Kodiak Island and shelf was near sealevel. After the early Oligocene exposure and the late Oligocene through middle Miocene marine inundation, the magmatic arc became inactive, and the shelf was again exposed, this time for the remainder of the Miocene. During this exposure, the regional unconformity that is shown by contours in structure maps (Figure 2, plate 1) was formed. Topographic maps of Kodiak Island show that ridges have accordant summits. This accordant surface was probably cut during the Miocene and may correlate with the Miocene unconformity offshore.

In the late Miocene the magmatic arc resurged. This volcanism was contemporaneous with uplift of the Chugach Mountains on the Kenai Peninsula, which uplift produced alluvial fans that were deposited in the Cook Inlet basin (Kirschner and Lyon, 1973). Furthermore, major anticlines formed along the Pacific shore of the Alaska Peninsula, southwest of Kodiak Island. During this tectonism, the Kodiak shelf began to subside differentially and to recieve the oldest part of the Pliocene deep-basin fill. After the basins had subsided for some time during the Pliocene, the shelf-edge uplifts that bound the basins began to grow, shifting the basins' depocenters landward. The uplifts eventually rose by 2 to 3 km. As the shelf-edge structures grew, the transverse Portlock anticline formed, arching units of the Pliocene shelf deposits. Thus, most of the structures that are evident in seismic-reflection data are young features, and we have little data to determine whether these structures occupy the sites of older structures, that is, whether long-lived traps for petroleum are present under the shelf.

The area of Kodiak shelf was exposed again during the Pleistocene. A major canyon formed in Stevenson basin, and then the canyon filled. Contemporaneous unconformities were cut across deposits of the other shelf basins.

CHAPTER 2 - PETROLEUM GEOLOGY

Richness and Type of Organic Matter

Organic-geochemical data from rocks exposed on Kodiak Island (Figures 10 and 11) are from Lyle and others (1977) and Moore and Allwardt (1980). Samples of Paleocene rocks were analyzed by GeoChem Research, Inc. Samples from Pliocene strata in Albatross basin were obtained by dart cores during a cruise aboard the R/V Sea Sounder in 1978. Samples from below the continental slope are from DSDP (Deep Sea Drilling Project) Sites 181 and 182.

Tissot and Welte (1978) stated that clastic rocks that are sources for petroleum contain a minimum of 0.5 wt. % of organic carbon and that most good source rocks contain an average of about 2.0 wt. %. Similarly, Momper (1978) proposed that for primary migration of petroleum from source rocks to occur, the source rocks must contain at least 0.4 wt. % organic carbon, provided the carbon is in hydrogen-rich kerogen. Kerogen that contains relatively low amounts of hydrogen may require as much as 0.8 to 1.2 wt. % organic carbon. Values given in Figure 11 and mean values graphed in Figure 12 show that few rocks on Kodiak Island, in Albatross basin, or under the continental slope contain more than 0.5 wt. % organic carbon. The lean organic carbon content typifies strata deposited throughout Cenozoic time and from a wide geographic area. Three groups of rock contain more than 0.5 wt. % organic carbon: (1) Oligocene rocks of the Sitkinak Formation locally contain more than the minimum; (2) onshore Pliocene strata of the Tugidak Formation contain 0.58 wt. %, on the basis of results from only one analysis; and (3) rocks penetrated under the continental slope at DSDP Sites 181 and 182 that range in age from early Pleistocene(?) to Holocene (Kulm et al, 1973) and contain an average of 0.6 wt. % (Bode, 1973).

Total hydrocarbons extracted (C_{15+} Soxhlet extraction) from Eocene through Miocene strata are generally below the average amount extracted from hydrocarbon source rocks. Tissot and Welte (1978) stated that an average of 300 ppm hydrocarbons can be extracted from nonreservoir rocks in basins that contain petroleum and that a minimum of 800 ppm hydrocarbons can be extracted from source rocks in such basins. Momper (1978) reported that 825 to 850 ppm extractable hydrocarbons are needed before oil can migrate from source rocks. Hunt (1979), however, stated that adequate source rocks can have as little as 50 to 150 ppm extractable hydrocarbons. The amount of hydrocarbons extracted from the Pliocene sample (606 ppm; Figures 10 and 11) is anomalously high considering the thermal immaturity and the low organic-carbon content of the sample. In contrast to this high value, samples from older rocks show lower values, and the values show that increasing amounts of hydrocarbons can be extracted from progressively older strata. Judged by the criteria of Tissot and Welte (1978) and Momper (1978), the amounts of extractable hydrocarbons in these older strata are below the minimum amount usually extracted from good source rocks.

The Paleocene and Eocene Ghost Rocks Formation contains woody and coaly types of indigenous kerogen in subequal proportions; amorphous and herbaceous kerogen are present only in trace amounts (less than 20%). Indigenous kerogen in rocks of post-Paleocene age is predominantly (60 to 100%) herbaceous, except for the fill in Albatross basin, which contains mostly woody kerogen. Coaly kerogen is generally present in post-Paleocene rocks in secondary (20 to 40%) amounts, and amorphous kerogen is present mostly in trace amounts. The predominance of herbaceous and woody kerogen shows that a continental area was the dominant source terrane for organic matter deposited along the Kodiak margin throughout the Cenozoic.

Thermal Maturity of Cenozoic Rocks

The beginning of the thermal phase of peak oil generation is signaled by a thermal alteration index (TAI) of 2 (Dow, 1977, 1979; Geochem Laboratories, Inc., written commun., 1978). Peak oil generation begins when vitrinite-reflectance values are between 0.5 to 0.7%, the exact value depending on the type of kerogen in the rocks (Tissot and Welte, 1978, p. 451). Other values cited for the reflectance of vitrinite that occurs at the beginning of peak oil generation are 0.5% (N.H. Bostick, oral commum., 1979) and 0.6% (Dow, 1977, 1979). We use 0.6% in this report. Peak oil generation ends when vitrinite reflectance is 1.35% (Dow, 1979; Waples, 1980) or when the TAI is 3 (Dow, 1977, 1979; Geochem Laboratories, Inc., written commum., 1978).

Kerogen in lower Pleistocene(?) strata at DSDP Site 181, on the continental slope, is carbonized to the same degree as kerogen in strata in the Gulf Coast of Mexico that has been heated to 68°C and buried to 2,600 m; also, abundant reworked, highly carbonized kerogen is present in the slope strata (Grayson and Laplante, 1973). Vitrinite-reflectance values from the slope strata are between 0.55 and 0.65% and indicate a higher level of thermal maturity than the TAI of 1 to 1 +. Either lower Pleistocene(?) rocks are thermally mature or the vitrinite has been reworked from older rocks or altered before deposition. The vitrinite could have been reworked because the slope strata were deposited in a glacial-marine environment, and abundant debris from older rocks would have been available. Also during the Pleistocene, cold climate and ice sheets probably reduced the extent of higher land plants; consequently, indigenous vitrinite could have been relatively rare. Very low proportions or absence of indigenous or unaltered vitrinite is characteristic of upper Cenozoic rocks bordering the eastern Gulf of Alaska (K. W. Schwab, oral commun., 1979). Accordingly, the slope rocks probably have the lower level or thermal maturity indicated by the TAI, and the vitrinite has been reworked or altered before deposition.

Hydrocarbon gases are present in the upper 2.5 m of shelf sediment (Redden et al, in press). Average ratios of C1/(C2+C3) of 12,000 and average _^{13}C values of - 79 per mil PDB (Pedee belemnite) suggest that the gas is biogenic and that it does not show the presence of mature source rocks at depth. High-resolution acoustic records show anomalies that suggest the presence of near-bottom gas-charged sediment.

The thermal maturity of other strata around and on the Kodiak islands generally increases with age of the strata (Figures 10 and 11). The Tugidak Formation (Pliocene) and the fill in Albatross basin (upper Miocene and Pliocene) are thermally immature, whereas Eocene (vitrinite reflectance averages 0.8%; Moore and Allwardt, 1980) through middle Miocene strata are mature. However, only one sample from lower and middle Miocene rocks was analyzed, and exposed rocks of this age are sandstone; consequently, the level of thermal maturity of these rocks is not well determined.

The TAI values from Paleocene rocks suggest a lower level of thermal alteration than the level suggested by vitrinite reflectance (Figures 4 and 5). On the basis of the TAI, Paleocene rocks are in the phase of peak oil generation or just higher than that phase, whereas vitrinite reflectance suggests that Paleocene rocks are severely altered. Reflectance values from Moore and others (1983) also suggest that these rocks are highly altered, in that the average reflectance from this formation is about 2.15%. Histograms of vitrinite reflectance show well-defined peaks at the high reflectances without any reflectance of low enough value to agree with the TAI. Higher land plants flourished during the Paleocene in areas near Kodiak Island (J. A. Wolfe, oral commun., 1979); hence, the vitrinite is not all reworked. However, if the rocks were as severely altered as indicated by the vitrinite reflectances, kerogen in the rocks would have been carbonized so that the different types of kerogen would be very difficult to distinguish, and the TAI would be 5. The results of pyrolysis of Paleocene rock samples (G.E. Claypool, written commun., 1979; Table 1) show that despite the significant amounts of organic carbon in the samples, only traces of hydrocarbons were evolved. The low hydrocarbon yield and the high temperatures at which maximum pyrolytic yield occurred suggest that the Paleocene rocks have already generated hydrocarbons, as may be concluded from the vitrinite-reflectance values. These results indicate that Paleocene rocks are within economic basement for oil. The heating responsible from the high vitrinite reflectances may have been caused by subduction of the Kula-Pacific ridge, which has also been proposed as the mechanism responsible for the Paleocene forearc magmatic activity. If so, the heating is likely to have affected the entire region of the Kodiak shelf, so that the Paleocene rocks probably form the regional economic basement for hydrocarbons. Whatever the source for the heat that affected the Paleocene rocks, the heat caused the rocks to have a much higher level of thermal alteration than the Eocene rocks.

The levels of thermal maturity of Paleocene through Miocene onshore rocks are minimum levels for coeval offshore rocks because some offshore rocks are buried beneath as much as 5 to 7 km of strata of Pliocene and younger age. Paleogene rocks exposed onshore are thermally mature, and these mature strata have not been deeply buried during or since the Pliocene because offshore Pliocene strata onlap shoreward, thinning depositionally to less than 0.25 km nearshore. Hence, the thermal maturity of Paleogene rocks is a product of pre-Pliocene geologic events.

Present Temperature Regime

Numerical models of heat flow through a convergent margin show that areas adjacent to a trench have lower geothermal gradients than areas near a magmatic arc (McKenzie and Sclater, 1968; Hasebe et al, 1970; Toksoz et al, 1971; Anderson et al, 1978). Isotherms in the upper plate at such margins are depressed because of subduction of cold lithosphere at the trench. Heat-flow measurements made across the Japan margin substantiate this concept--along this margin, heat flow is low through the continental slope and shelf and is high through the area near the magmatic arc (Watanabe et al, 1977).

The only publicly available well data that show the magnitude of the present geothermal gradient near Kodiak Shelf are from the Tenneco Middleton Island 1 well (Figure 1). The geothermal gradient, calculated from corrected bottomhole temperatures, is between 30 and 35° C/km and theoretically should be lower than gradients in the Cook Inlet basin. However, gradients, calculated from corrected temperature data in two wells in the Cook Inlet basin, are between 25 and 30° C/km and are lower than the gradient beneath Middleton Island. Data are too sparse to explain why the geothermal gradient below Middleton Island is higher than the gradient below Cook Inlet.

Seismic-reflection data provide indirect evidence for the magnitude of the geothermal gradient. These data show a reflection that is believed to be from the base of a gas hydrate. The subbottom position of this reflection is strongly dependent on subsurface temperatures; hence, the depth to the hydrate reflection can be used to estimate the thermal gradient. In the area of the Shumagin Islands, a hydrate reflection is present, and the implied geothermal gradient is about 28 to 35°C/km (Macleod, 1982). Hydrate reflections are also evident in data from near the Kodiak Islands, and Kvenvolden (written commun., 1983) determined that the geothermal gradient there is in the range of 30 to 36 °C/km. The thermal gradients determined from well and seismic-reflection data are in good agreement, and these data suggest unusually high gradients, in comparison to the 10-to 20-°C/km gradients usually assumed for convergent margins.

Von Huene (1972) and Taylor and O'Neill (1974) showed that oceanic magnetic anomalies extend from deep-ocean areas across the continental slope and part of the shelf; hence, the geothermal gradient can be estimated because the source for the anomalies has not been heated to the Curie temperature. The Curie temperature for pillow basalts of Eocene age (von Huene, 1972; Pitman et al, 1974) in oceanic layer 2a is about 350° C (Gromme et al, 1979). The magnetic anomalies beneath the shelf could also be due to rocks in oceanic layer 3 for which the Curie temperature is as high as 580° C, as measured in an ophiolite exposed onshore (Beske-Diehl and Banerjee, 1979). The Benioff zone is about 20 km beneath the shelf, hence the geothermal gradient is between 18 and 29° C/km. This estimate and data from the well and the hydrate reflection suggest that the geothermal gradient through the Kodiak shelf is between 20 and 30° C/km.

Strata that fill Albatross basin are thermally immature where sampled at the seafloor; the level of thermal maturity at the seafloor, however, is a minimum level for coeval strata present deep in the basin. The burial history of strata within Albatross basin suggest that potential source rocks deep in the basin are mature, provided that the geothermal gradient has been as high as 30° C/km (Fig. 7). Phillippi (1965) reported that upper Miocene source rocks in the Ventura basin began to generate petroleum when the rocks were heated to 115° C. If potential source rocks in Albatross basin began to generate petroleum when heated to 115° C, then mature Pliocene source rocks could be present below depths of 6 and 4 km for geothermal gradients of 20 and 30° C/km respectively. If the geothermal gradient is as low as 20° C/km, no potential Neogene source rocks in Albatross basins or Tugidak have been heated sufficiently to produce oil. Stevenson basin is as deep as 6 or 7 km; the deepest part of that basin, therefore, could contain mature source rocks.

If the Neogene and Quaternary geothermal gradient has been as high as 30° C/km, mature Pliocene rocks lie below shelf areas where basin fill is deeper than 4-km (Figure 2, plate 1). In Albatross basin, mature source rocks underlie the area that is enclosed by the 3-km contour in the structure maps because basin strata underlie the contoured horizon. As these areas are small, potential hydrocarbon traps that are far from the basins must be charged by Paleogene source rocks.

Reservoir Rocks

Sandstone composition - Sandstones from Kodiak Island have been examined and described by Stewart (1976), Lyle and others (1977), Winkler (in Nilsen and Moore, 1979), and Moore and others (1983). Petrographic examination of samples from the Ghost Rocks Formation shows that the formation contains a large proportion of lithic fragments - average composition of the formation is $Q_{22}F_{40}L_{38}$ (Figure 13) - and almost all (95%) of the lithic fragments are from volcanic and plutonic rocks. Feldspar is predominantly plagioclase (92%).

Sandstones of the Sitkalidak and Sitkinak Formations do not differ much in average composition, as shown by overlapping QFL fields (Figure 13). Moore and others (1983) reported that the mean composition of sandstones in the Sitkalidak Formation (Eocene) is $Q_{31}F_{30}L_{39}$, which compares fairly well to $Q_{38}F_{22}L_{40}$, the composition obtained by Lyle and others (1977) and by Winkler (in Nilsen and Moore, 1979). These sandstones, on average, contain less quartz and lithic fragments than sandstones of the Sitkinak Formation (Oligocene). In both formations, 75% of the lithic fragments are from volcanic and plutonic rocks and about 20% are from sedimentary rocks. More than 90% of the feldspar is plagioclase.

No petrographic data are available from the upper Oligocene and lower Miocene siltstone on Sitkinak Island. The lower and middle Miocene Narrow Cape Formation has a mean composition of $Q_{57}F_{21}L_{22}$. Lithic fragments are mostly from sedimentary rocks (48%) and volcanic and plutonic rocks (47%). Most (75%) of the feldspar is plagioclase.

The QFL diagram shows that the proportion of quartz increases progressively in younger rocks. The increase in quartz is accompanied by a decrease in the amount of lithic fragments.

Zeolites, deformed detrital grains, authigenic clay coats, and silica fill pores in the Ghost Rocks and Sitkalidak Formations. In lower and middle Miocene rocks, pores are partly filled with deformed sedimentary-rock fragments and authigenic clay coats. The Sitkalidak, Sitkinak, and Narrow Cape Formations contain sparry calcite that locally comprises up to 50% of the rocks.

Porosity and permeability - Fair reservoirs for hydrocarbons have porosities between 10 and 15% and permeabilities between 1 and 10 md (Levorsen and Berry, 1967). Poor reservoirs have porosities between 5 and 10% and permeabilities less than 1 md. The graph of mean values (Figure 11) shows that the reservoir properties, especially permeability, worsen with increasing age of strata and that Paleogene rocks exposed on the island have exceedingly poor to poor reservoir properties. Miocene rocks have marginal reservoir properties because of poor porosity and fair permeability.

The poor reservoir characteristics of rocks exposed on Kodiak Island can be attributed to diagenetic changes. Galloway (1974, 1979) described a sequence of diagenetic changes in sandstones derived largely from magmatic arcs. Such sandstones contain a large proportion of chemically and mechanically unstable volcanic rock fragments, and nearly all feldspar is chemically unstable plagioclase. The diagenetic sequence described by Galloway was: (1) early filling of pores by calcite, (2) development of clay rims on framework grains, (3) phyllosilicate and zeolite filling of pores, and (4) late calcite and phyllosilicate replacement of grains, and growth of quartz and feldspar overgrowths. Whether rocks exposed on Kodiak Island strictly followed this diagenetic sequence is difficult to determine from the meager published petrographic reports. However, the Narrow Cape Formation is in stage 2 because clay coats are present, and the Ghost Rocks Formation is in stage 4 because these rocks contain zeolites and calcite locally replaced framework grains after clay coats developed (Lyle and others 1977). If these diagenetic-stage assignments are correct, then the Sitkalidak Formation is probably in diagenetic stage 3 because of the widespread presence of zeolites.

Galloway (1979) related porosity and permeability of sandstones to their diagenetic stage. Permeability is greatly reduced when clay coats develop in diagenetic stage 2 because the clay obstructs pore throats. On the Kodiak margin, lower and middle Miocene rocks are in diagenetic stage 2, and their permeability is low; and older rocks are in stage 3, and their permeability is nil. The porosities of some rocks exposed on Kodiak Island are within the ranges of porosities that characterize the various diagenetic stages; the porosities of most rocks, however, are below these characteristic ranges.

The refraction velocities of 3.5 to 4.5 km/sec measured in offshore Paleogene rocks suggest that these rocks are indurated and that, like the onshore rocks, the offshore rocks are poor reservoirs. Lower and middle Miocene rocks have the best reservoir quality of all onshore rocks; even these rocks, however, have only fair permeability and poor porosity. These strata do not appear to underlie the shelf extensively, on the basis of seismic refraction and reflection data (Fisher and Holmes, 1980).

No data exist concerning the reservoir properties of strata in the shelf basins near Kodiak Island. Dart cores collected in Albatross basin contain some sandstone, but the cores are unsuitable for measurement of porosity or permeability. The mean values (Figure 12) show that reservoir properties generally improve upward through the post-Paleocene section. Extrapolation of this observed trend suggests that Pliocene and younger strata could contain at least fair reservoirs.

Hydrocarbon Traps

Few structural traps are present in the shelf basins because most rocks in the basins are only gently deformed. Possible structural traps under the shelf include (1) Tugidak uplift, (2) Albatross Bank, (3) a transverse anticline that divides Albatross basin, (4) anticlines or fault structures in the central-shelf uplift, (5) a transverse structural high on the southwest side of Stevenson basin, and (6) Portlock anticline. Strata in Tugidak basin are extensively truncated at the seafloor on the northeast flank of the Tugidak uplift, and strata in Albatross basin are similarly truncated along the northeast-trending part of Albatross Bank; consequently any traps for hydrocarbons in these structures are most likely in Paleogene rocks. Strata are not extensively truncated at the seafloor along the east-trending part of Albatross Bank; the thinness of reflective strata in this part of the structure, however, suggests again that any traps present are in Paleogene rocks. Portlock anticline divides Stevenson basin so that, if hydrocarbons were generated in the area of the basin, they would tend to migrate updip to the crest of the anticline. The seismic grid for the structure contours (Figure 2, plate 1) is too coarse to show whether closure exists along the structures described here.

In summary, the assumption that offshore Paleogene rocks have the same source-rock characteristics as onshore Paleogene rocks results in a pessimistic assessment of the potential for major oil accumulations beneath Kodiak Shelf. Organic-geochemical analyses of onshore rocks do not reveal any good source rocks for oil because Paleocene through Oligocene rocks contain less than 0.5 wt. % organic carbon. The low hydrogen content of the herbaceous and coaly kerogen that characterizes onshore rocks suggests that the minimum amount of organic carbon needed to generate oil may be close to 1.0 wt. %. The predominance of herbaceous and coaly kerogen further suggests that gas and condensate may be the most abundant hydrocarbons generated from offshore equivalents of the onshore Paleogene strata.

Dart-core samples of Pliocene strata from Albatross basin contain low amounts (less than 0.5 wt. %) of organic carbon, and low-hydrogen kerogen predominates. These sampled rocks are poor sources for oil; the type of kerogen present in the rocks suggests that gas is the only hydrocarbon that can be generated. As rock samples of this age are available only from Albatross basin, coeval strata elsewhere under Kodiak Shelf may have better source-rock characteristics.

The characteristics of onshore rocks suggests that reservoirs for hydrocarbons in Paleogene rocks are scarce. Onshore rocks of this age are plugged by diagenetic minerals, and offshore rocks have refraction velocities indicative of indurated sedimentary rocks. We have no specific data on the reservoir properties of Pliocene rocks, but we believe that adequate reservoirs exist in these rocks.

Numerous traps for hydrocarbons underlie the shelf; all appear to have formed during and since the Pliocene. We have insufficient data to show whether closure exists along these structures.

CHAPTER 3 - ENVIRONMENTAL ASSESSMENT

This environmental assessment is a summation of the applied aspects of the geology of the Kodiak Shelf. The assessment is regional in scope, but its most useful application is as a quide for site-specific engineering studies. Examples of the possible impact of geology on resource development are drawn from experiences in similar settings elsewhere. But, because both observational and theoretical data are sparse and because the overall geologic situation on the Kodiak Shelf is different from other offshore areas where development has taken place, estimation of the magnitude of impact involves a liberal amount of conjecture.

Geologic processes pose several environmental constraints on offshore resource development. Some processes can affect the operation and safety of offshore engineering activities: for example, seismic events can severely disrupt petroleum exploration and production activities conducted from drilling platforms. Other geologic processes in turn can be affected by resource development, with deleterious environmental consequences: for example, incorporation of spilled contaminants into bottom sediment can affect benthic life.

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

Tectonism

Convergence of the Pacific and North America lithospheric plates creates many potential environmental hazards. Strong earthquake ground shaking, fault rupture, sediment displacement, warping of the sea floor, and volcanic eruptions have occurred on or adjacent to the Kodiak Shelf and can be expected in the future (Kachadoorian and Plafker, 1967; Plafker, 1972; von Huene, 1972). Tectonic processes are spatially variable across the region, posing different sets of concerns from place to place. Regional zonation of seismicity has been postulated, with identification of a seismic gap near the Kodiak Shelf where the potential for a great earthquake is high (Pulpan and Kienle, 1979). Folding and faulting are more severe along some sections of the shelf break and near Kodiak Island than at other places (Figure 14), and postulated transverse tectonic boundaries may indicate other areas of concentrated deformation (Fisher and others, 1981).

Recurrence intervals of potentially damaging earthquakes are imprecisely known; estimates for the Kodiak Shelf range from 30 to 800 years (Sykes, 1971; Plafker and Rubin, 1967). The minimum estimate of 30 years for a great earthquake could be exceeded by the lifetime of an oil-producing province, because the last event to affect the Kodiak Shelf was in 1964. So, although earthquakes cannot be predicted with confidence, seismic hazards are a valid concern for offshore development.

Seismic ground shaking is considered to be the source of one of the largest and most complicated loads to which offshore platforms are exposed in the Gulf of Alaska, and innovative design procedures are employed to minimize the risk of structural failure (Bea, 1976). The Kodiak Shelf might experience damaging ground motion from seismic events in either of two regional zones: that involved with the 1964 Alaska earthquake or that identified as the Shumagin seismic gap (Pulpan and Kienle, 1979). Aftershocks from the 1964 earthquake occurred across the entire Kodiak Shelf and many exceeded magnitude 6, the level above which serious damage potential is assumed (Algermissen and others, 1972; Page, 1975).

A major event in the Shumagin seismic gap would not have epicenters located on the Kodiak Shelf, if present theory is correct (Sykes, 1971; Pulpan and Kienle, 1979). But there is some chance that significant ground shaking could extend to at least the southwest part of the area, because observational data indicate that damage can occur to about 150 km from the causative fault of a magnitude 8 earthquake (Page, 1975).

An area of local seismic concern is near the mouth of Kiliuda Trough and adjacent sections of southern and middle Albatross Banks, where a cluster of earthquakes that is independent of great events has been recorded (Pulpan and Kienle, 1979; Hampton and others, 1979). This area displays a much higher rate of strain release than elsewhere on the Kodiak Shelf, and seismic-reflection profiles show evidence of folding, faulting, sea-floor deformation, and sediment sliding (Hampton and Bouma, 1977). The shelf-break area of Portlock Bank shows similar deformational features, but the historic record shows no concentration of seismic activity there.

The area along the shelf break on northern Albatross Bank, to judge from structural and seismic evidence, appears to be undergoing less intense tectonism and is therefore less prone to local tectonic hazards than the two adjacent zones described above (Hampton and Bouma, 1977). Regional seismicity could still produce hazardous levels of ground shaking there.

Localized displacement of the sea floor can result from movement along shallow faults, causing damage to installations that span them. Records of epicenter locations on the Kodiak Shelf do not indicate any clear linear seismic trends that define active faults (Pulpan and Kienle, 1979). But fault offset in 1964 within the zone that extends along and offshore of 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 runs along the shelf break of southern and middle Albatross Banks, and other individual faults have been noted across the shelf (Figure 13). Faulting and tectonic deformation of the sea floor can generate tsunamis that might devastate coastal areas, as happened on Kodiak Island in 1964 (Kachadoorian and Plafker, 1967).

Volcanic eruptions have occasionally produced large volumes of ash that have been spread across the Kodiak Shelf, the Katmai event in 1912 being an example (Wilcox, 1959). The most severe volcanic hazards (lava flows, for example) are local and do not pose a danger to the Kodiak Shelf, because the nearest volcanoes are about 200 km away on the Alaska Peninsula. But the abrasive action of ash particles and corrosion from acid rains, both of which caused problems in Alaska communities after the 1912 Katmai eruption, could be potential problems (Center, 1974).

Sediment

The sedimentary environments of the Kodiak Shelf have many features of practical significance. Semilithified to lithified bedrock is exposed over large areas, and a diverse and sharply segregated suite of unconsolidated sediment types is present that includes gravel, volcanic ash, clean sand, and terrigenous mud (Hampton, 1981, 1983a). Input of modern sediment is small, and ocean currents that impinge on the sea floor can be strong in places but insignificant in others. Sediment is being reworked over broad areas, whereas other areas serve as quiet repositories for winnowed debris.

Sedimentary bedrock appears to provide firm support for structural foundations where outcrops occur (Figure 15), as judged from the semilithified to lithified state of dart core samples. However, the presence of erosional hogback ridges implies abrupt variation in physical properties, and geotechnical testing is required in order to quantify the differences. Federal regulations generally require burial of pipelines in water depths less than 61 m and in deeper areas where interference with trawling is expected. The stiff bedrock is resistant to trenching, and the path of pipeline corridors might thereby be influenced by the distribution of outcrops. Moreover, the rough topography of the bedrock ridges must be considered in the design of pipelines that lie on the sea floor, because irregularities on the order of 1 m can cause large unsupported spans (Palmer, 1980).

Accumulations of unconsolidated sediment on the Kodiak Shelf are generally thin, and in many places firm bedrock is within reach of pile foundations for large platform structures (Figure 15). Abrupt changes in sediment type occur on the sea floor (Hampton, 1981; Thrasher, 1979) and also can be expected in the subsurface, as study of glacially deposited sediment in other offshore areas has shown (Fannin, 1980). The banks appear to be composed of stable coarse material at the sea floor. But, the possibility of weak subsurface layers must be considered in the prediction of pile capacity, even below the depth of pile penetration. Also, false indication of longterm performance can be obtained if piles encounter isolated boulders in otherwise compressible material (see Johnson and Kavanagh, 1968; Milligan, 1976).

Drilling operations might be influenced by coarse sediment. For example, King (1980) describes a situation on the eastern Canadian continental shelf in which repositioning of some exploratory wells was necessitated when glacial boulders prevented spudding of the holes. Boulders might also be an impediment to trenching operations (Palmer, 1980).

The troughs that traverse the Kodiak Shelf contain relatively soft, fine-grained sediment that might have engineering importance. The deposits in Kiliuda and Chiniak Troughs are only a few tens of meters thick and might only impose a minor constraint to engineering design. But, sediment samples are composed of volcanic ash grains and siliceous microfossil tests, which are fragile and highly vesicular. Individual grains are weak, and the sediment has a high void ratio (Hampton, 1983b). If this sediment composition continues at depth, an abnormal amount of consolidation during loading might occur due to grain crushing and rearrangements. Lee (1973) detected this type of behavior in diatomaceous sediment from the Bering Sea. The sediment in Chiniak Trough is extremely susceptible to failure when subjected to earthquake accelerations (Hampton, 1983b).

The fine-grained sediment in Sitkinak Trough has a terrigenous composition that is common in marine deposits. The local steep slopes and the great thickness of sediment accumulation might necessitate different foundation design than in the other troughs (Figure 15).

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). Thus, the sediment stability problems commonly encountered in terrestrial ash deposits that have been altered to clay are unlikely on the Kodiak Shelf (see Mitchell, 1976).

Strong currents and intense sediment transport are indicated where large sand waves occur (Figure 16), although the degree of modern activity compared to times of lower sea level is uncertain. Unusual loads can be applied to structures as sand waves migrate past them. Furthermore, strong currents can induce scour of sediment, which can cause loss of support and differential settlement at the base of sea-floor installations (Posey, 1971; Wilson and Abel, 1973; Palmer, 1976). Fluttering due to resonance set up by vortex shedding can occur where pipelines have become suspended as a result of scour. This mechanism has been hypothesized as the cause of pipeline failures 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 (Figure 16) (Hampton and Bouma, 1977). The high degree of stability is related to the restricted occurrence of soft sediment mainly on flat areas of the sea floor, whereas most slopes are underlain by coarse-grained material. Sitkinak Trough is a notable exception, but no large slides have been specifically located there. Because there is 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).

Sediment slides are abundant on the upper continental slope and will become of prime concern only as development moves beyond the shelf break. However, the distribution of these slides does have important implications regarding tectonic hazards on the shelf. Areas near the shelf break that contain large slides appear to be sites of modern tectonic deformation, with growth of folds, tilting of the sea floor, and earthquakes occurring there. The subdued geologic structures and seismic activity in shelf break areas that do not contain large slides indicate relatively minor tectonic deformation and related hazardous conditions.

Locations of gas-charged sediment have been identified on the Kodiak Shelf, and environmental problems are possible (Figure 16) (Hampton and Kvenvolden, 1981). Most gas appears to be generated by shallow microbial decay and is not likely to be an economic resource, although a gas seep on middle Albatross Bank (57°01.1'N, 152°10.3'W) might indicate a deeper thermogenic source. Potentially hazardous slope instability, low strength, and overpressuring have been found associated with gas-charged sediment in other geographic areas (Whelan and others, 1976; Nelson and others, 1978). Direct evidence that similar problems exist on the 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 could perhaps trigger them (see Ocean Industry, 1981), and special attention is warranted in the specified areas.

Pollution of Kodiak Shelf waters can have magnified effects at certain places on the sea floor. Fine-grained 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 location of depositional sites. (Refer to the study by Kolpack and others, 1971, of hydrocarbon distribution as related to sediment transport patterns after the Santa Barbara Channel oil spill.) Because the distribution of benthic fauna varies spatially with sediment type (see Thorson, 1957), specific faunal populations might be affected more than others by a contamination event. The localized occurrence of fine-grained material in Kiliuda, Chiniak, and Sitkinak Troughs implies that these sites are presently repositories for sediment. Pollutants that become incorporated into bottom sediment should be swept from other areas into the troughs, and local fauna would be affected. Also, it is likely that sediment transport across the shelf break is localized where physiographic barriers (sills) are absent or have been breached, which could cause disturbance of local populations after a pollution event.

CHAPTER 4 - HARD-MINERALS GEOLOGY

We have no data from which to evaluate the geology of hard-mineral deposits.

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Table 1. Pyrolytic Data from Paleocene Rocks

Organic Carbon Yield (wt.%) (°C)	Total Pyrolytic	Volatile Hydrocarbon Yield (wt.%)	Hydrocarbon Content (ppm)	Temperature of Maximum Pyrolytic Pyrol. HC Organic C	
0.58		0.002	4	0.4	*
0.71		0.003	2	0.4	652
0.49		0.002	6	0.5	*
0.38		0.002	3	0.7	564
0.19		0.004	8	2.1	572
0.49		0.002	8	0.6	*

*Peak of yield indistinct.

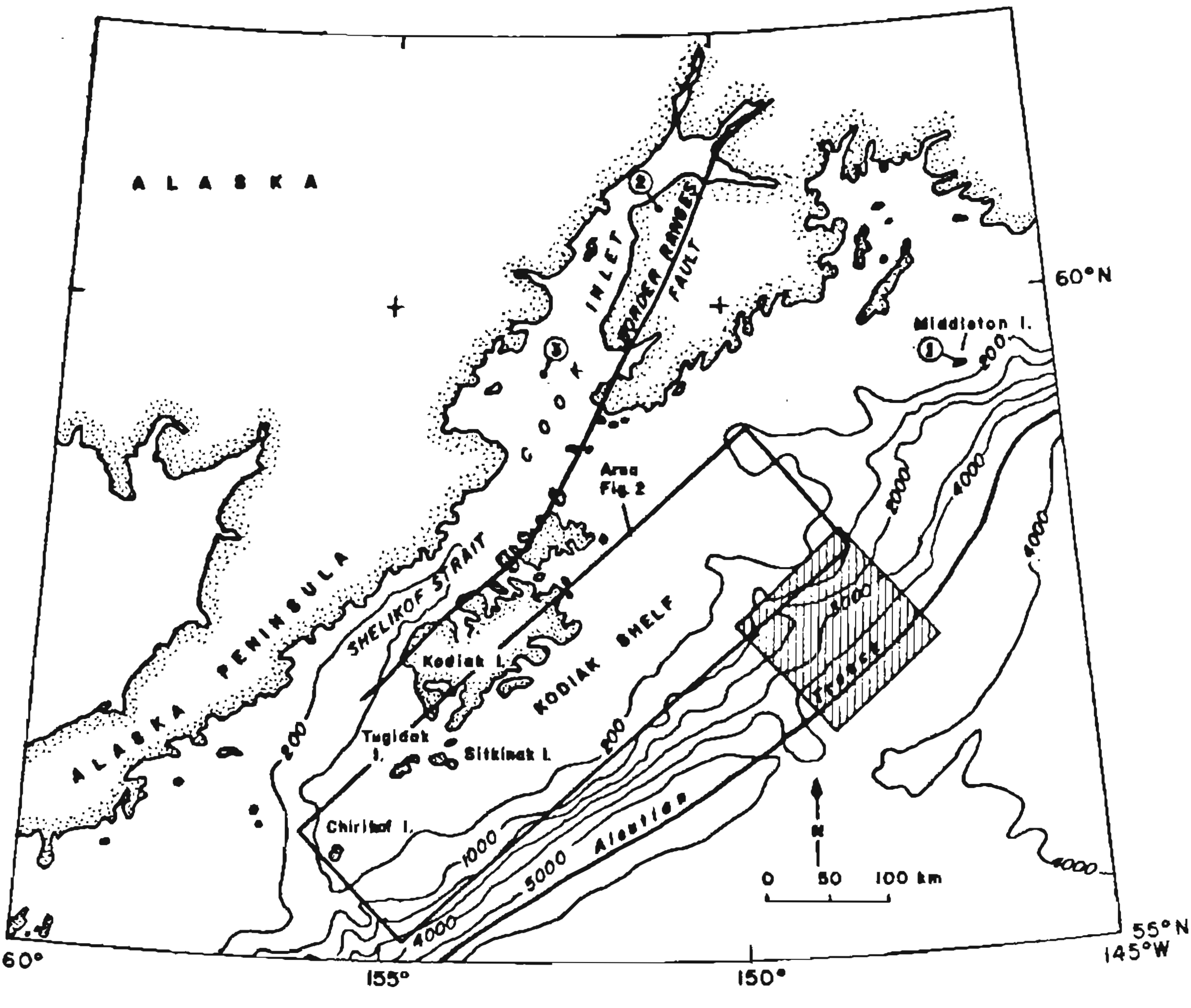

Figure 1. Geography and bathymetry of Kodiak Shelf area

Line from circled number shows location of the Tenneco Middleton Island 1 well. Hachured box shows location of migrated seismic lines that cross the slope. Depths are in meters

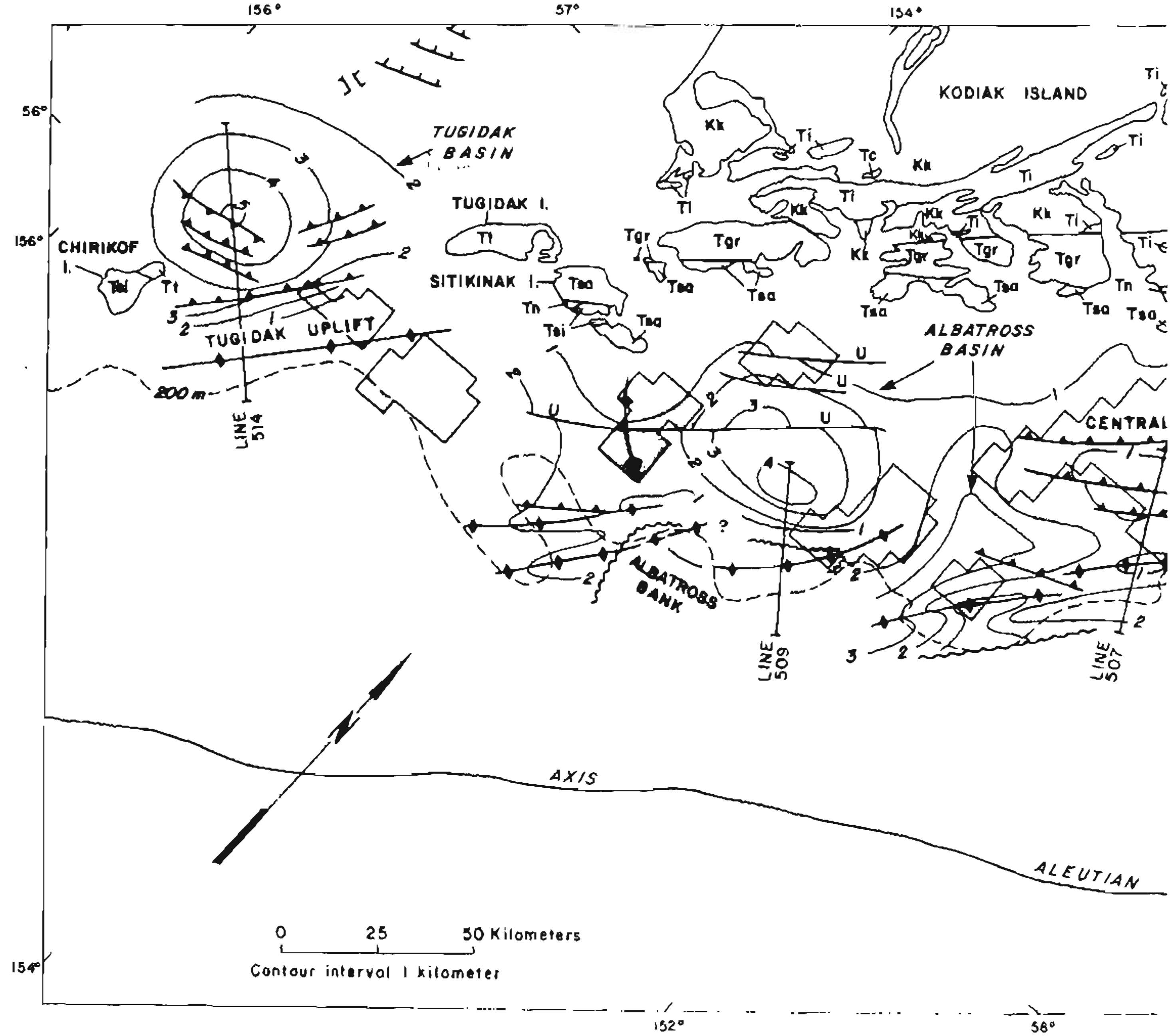

Figure 2, part 1. Geology of Kodiak Island and offshore structure. Contours are drawn on horizon C unconformity at base of strata as old as Pliocene Proposed sale areas are shown as nominated tracts.

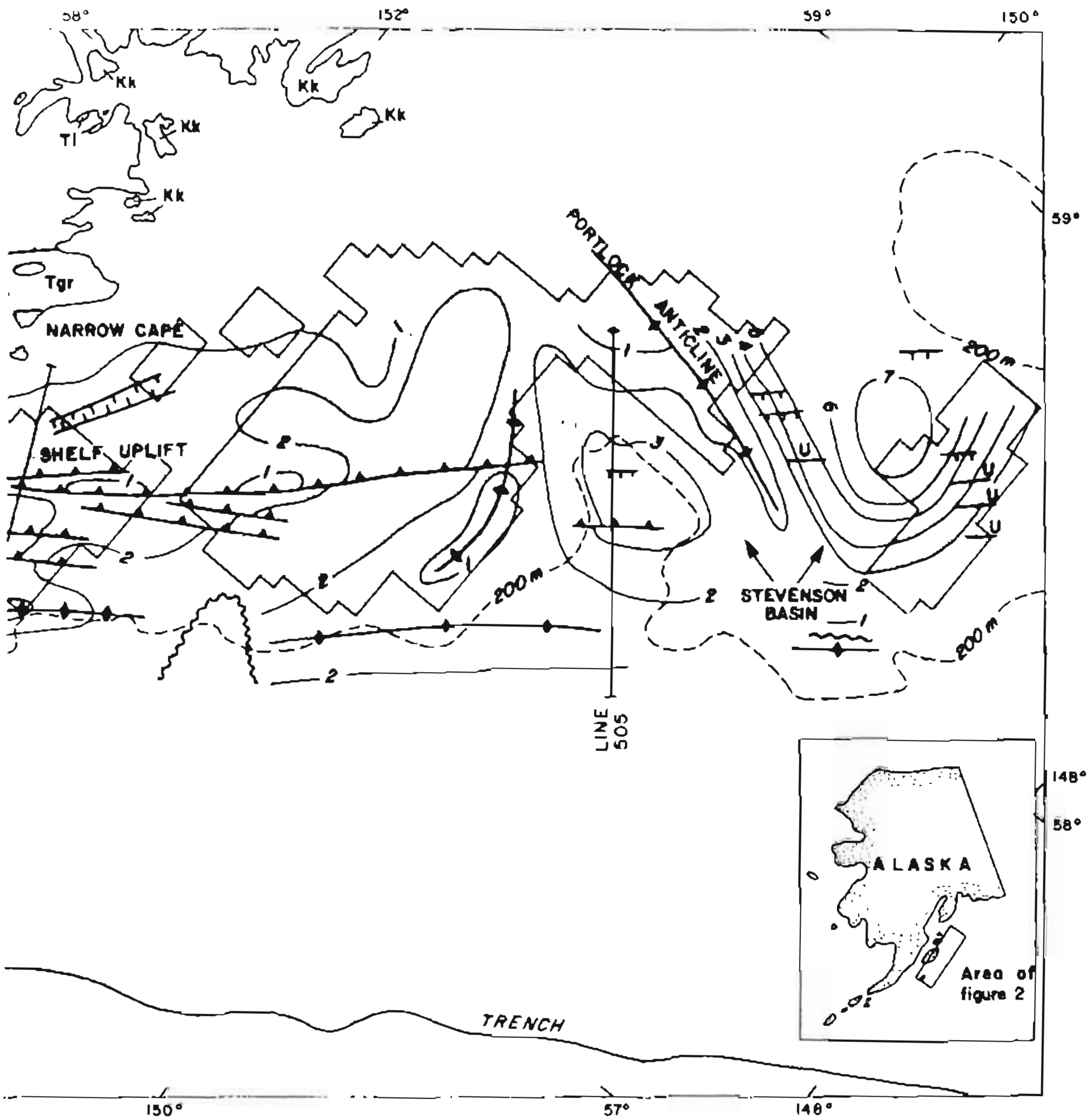

Figure 2, part 2.

EXPLANATION

Anticline, dashed where inferred

Reverse fault, dashed where inferred, barbs on upthrown side

Normal fault, hachure on down-thrown block

Contact

Fault

U

Fault, dip undetermined, U on upthrown side

Erosional termination of horizon C

3

Contours of depth(km) to horizon C, base late Miocene or Pliocene

Outline of nominated tracts

	SEDIMENTARY ROCKS	AGE
Tt	Tugidak Formation	Pleistocene and Pliocene
Tn	Narrow Cape Formation	Miocene and Oligocene(?)
Tsi	Sitkinak Formation	Oligocene
Tsa	Sitkalidak Formation	Eocene
Tgr	Ghost Rocks Formation	Paleocene
Kk	Kodiak Formation	Upper Cretaceous

	IGNEOUS ROCKS	
Ti	Plutonic Rocks	Lower Tertiary

EXPLANATION OF FIGURE 2.

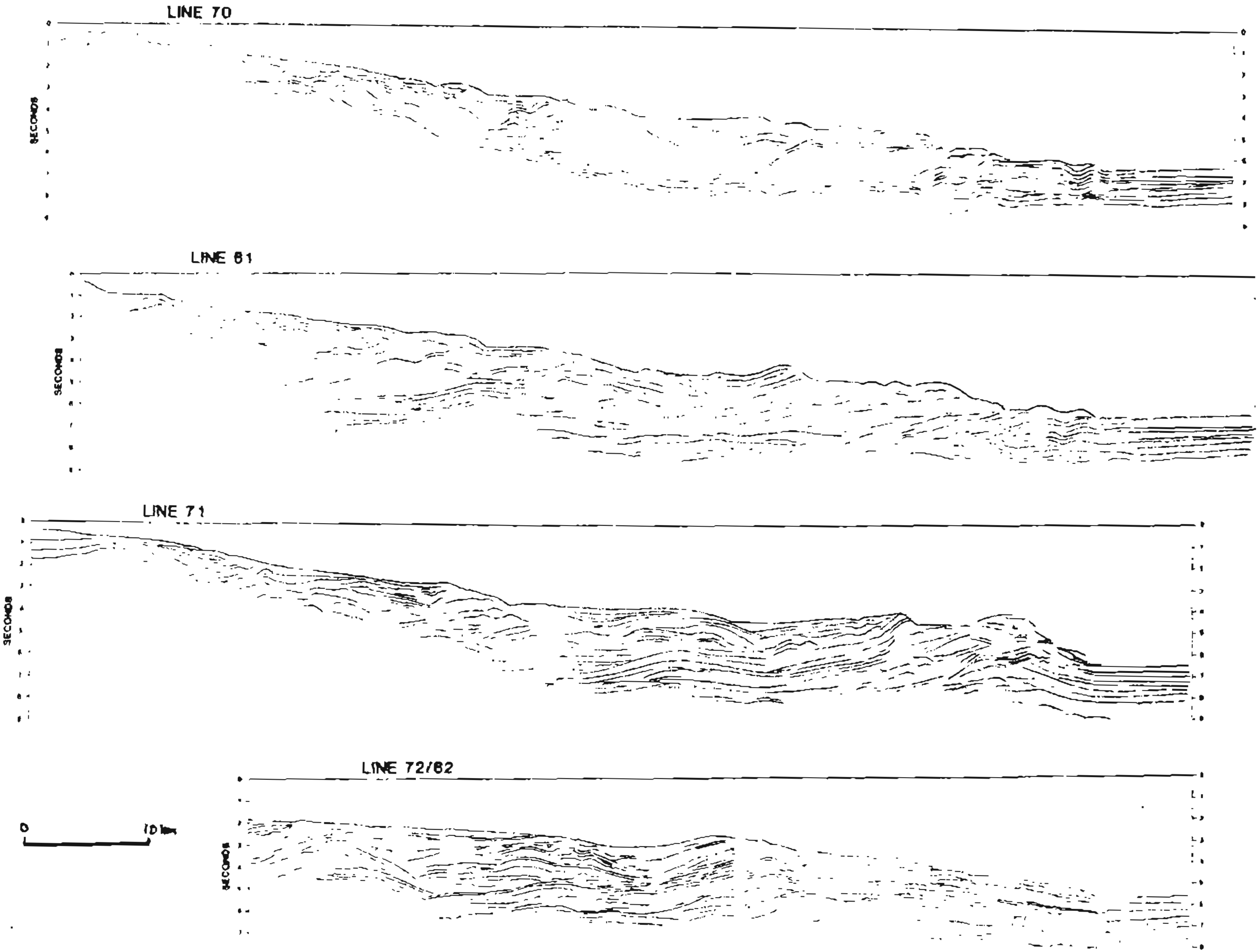

Figure 3. Migrated time sections along tracklines shown in boxed area of Figure 2.

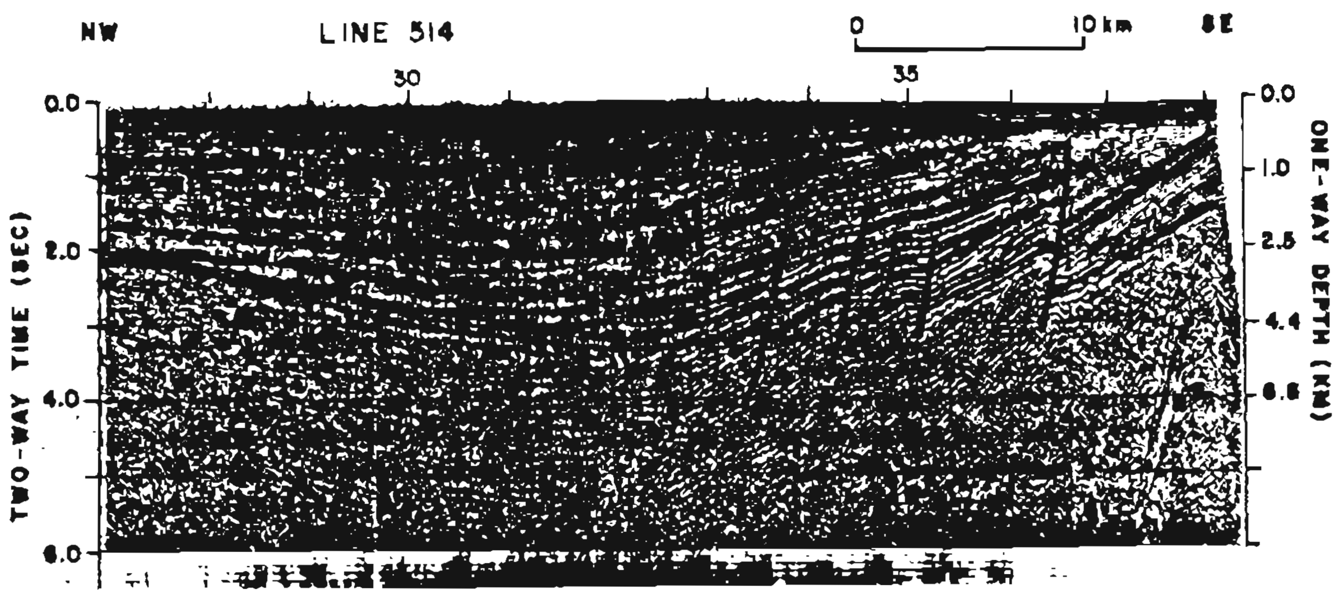

Figure 4. Multichannel-seismic section through Tugidak Basin. Location shown in Figure 2.

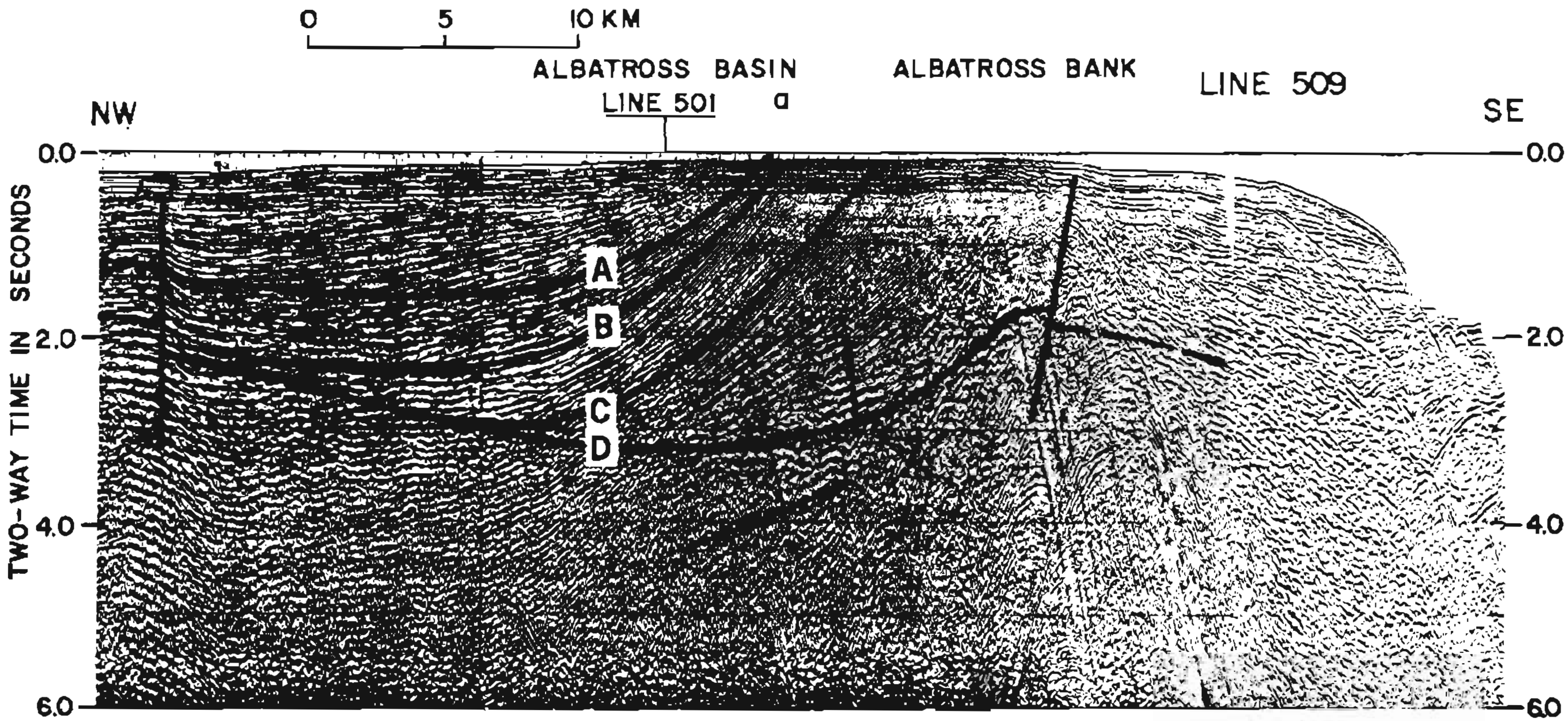

Figure 5. Multichannel-seismic section through Albatross Basin. Location shown in Figure 2.

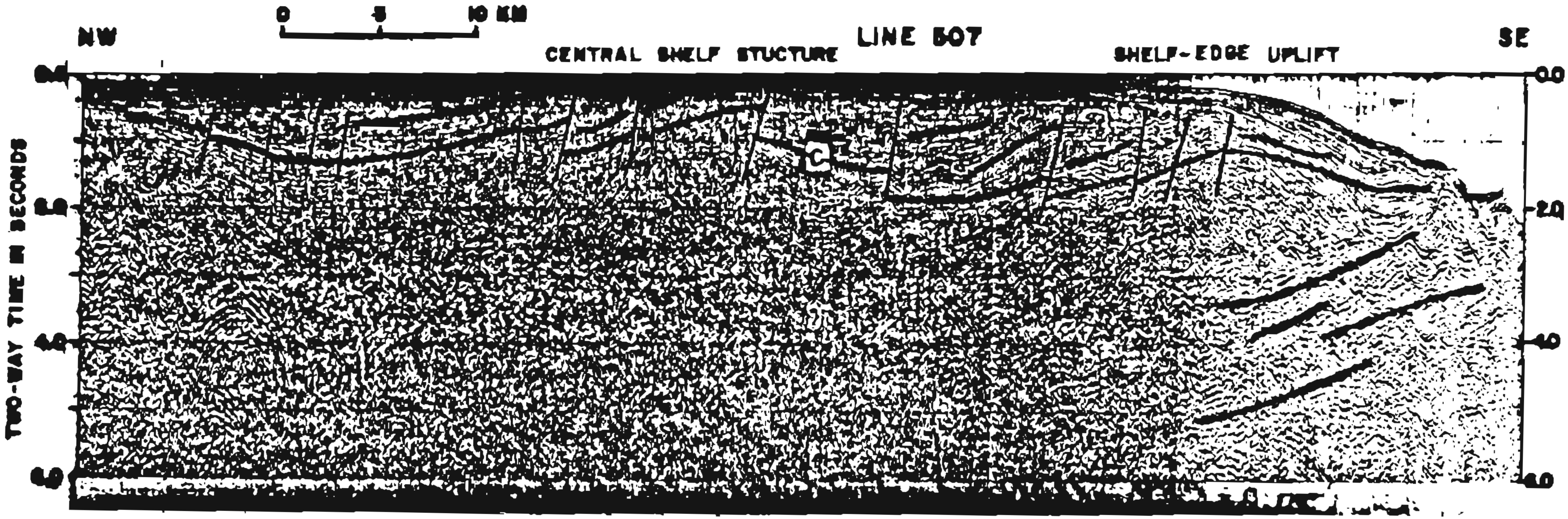

Figure 6. Multichannel-seismic section through the central-shelf uplift.

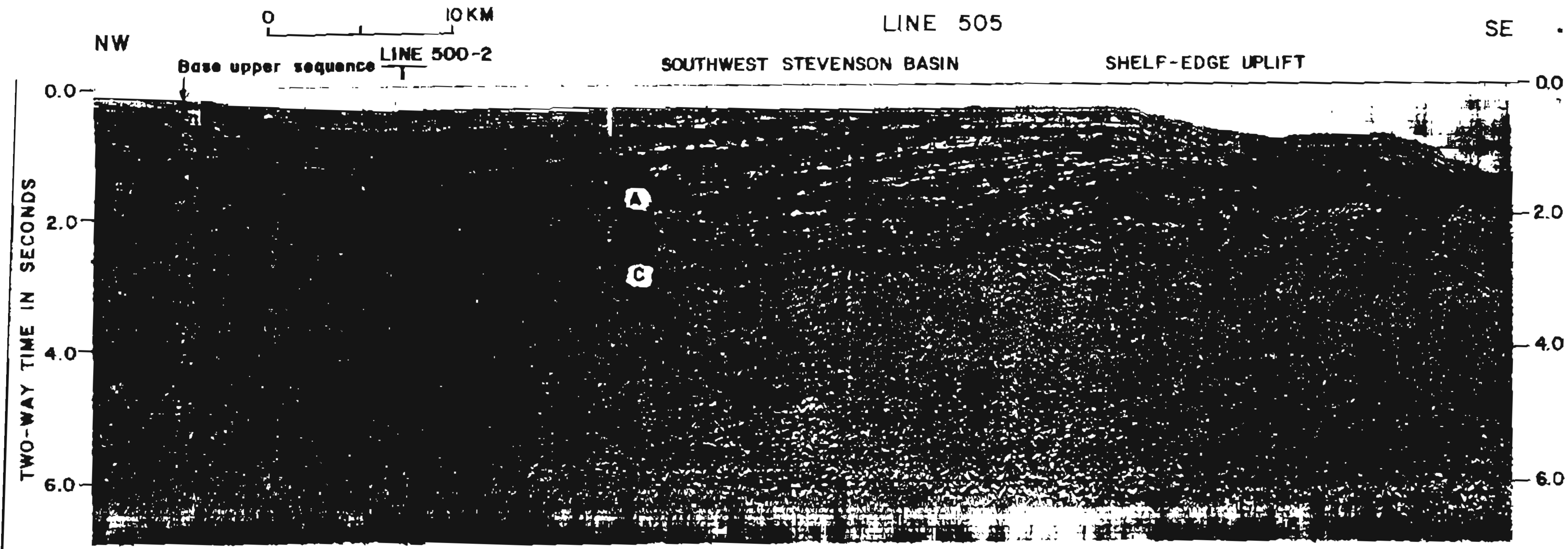

Figure 7. Multichannel-seismic section through Stevenson Basin. Location shown in Figure 2.

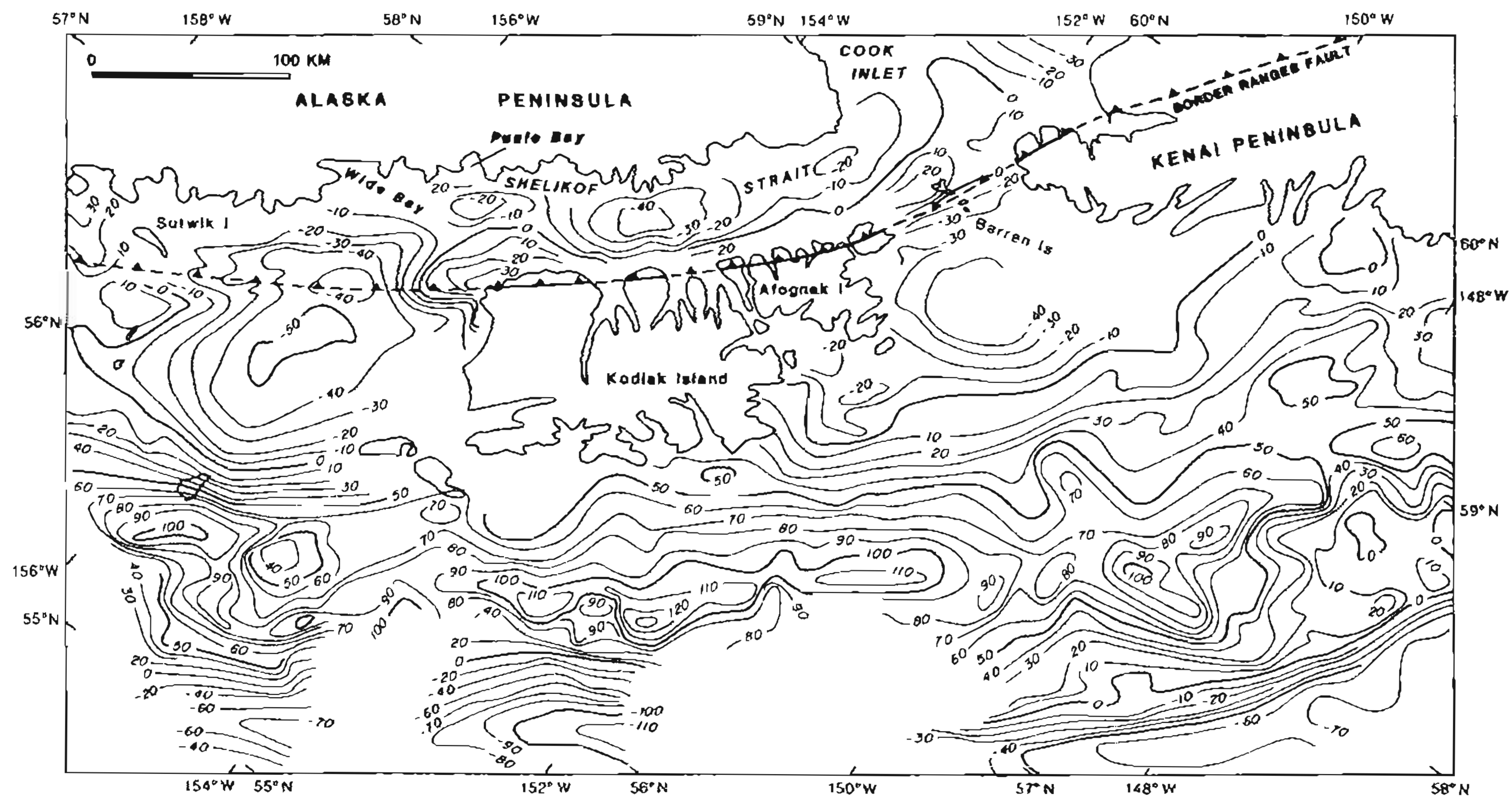

Figure 8. Gravity map generalized from Fisher and others (1983).

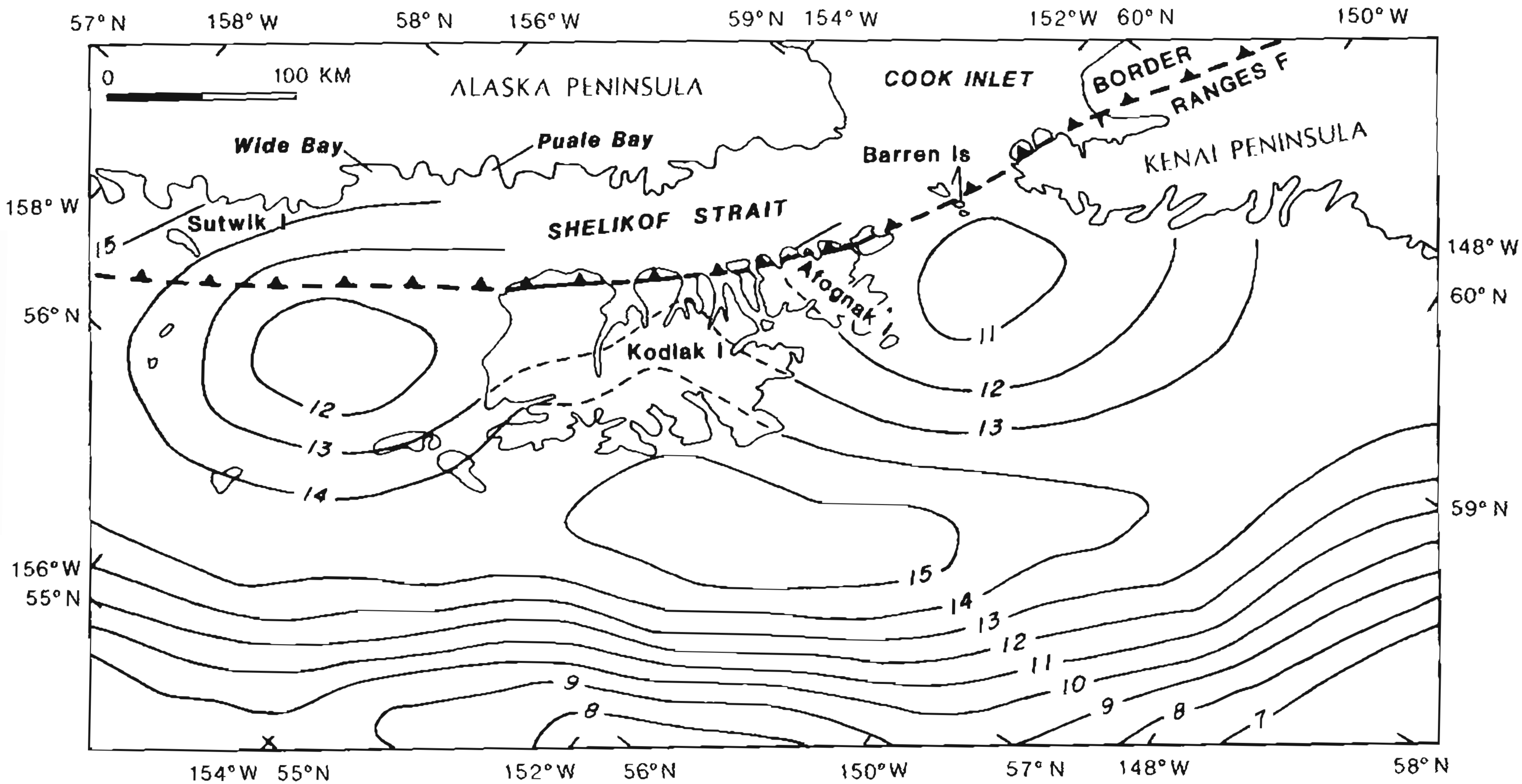

Figure 9. Geoid map (I.G. Marsh, written commun., 1982).

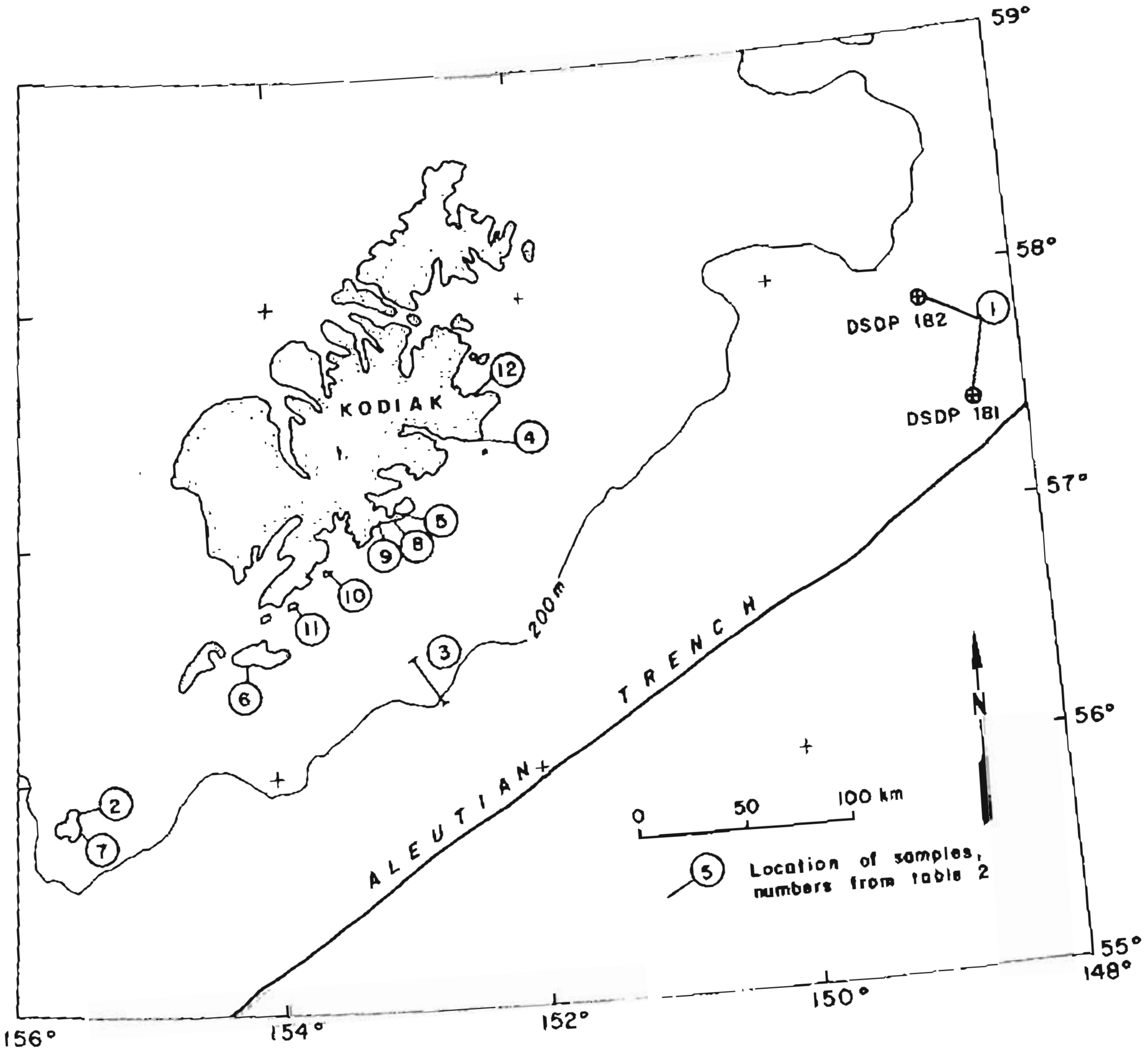

Figure 10. Locations of samples analyzed for geochemical data from Kodiak Island, shelf, and slope. "Map numbers" of Figure 4 are circled.

SOURCE – AND RESERVOIR – ROCK DATA

MAP NO.	ROCK UNIT	AGE	TOTAL ORGANIC CARBON				TOTAL EXTRACTABLE HYDROCARBONS				INDIGENOUS KEROGEN		THERMAL ALTERATION		VITRINITE REFLECTANCE (% IN OIL)				POROSITY				PERMEABILITY			
			n	MEAN (WT.%)	MAX (WT.%)	MIN (WT.%)	n	MEAN (PPM)	MAX (PPM)	MIN (PPM)	n	TYPE[1]	n	INDEX[2]	n	MEAN (WT.%)	MAX (WT.%)	MIN (WT.%)	n	MEAN (%)	MAX (%)	MIN (%)	n	MEAN (MD)	MAX (MD)	MIN (MD)
1	Slope Strata	Early Pleist.(?) to Holocene	75	0.60	0.90	0.20	–	–	–	–	4	H: C: W	4	1 to 1+	3	0.60	0.65	0.55	–	–	–	–	–	–	–	–
2	Tugidak Fm.	Late Pliocene and Early Pleist.	1	0.58	–	–	1	606	–	–		H: C: W	1	1+ to 2-	–	–	–	–	–	–	–	–	–	–	–	–
3	Albatross Basin Fill	Late Miocene or Pliocene	10	0.45	0.65	0.24	–	–	–	–	10	W-H:Am-W:Am	10	1+ to 2-	8	0.39	0.48	0.32	–	–	–	–	–	–	–	–
4	Narrow Cape Fm.	Early to middle Miocene	1	0.36	–	–	1	165	–	–		H: C: Am	1	2 to 2+	–	–	–	–	16	7.4	17.0	0.6	16	7.8	30	0.01
5	Sitkinak Fm.	Oligocene	6	0.62	0.95	0.35	6	380	601	227	6	H:C-Am:Am	6	2- to 2+	–	–	–	–	11	2.5	4.1	0.2	11	0.2	1.9	0.01
6	Sitkinak Fm.	Oligocene	2	0.44	0.50	0.38	2	309	389	229	2	H: C: -	2	2- to 2	–	–	–	–	3	10.0	10.7	9.0	3	0.8	1.3	0.08
7	Sitkinak Fm.	Oligocene	4	0.43	0.60	0.35	4	243	376	173	4	H: C: W	4	2- to 2+	–	–	–	–	3	5.8	7.4	4.8	3	0.01	0.01	0.01
8	Sitkalidak Fm.	Eocene and Oligocene	6	0.49	0.53	0.42	6	284	323	197	6	H: C: Am	6	2- to 2+	–	–	–	–	14	1.1	2.9	0.2	14	0.01	0.02	0.01
9	Sitkalidak Fm.	Eocene and Oligocene	5	0.47	0.70	0.21	5	412	556	135	5	H: Am: C	5	2- to 2+	–	–	–	–	6	2.5	5.3	0.8	6	0.06	0.11	0.01
10	Sitkalidak Fm.	Eocene and Oligocene	4	0.50	0.64	0.44	4	400	564	302	4	H: C: Am	3	2 to 2+	–	–	–	–	6	1.7	2.3	1.1	8	0.01	0.01	0.01
11	Sitkalidak Fm	Eocene and Oligocene	9	0.45	0.64	0.28	9	335	620	226		H: C: Am	9	2 to 2+	–	–	–	–	11	0.85	1.6	0.2	11	0.01	0.01	0.01
12	Ghost Rocks Fm.	Paleocene	6	0.47	0.71	0.19	–	–	–	–	4	-:C-W:Am-H	4	2 to 2+ and 3 to 4-	4	2.95	3.74	2.21	–	–	–	–	–	–	–	–

Figure 11. Source and reservoir rock data. [1]Am, amorphous; H, herbaceous; W woody; C coaly. Types are shown in order of abundance: predominant, 60 to 100%; secondary, 20 to 40%; trace, 1 to 20%. [2]1 to 2-, immature; 2- to 2, moderately immature; 2 to 2+, moderately mature; 2+ to 3, mature; 3 to 4-, very mature; 4- to 4 severely altered; 5, metamorphosed. Underline indicates that index is closer to underlined reading; for example, an index of 1 to 1+ is closer to 1+.

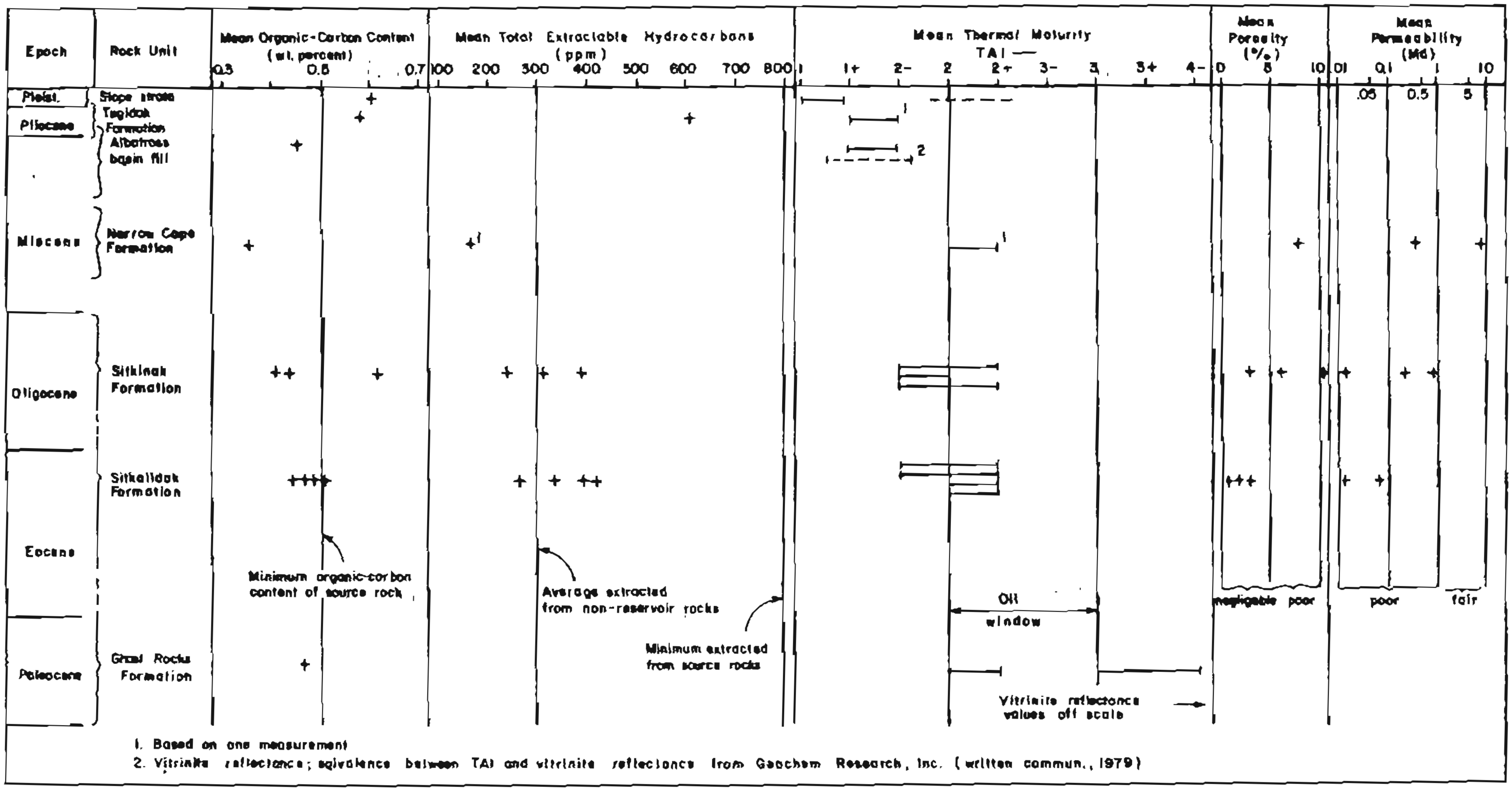

Figure 12. Mean hydrocarbon source rock and reservoir properties of various rock units versus geologic age of units.

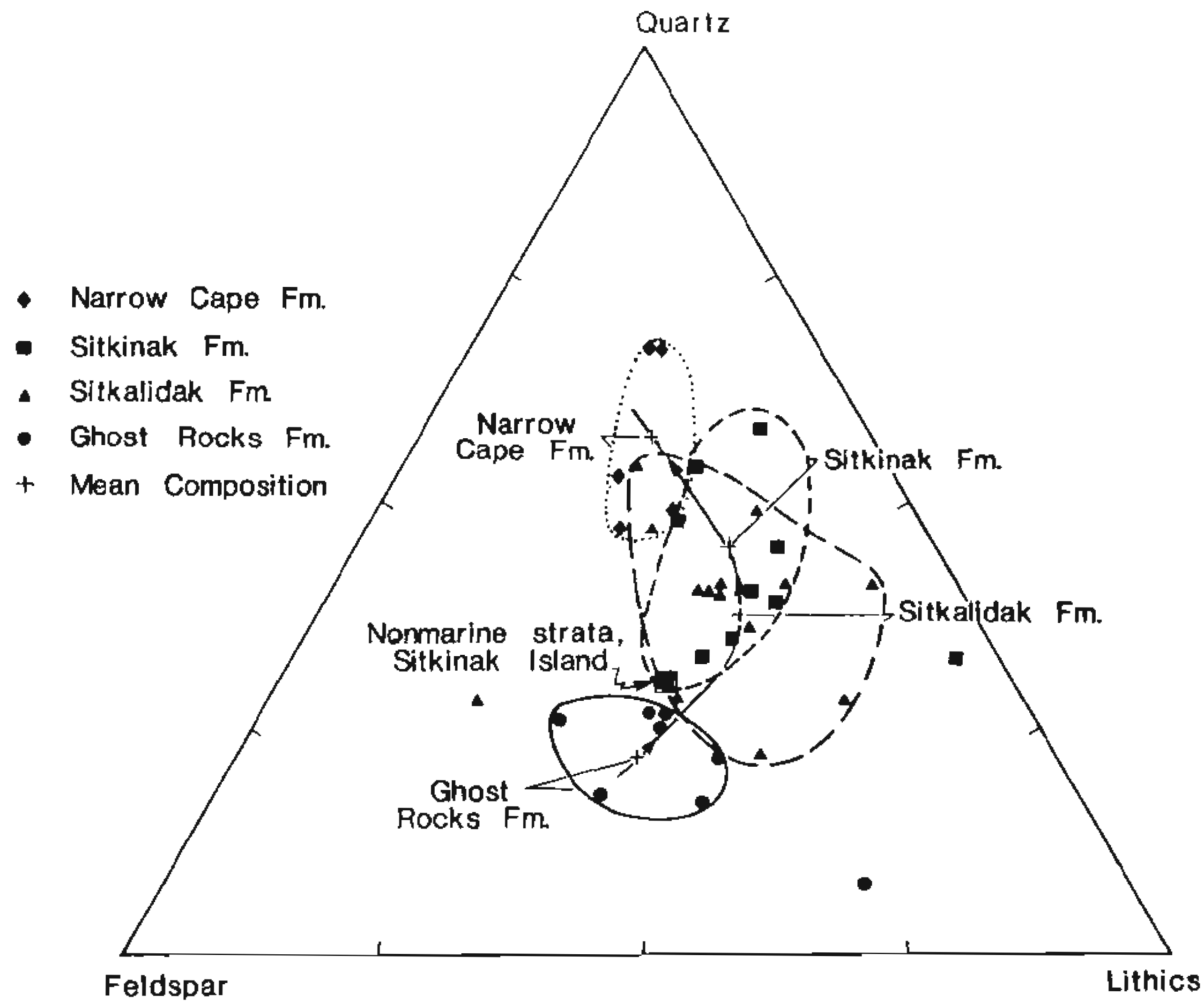

Figure 13. QFL diagram for rocks exposed on Kodiak Island. Q includes polycrystalline quartz.

Figure 14. Shallow folds and faults on the Kodiak Shelf.

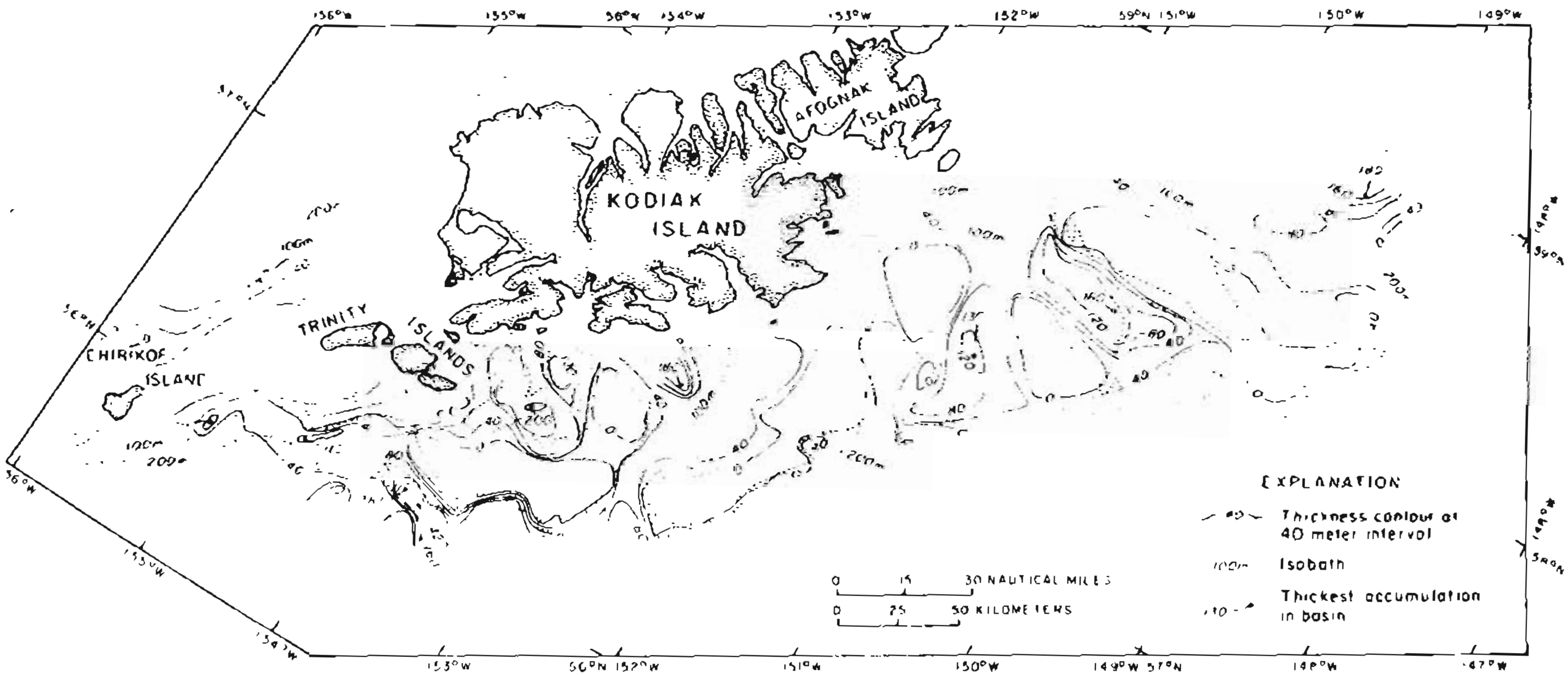

Figure 15. Generalized thickness map of unconsolidated sediment on the Kodiak Shelf. Contours in meters. Contour interval equal to 40m.

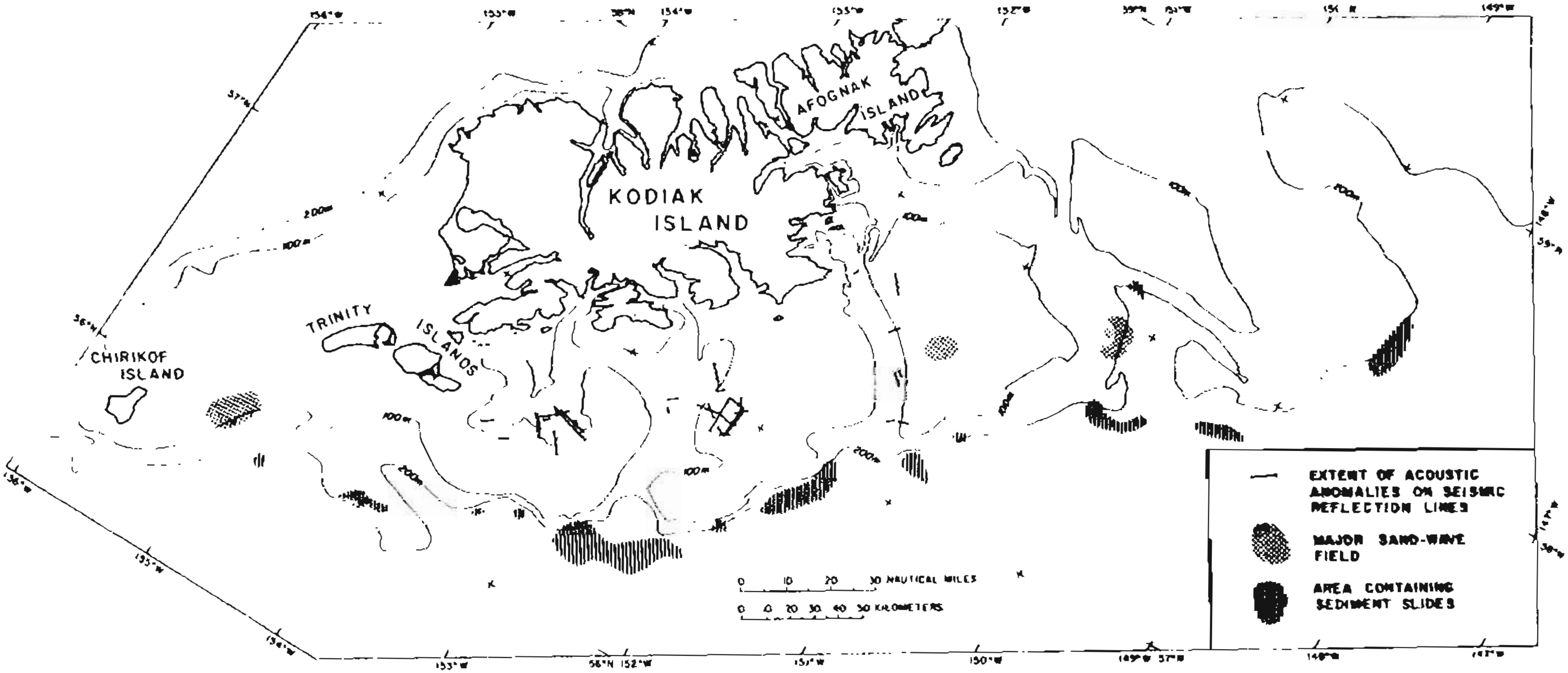

Figure 16. Location of some environmentally significant geologic features on the Kodiak Shelf.