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Geology and Petroleum Potential of the Norton Basin Area, Alaska

By

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ABSTRACT

The rocks that floor the Norton basin and the northwestern Bering Sea are most likely of Precambrian and Paleozoic age, like those that crop out around the basin. A maximum of 6.5 km of mainly Cenozoic rocks lie over basement in the basin. On the basis of the geometry of reflections in seismic data, we believe alluvial fans to be present deep in the basin and to border major basement fault blocks. These fans are the lowest units of the basin fill in many areas, and the fans consist of uppermost Cretaceous and Paleogene, possibly coal- and volcanic-rich rocks. Mainly clastic non-marine sedimentary rocks overlie the fan deposits. The Neogene and Quaternary basin rocks apparently were deposited in a marine environment.

The basement of the northwestern Bering Sea, west of Norton basin, is 1 km below sea level for the most part, but local structural lows are filled with at most 2 km of strata of probable late Neogene and Quaternary age. The continental shelf in this area is separated structurally from the Seward Peninsula by a zone of anticlines, over which relatively high gravity values have been measured.

The Norton basin comprises two structural areas that are separated by a major northwest-striking horst. The first structural area lies west of this horst, where major normal faults strike northwest to form local areas where the basin is as deep as 5.0 km. The second area, east of the horst, includes major normal faults that strike east and northeast; the deepest part of the Norton basin (6.5 km) lies there.

During the Late Jurassic and Early Cretaceous, basement rocks now beneath the Norton basin were affected by the orogeny that formed the Brooks Range. These basement rocks were metamorphosed and thrust, and then eroded deeply nearly 50 m.y. before the basin began to form. In the middle Late Cretaceous, the area of the eastern Seward Peninsula and eastern Norton Sound was subjected to east-west compression and consequent eastward thrusting. The strike-slip Kaltag fault probably formed at this time. If Norton basin formed as a pull-apart basin along this fault, then the basin may be as old as middle Late Cretaceous. However, during the latest Cretaceous and early Paleogene, the compression gave way to regional extension that formed northeast-trending grabens onshore, east of Norton basin. We believe that the extensional Norton basin most likely formed in response to this regional extension. Initial deepening of the basin was controlled by major normal faults and occurred rapidly, whereas later subsidence was slower and more regional in scale.

Basement rocks beneath the main part of the Norton basin were deformed and heated during the Late Jurassic and Early Cretaceous to the extent that these rocks were not capable of generating hydrocarbons when the basin formed during the latest Cretaceous or early Paleogene. Consequently, source rocks for oil, if they exist, are most likely to be within the basin fill. If the Norton basin began to form 65 m.y. ago, subsided at a nearly constant rate, and had an average geothermal gradient of between 35 and 45° C/km, then rocks as young as late Oligocene are in the oil window (vitrinite reflectance between 0.65 and 1.30%). The appearance on seismic sections of reflections from rocks in and below the calculated oil window suggests that these rocks

were deposited in a nonmarine environment. Thus, gas and condensate are the most likely hydrocarbons to be present in the basin. Because of their shallow depth of burial, Neogene, possibly marine rocks are not likely to be thermally mature anywhere in the basin. Deep parts of the basin formed as isolated fault-bounded lows; consequently, the volume of mature rocks makes up at most 11% of the total basin fill. Numerous potential traps for hydrocarbons exist in the Norton basin; the traps include fractured or weathered basement rocks in horsts, strata in alluvial fans on the flanks of horsts, and arched strata over horsts. The last type is the most likely to contain hydrocarbons.

INTRODUCTION

The northern Bering Sea is bounded by the Seward Peninsula on the north, the Yukon-Koyukuk geologic province on the east, the Yukon delta and St. Lawrence Island on the south, and the Chukotsk Peninsula of Siberia on the west (Fig. 1). The United States-Russia Convention Line of 1867 marks the western end of the area that is likely to be included in a lease sale. The Norton basin, adjacent to the Yukon delta lies beneath the east-central part of the northern Bering Sea. The sea bottom over the basin is an almost featureless plain that is shallower than 30 m and averages 15 m in depth.

In this report, we use geophysical data and regional geology to describe the structure of rocks under the northern Bering Sea and to give a preliminary description of the stratigraphy and geologic history of the Norton basin. In the final section, we discuss the petroleum geology of the Norton basin.

Geophysical data that form the basis of this report were collected in 1969, 1978, and 1980 (Fig. 2). In 1969, a minor part of these data were collected from the USC and GSS Surveyor and consist of single-channel seismic-reflection, magnetic, and gravity data (Walton, Perry, and Greene, 1969; Department of Commerce, 1969 a, b). The sound source was a single 0.66 liter (40 in.^{3}) air gun. In 1978 and 1980, gravity, seismic-reflection, and seismic-refraction data were obtained. The gravity data were collected with a La Coste and Romberg[1] sea gravimeter S-53 mounted on a three-axis inertial platform in 1978 and on a two-axis platform in 1980. The gravity data from 1978 have been published in preliminary contoured form (Fisher et al., 1980). The seismic-reflection data were recorded using a GUS 4200[1] digital recording system, a 2400-m, 24-channel streamer, and an array of five air guns totaling 21.7 liters (1326 in^3.). Seismic-refraction data were collected by means of SSQ-41B sonobuoys provided by the U.S. Navy. Ship's position was determined with a satellite navigation system that integrates doppler-sonar data to compute dead-reckoned positions.

Early work in the area of the Norton basin resulted in reports by Payne (1955), who first proposed the presence of a basin beneath Norton Sound, and by Scholl and Hopkins (1969), who used high-resolution seismic data that indicated that the Norton basin was about 2 km deep. On the basis of

1 Any use of trade names is for descriptive purposes only and does not imply endorsement by the U. S. Geological Survey.

biostratigraphic information from scattered onshore outcrops, Scholl and Hopkins (1969) proposed that rocks in the basin are at least as old as Oligocene. They also suggested that in the western, northern, and eastern parts of the Norton basin, the Tertiary basin fill overlies mainly Paleozoic rocks that are locally intruded by late Mesozoic plutons. Hite and Nakayama (1980), in their discussion of potential petroleum basins in Alaska, stated that the Norton basin contains between 5.5 and 6.1 km of mainly Tertiary fill that overlies a basement of highly deformed and indurated pre-Tertiary rocks.

REGIONAL GEOLOGY

Rocks of Pre-Late Cretaceous Age

Rocks of pre-Late Cretaceous age of the northern Bering Sea shelf and of parts of northeast Siberia and Alaska adjoining the shelf can be divided into three broad geologic belts that have distinctive rock assemblages. The belts are, in rough geographic order from north to south: 1) a miogeoclinal belt, in which Precambrian through lower Mesozoic rocks predominate; 2) a volcanic belt, in which middle and upper Mesozoic volcanic rocks predominate; and 3) a forearc belt, which consists of Mesozoic sedimentary and minor volcanic rocks. Rocks of these three belts form the basement underlying the Bering Sea.

Miogeoclinal Belt- Included in this belt are rocks exposed in the Brooks Range, on the Seward Peninsula, in the eastern and central parts of St. Lawrence Island, in the eastern and northern parts of the Chukotsk Peninsula, and on Wrangel Island (Fig. 3). Rocks in this belt are mainly Precambrian, Paleozoic, and lower Mesozoic nonvolcanic rocks that accumulated on ancient continental crust. In the Brooks Range, Paleozoic and lower Mesozoic rocks were thrust northward in imbricate slabs. Southwest from the Brooks Range to the eastern and central parts of the Seward Peninsula, rocks in this belt were thrust eastward and are mainly a complex of Precambrian and Paleozoic schist and marble of greenschist and amphibolite metamorphic facies (Sainsbury, 1975; Hudson, 1977). The western part of the Seward Peninsula is underlain by a thick sucession of Precambrian slate and conformably overlying Paleozoic carbonate rocks. These carbonate rocks and slate are unmetamorphosed in comparison with schists that lie to the east (Sainsbury, 1969b, 1972, 1975). On St. Lawrence Island, the miogeoclinal rocks are unmetamorphosed Paleozoic and lower Mesozoic carbonate, chert, and fine-grained clastic rocks that are similar in many respects to rocks of the same age exposed in the northern part of the Brooks Range (Fig. 4; Patton and Dutro, 1969; Patton and Csejtey, 1971, 1980). On the Chukotsk Peninsula and on Wrangel Island, the miogeoclinal belt is mostly made up of unmetamorphosed Paleozoic and lower Mesozoic carbonate and nonvolcanic rocks (Parfenov et al., 1978, 1979). However, gneiss and schist of probable Precambrian age underlie unconformably the Paleozoic strata on the eastern part of the Chukotsk Peninsula, and Precambrian or Paleozoic sedimentary rocks of low metamorphic grade are present in a small area in the central part of Wrangel Island.

Volcanic Belt --Rocks of the volcanic belt are present in: 1) the Yukon-Koyukuk geologic province in western Alaska; 2) western St. Lawrence Island and St. Matthew Island in the Bering Sea; and 3) the region of the southern

Chukotsk Peninsula and the Anadyr River in Siberia (Fig. 3). The volcanic and volcaniclastic rocks that make up most of this belt are mainly of late Mesozoic age.

In western Alaska, rocks of the volcanic belt are in the Yukon-Koyukuk province, within a broad wedge of Cretaceous rocks that stretches along the west coast of Alaska, from the Brooks Range to the Yukon delta (Patton, 1973). The oldest rocks in the province are marine andesitic volcanic rocks of earliest Cretaceous age (Neocomian) that are at least 1500 m thick. These volcanic rocks are overlain by middle Cretaceous (Albian and Cenomanian) volcanic graywacke and mudstone, which may be as much as 8000 m thick. Some coal-bearing paralic deposits are present in the upper part of this middle Cretaceous sequence. In the western half of the province, the upper part of the sequence consists of calcareous graywacke, mudstone, and conglomerate. These rocks generally coarsen westward across the province, and at the western province margin, grade into nonmarine coal-bearing deposits.

On the Bering Sea shelf, Upper Cretaceous rocks of the volcanic belt crop out on western St. Lawrence Island and compose virtually all of the exposed bedrock on St. Matthew Island. Marine magnetic data (Verba et al., 1971; Marlow et al., 1976) obtained on the Bering Sea shelf suggest that these exposed volcanic rocks are part of a broad magmatic arc that swings across the shelf from southwestern Alaska to the Gulf of Anadyr. Close to the Siberian coast, the belt is about 200 km wide and is sharply delineated. Eastward from Siberia, however, the boundaries of the volcanic belt become vague as the belt widens to as much as 600 km along the west coast of Alaska. This change appears to reflect differences between Siberia and Alaska in the characteristics of the volcanic belt: in Siberia the belt is narrow and is composed almost exclusively of volcanic rocks, whereas in Alaska the volcanic rocks are distributed over a broad area and are intercalated with nonmagnetic sedimentary rocks.

In northeastern Siberia, middle Cretaceous (Albian and Cenomanian) volcanic rocks (Belyi, 1973; Partenov and others, 1978, 1979; Filatova, 1979) extend from the southern Chukotsk Peninsula northwestward nearly to Chaun Gulf, and southwestward from the peninsula to the Sea of Okhotsk. This volcanic belt separates Mesozoic rocks in the miogeoclinal belt on the north and northwest from Mesozoic rocks in the Anadyr basin and Koryak Mountains on the southeast. In contrast to the intensely deformed middle Cretaceous volcaniclastic rocks in Alaska, coeval volcanic rocks in Siberia are gently deformed in most areas.

Cretaceous granitic rocks are widely exposed in land areas around the northern Bering Sea; such rocks are present in a broad belt that extends from the Chukotsk Peninsula to the Yukon-Koyukuk province and the Yukon delta (Fig. 3). Potassium-argon ages on these rocks range from 110 to 75 m.y.

Forearc Belt-- The Cretaceous volcanic belt is bounded on the south by the forearc belt, composed of late Mesozoic sedimentary rocks and a minor fraction of crystalline volcanic rocks. In the Koryak-Anadyr region, Upper Jurassic and Lower Cretaceous deep-water flysch deposits, interbedded with mafic volcanic rocks, and Upper Cretaceous and lower Tertiary shallow-water and nonmarine deposits make up the forearc belt. Recent dredging along the continental slope in the Bering Sea revealed that shallow-water deposits of Late Jurassic and Cretaceous age lie under the continental slope (Marlow and others, 1979; Marlow and Cooper, 1980); therefore, rocks of the forearc belt also lie under the outer edge of the Bering Sea margin, southeastward from Siberia.

Rocks of the three belts just described form the basement complex beneath the Bering Sea. In the area of the Norton basin, rocks of the miogeoclinal belt and rocks of the volcanic belt could form the basement complex. Miogeoclinal rocks are exposed on the Seward Peninsula, at Cape Denbigh (northeast of the Norton basin; Figs. 1, 3), and on eastern and central St. Lawrence Island. Andesite and volcanic graywacke of the volcanic belt crop out in the Yukon-Koyukuk province, along the eastern and southern shores of Norton Sound. Precambrian crystalline rocks of continental affinity lie under the miogeoclinal rocks, whereas Paleozoic and early Mesozoic oceanic crust is thought to be basement under the Yukon-Koyukuk province (Patton and Tailleur, 1977). Miller (1972) and Patton (1973) suggested that the suture between these crustal types strikes south or southwest from Cape Denbigh (Fig. 1). However, the location of the suture south of this cape is known only from three pieces of information. First, undated marine volcanic rocks and chert are exposed on Besboro Island. Assuming that these rocks are coeval with the similar Neocomian marine volcanic rocks of the Yukon-Koyukuk province, we believe that the suture lies just west of Besboro Island. Second, middle Cretaceous volcanogenic rocks of the province crop out along the south shore of Norton Sound and indicate that the suture lies north of this shore. Third, along the southern shore of Norton Sound lies a middle Cretaceous conglomerate that contains clasts of calc-silicate schist (J. M. Hoare, oral commun., 1981). The presence of these clasts suggest that rocks like those exposed on the Seward Peninsula were proximal to the south shore of the sound. From this scanty evidence we believe that Precambrian crystalline continental rocks form the basement under most parts of Norton basin, and that only those parts of the basin that are close to the Yukon delta may lie over Cretaceous rocks of the Yukon-Koyukuk province. The location of the suture west of the Norton basin is believed to be marked by ultramafic rocks that crop out on western St. Lawrence Island (Patton and Csejtey, 1980) and in northeastern Siberia.

Upper Cretaceous and Tertiary Rocks

Superimposed across the three belts of basement rocks are the Anadyr basin in Siberia, the Hope basin north of the Seward Peninsula, and the Norton basin. In this section we describe briefly the stratigraphy of the Anadyr and the Hope basins and the onshore stratigraphy near the Norton basin.

Anadyr Basin -- The Anadyr Basin of northeastern Siberia partly underlies the Bering Sea, southwest of the Chukotsk Peninsula (Fig. 3). Upper Cretaceous and Tertiary deposits are superimposed on rocks of the forearc belt in the south and central parts of the basin, and these deposits lap onto rocks of the volcanic belt along the north and northwest perimeter (Figs. 3, 4; Meyerhoff, 1972; Agapitov and others, 1971, 1973; McLean, 1979).

Upper Cretaceous and Paleocene deposits have an aggregate thickness of 1500 to 2000 m. The Upper Cretaceous strata are composed of flysch deposits of fine-grained sandstone and argillite of Albian to Senonian age, and coal-bearing molasse deposits of Senonian to early Paleocene age. These rocks are intruded and overlain by Paleocene and lower Eocene mafic and intermediate volcanic rocks. Upper Eocene and Oligocene predominantly nonmarine sandstone and argillite overlie the volcanic rocks. The Upper Cretaceous and Paleocene section is moderately folded; some rocks dip as steeply as 40°.

Neogene deposits of the Anadyr basin have an aggregate thickness of nearly 3000 m and are the principal basin fill. More than 2000 m of this section is made up of middle and upper Miocene strata, including shallow-marine, littoral, and coal-bearing non-marine deposits. Miocene strata are overlain by 400 to 500 m of Pliocene strata and by 70 to 120 m of Quaternary unconsolidated deposits.

Hope Basin -- The Hope basin lies north of the Seward Peninsula (Fig. 3) and contains more than 3000 m of Tertiary and possibly some Upper Cretaceous strata. Geophysical data and regional geologic relations suggest that the basin fill overlies Lower Cretaceous rocks (Eittreim and others, 1978). Standard Oil Company of California drilled two wells in the eastern part of this basin (Fig. 3). The wells penetrated rocks of probable Cenozoic age, mainly coal-bearing sedimentary rocks (Fig. 4). Rocks at the bottom of the well at Cape Espenberg are rich in coarse-grained volcaniclastic debris and crystalline volcanic rocks, whereas volcanogenic rocks in the well at Nimiuk Point are mainly tuffs. The wells bottomed in Precambrian(?) schist and Paleozoic(?) carbonate rocks like those exposed on the Seward Peninsula (American Stratigraphic Company, 1977a,b).

St. Lawrence Island -- Two separate stratigraphic units of lower Tertiary volcanic and non-volcanic coal-bearing deposits are exposed on St. Lawrence Island (Patton and Csejtey, 1971, 1980). Both units are so poorly exposed that little can be determined about their thickness and structure; their aggregate thickness, however, probably does not exceed 200 m. The older unit is composed of primarily felsic, intermediate, and mafic flows and tuffs that are intercalated with lignitic coal and tuffaceous sedimentary rocks. The younger unit consists of poorly consolidated sandstone, conglomerate, carbonaceous mudstone, ashy tuff, and volcanic breccia. On the east-central part of the island the younger unit is intercalated with rhyolitic and dacitic welded tuffs. Potassium-argon analyses from volcanic rocks give ages of 65 to 62 m.y. (Paleocene) for the older unit and 39 m.y. (late Eocene) for the younger unit. Plant fossils indicate an Oligocene age for rocks of the younger unit.

Western Alaska -- Two small outcrops of poorly consolidated, coal-bearing beds of late Oligocene or early Miocene age are known near Unalakleet on Norton Sound (Fig. 3; Patton, 1973). One outcrop is located about 16 km south of Unalakleet where about 10 m of clay, containing lignitic coal, are exposed in low beach bluffs. Similar rocks are present at the other outcrop, along a 20-m-high river bluff on the Unalakleet River, 50 km east-northeast of Unalakleet. Both deposits appear to be confined to small structural or topographic basins.

A small, isolated patch of Cretaceous or Tertiary conglomerate is exposed in the Sinuk River valley on the Seward Peninsula, 35 km northwest of Nome. The conglomerate is composed largely of poorly-sorted metamorphic debris, which clearly was derived from the Precambrian metamorphic complex that crops out around the conglomerate. Sandstone, shale, and coal are present in minor amounts.

ONSHORE STRUCTURE

The Norton basin is an extensional basin that most likely developed on a basement composed of Precambrian and Paleozoic rocks like those exposed on the Seward Peninsula and St. Lawrence Island. Because grabens typically follow pre-existing zones of weakness in the basement (Illies, 1981), we made a rose diagram from the lengths and strikes of high-angle faults on the southern and western Seward Peninsula to determine whether a preferred fault orientation exists there and whether high-angle faults in nearby Norton basin may have developed along a pre-existing trend of basement fractures (Fig. 5). Rose diagrams for three areas of the peninsula show considerable differences in their predominant fault strikes; a north strike, however, seems to predominate, and northeast and northwest strikes predominate locally. As only 11% of high-angle faults strike north, we conclude that no predominant strike exists for faults on the peninsula. If an analysis of weak zones in the basement offshore would yield rose diagrams like those in Figure 5, offshore basin-forming faults could strike in almost any direction and still be due to pre-existing basement fractures.

The most evident high-angle faults on the Seward Peninsula are two major normal faults that strike nearly east and bound the Kigluaik and Bendeleben Mountains (Fig. 1; Hudson and Plafker, 1978). These faults together extend for about 175 km along the peninsula, and they show a maximum post-Wisconsinan vertical movement of between 6 and 8 m. The Darby Mountains (Fig. 1) were uplifted along other prominent normal faults that strike north, but no evidence for Holocene movement is known from along these faults (Hudson and Plafker, 1978).

Along the east shore of Norton Sound, middle Cretaceous rocks in the Yukon-Koyukuk geologic province are strongly deformed into recumbent and chevron folds and are thrust to the east. Farther east, along the Yukon River, rocks in the upper part of the middle Cretaceous sequence are deformed mainly into broad open folds (Patton, 1973). However, the Nulato No. 1 well penetrated steeply dipping rocks near the Yukon River (Hite and Nakayama, 1980).

Anticlines in the western Yukon-Koyukuk province strike generally north except in the area of the Kaltag fault where axes of anticlinal folds curve sharply to the southwest, indicating large-scale drag along this fault (Patton, 1973; Patton and Tailleur, 1977). Other geologic evidence (Patton and Hoare, 1968) suggests that the Kaltag fault is a right-lateral, strike-slip fault along which 60 to 130 km of separation has occurred. This fault may have been active as early as the middle Late Cretaceous and is inferred to have been active in the early and middle Tertiary (Patton and Hoare, 1968;

Patton and Tailleur, 1977). Offset streams and alluvial deposits attest to between 1 to 2.5 km of Quaternary movement along the fault. The fault has been traced for 450 km northeastward from Unalakleet, along the Yukon River to Tanana.

CONVERSION OF SEISMIC TIME TO DEPTH

To show the structure of the top of basement rocks, two-way seismic travel time to the basement horizon below the northern Bering Sea is converted to depth. Two sources of velocity information exist: interval velocities computed from seismic-reflection data and refraction velocities measured from sonobuoys deployed in Norton Sound. Interval velocities shown in the curve on the left side of Figure 6 were computed from stacking-velocity curves that first were averaged together. The upper part of the interval-velocity curve closely follows the velocity curves derived from sonic logs from the Cape Espenberg No. 1 and the Nimiuk Pt. No. 1 wells. The time-depth curve derived from refraction velocities (M. L. Holmes, unpub. data, 1980) does not differ greatly from the time-depth curve derived from interval-velocity data (right hand graph, Fig. 6). In converting time to depth, we used the time-depth curve derived from seismic-reflection data.

BASIN STRUCTURE

For the purpose of discussion, we divide the region of the northern Bering Sea into three structural areas that are distinguished either by depth to basement or by a difference in strike of major geologic features (Fig. 1). The first structural area lies north of St. Lawrence Island and west of long. 168° W, where the basement is generally less than 2 km below sea level. The second and third structural areas are underlain by subbasins of the Norton basin. These subbasins are separated by a structure, informally called the Yukon horst, which strikes northwest from near the mouth of the Yukon River. The St. Lawrence subbasin lies northeast and east of St. Lawrence Island and south and west of the Yukon horst. Major structures deep in this subbasin strike northwest. The Stuart subbasin lies west and north of Stuart Island and east of the Yukon horst. Major structures in this subbasin strike northeast and east. These three areas are described separately below, in order from west to east.

Seismic sections shown in this paper fall into two groups: five sections show the regional structure and stratigraphy of Norton basin, and five sections show local details. The regional sections are all at the same scale; they show structure with considerable vertical exaggeration (about 10:1 in the upper 1 s) to permit the inclusion of whole long sections. Dips shown on some sections were calculated using a migration program on a hand calculator (Michaels, 1976).

Structural Area North of St. Lawrence Island

The first structural area lies north of St. Lawrence Island (Fig. 1). Multichannel-seismic data from this area are sparse; consequently, most of the structure shown in contours of the basement, or horizon A (Fig. 7), is interpreted from single-channel seismic-reflection data. These single-channel data do not show basement reliably where the basement is at depths greater than about 1.0 km. Although isolated structural lows do exist in this area, seismic and gravity data suggest that these lows have small areas and are filled with strata less than 2 km thick. Because of the shallow penetration of acoustic energy from the single-channel-seismic system, we used gravity data to estimate the depths of structural lows. Dolzhanskiy et al. (1966) reported an almost linear relation between depth of basement in the Anadyr basin and gravity value. For the Norton basin, however, the relationship between free-air-gravity value and depth to horizon A seems to be a quadratic curve (Fig. 8). This relation was derived from data obtained in the area of the Norton basin where CDP-seismic and gravity data were collected in a 10 to 20 km grid of lines. For depths less than 4 km, a coefficient of determination (R^2) of 0.73 results from the least-squares analysis, indicating that a relation exists between gravity value and basement depth.

Structures north of St. Lawrence Island include a possible fault along the north coast of the island, several grabens, and a zone of anticlines between the grabens and the Seward Peninsula (Fig. 7). The north coast of St. Lawrence Island is straight except for a bulge to the north that is underlain by a Quaternary volcanic edifice. The straight coastline and the volcanism have been used as evidence that a fault, possibly a splay of the strike-slip Kaltag fault, lies along the north coast (D. M. Hopkins, oral commun., 1979). We collected common depth point (CDP) seismic data at the east end of the island, across the strike of the supposed fault, but no evidence for a fault is apparent in these data.

Seismic reflection data show that northwest-striking grabens lie north of St. Lawrence Island. Horizon A is at most 3 km below sea level in the grabens, and average gravity values of -10 mgal over many of these grabens indicate that basement is less than 1.5 to 2 km below sea level (Fig. 7). The grabens generally shoal to the northwest so that the basement is very shallow (less than 0.25 km) near the U. S.-Russia Convention Line of 1867.

Low-relief basement anticlines underlie the area between the grabens and the Seward Peninsula (Fig. 7). The anticlines are flanked on the north by a longitudinal normal fault. Strata above basement lap onto the anticlines, and Cretaceous granitic rocks that are exposed on King Island (Hudson, 1977) are uplifted along one of the anticlines. The anticlinal zone strikes 45 degrees across the trend of the Kigluaik and Bendeleben normal faults, which are exposed on the Seward Peninsula (Figs. 1, 9). The anticlinal zone, then, separates the western Seward Peninsula where major recently active normal faults strike west, from the continental shelf north of St. Lawrence Island, where normal faults strike northwest. This difference in strike of faults is mirrored by the difference between the west strike of the gravity low that follows the Kuzitrin River drainage on the peninsula (Barnes and Hudson, 1977) and the northwest grain of gravity anomalies that have been measured over the continental shelf (Fig. 9).

Basement rocks deepen on the north side of the anticlines, west of Port Clarence, so that an isolated structural low lies between the anticlines and the Seward Peninsula in the extreme northwestern part of this structural area (Fig. 7). Single-channel seismic reflection data show a low, but they do not show a reflection from the basement in the area of this low. Gravity values of less than -20 mgal suggest that the low is 2 to 3 km deep. This offshore gravity and structural low is on strike with the topographic low that forms the flooded areas of Port Clarence, Grantley Harbor and the Imuruk basin, and with the gravity low that follows the Kuzitrin River (Fig. 9). The low along the river is interpreted to be due to low-density rocks that fill a series of west-trending grabens (Barnes and Hudson, 1977). On the basis of a 5.7 m.y. maximum age for flood basalt on the Seward Peninsula, Barnes and Hudson (1977) believe that the peninsular grabens began to form in the latest Miocene or earliest Pliocene.

Magnetic data obtained over the continental shelf north of St. Lawrence Island show that isolated clusters of 100- to 300-gamma anomalies occur in an otherwise featureless magnetic field (Department of Commerce, 1969a). One of these clusters occurs around King Island, on which Cretaceous granodiorite is exposed (Hudson, 1977). Cretaceous silicic plutonic rocks around the Norton basin are commonly magnetic. Cretaceous quartz monzonite on the Darby Peninsula of the southeastern Seward Peninsula contains a high amount of magnetite (Miller and Bunker, 1976) and produces a large aeromagnetic anomaly (compare geologic map of Hudson, 1977 with magnetic anomalies in Decker and Karl, 1979b). Also exposed on the Darby Peninsula are Cretaceous alkaline plutonic rocks and Precambrian high-grade metamorphic rocks, all of which are nonmagnetic. Magnetite is a common accessory mineral in Cretaceous granodiorite in the Yukon-Koyukuk province (Miller and others, 1966), and Cretaceous granodiorite exposed on the Yukon delta is magnetic (compare geologic map of Hoare and Condon, 1968, with magnetic anomalies in Decker and Karl, 1977a). Thus, clusters of magnetic anomalies offshore near King Island are most likely due to Cretaceous silicic plutonic rocks. Cretaceous alkaline plutonic rocks could also lie offshore, but they probably would have little or no magnetic expression. The locations of the inferred subcrops of silicic plutonic rocks are shown in Figure 7.

St. Lawrence Subbasin

Structure and gravity maps- The area of the Norton basin comprises the second and third structural areas of the northern Bering Sea (Fig. 1). The structure of the Norton basin is shown by contours drawn on horizon A (Fig. 10), which separates basement rocks of probable Precambrian and Paleozoic age from the basin fill, which is as old as latest Cretaceous or early Paleogene. The second of the three structural areas of the northern Bering Sea is the St. Lawrence subbasin, which is bounded on the east by the Yukon horst and the shallow basement that lies along the west side of the Yukon delta. The south boundary of the subbasin is a major normal fault, called the "south-boundary fault," that strikes northwest. On the southwest side of the subbasin lies a shallow basement platform, from which St. Lawrence Island protrudes. The northwest boundary of the subbasin is arbitrarily placed along long. 168° W. The subbasin is flanked on the north by a shallow basement platform that extends south from the Seward Peninsula.

The predominant strike of faults in the St. Lawrence subbasin is northwestward (Fig. 10). The south-boundary fault and the faults that form a structural low that flanks the Yukon horst on the south all strike northwest. Numerous small faults, most not shown in Figure 10, also strike northwest. The fault-bounded low on the south side of the Yukon horst contains basin fill as thick as 5 km. This low strikes parallel to the Yukon horst near the Yukon delta. Northwestward from the delta, the horst and the low diverge, strata in the low thin gradually, and the low is formed more by dip of the basement toward the low than by faulting. In the westernmost part of the subbasin, the basin deep is formed by both faulting and dip of basement rocks. Overall, the activity of faults that control major aspects of the basin structure was highest adjacent to the Yukon delta.

We do not know precisely how far deep-basin areas extend to the east and southeast near the mouth of the Yukon River; shallow water near the river mouth precluded our collecting seismic reflection data there. South of the river mouth, however, seismic reflection data show that basement rocks are shallow (Fig. 10). A gravity map shows that Bouguer-gravity values of between -10 to +10 mgal were measured over the Yukon delta (Barnes, 1977; Fig. 11). Because of low land elevations on the delta, the difference between Bouguer-gravity and free-air-gravity values is negligible (about 1 mgal for each 5 m of elevation). Consequently, we use the relationship between free-air-gravity value and basement depth (Fig. 8) to suggest that under the northern lobe of the Yukon delta, basement is less than 2 km deep, and is mainly about 1 km deep. Gravity values of +10 mgal, measured along the west side of the delta, suggest that basement is about 0.5 to 1 km deep; this depth agrees well with that interpreted from seismic reflection data obtained 30 km offshore, west of the delta. Hence, we believe that rocks above basement are only about 1 km thick under the northern part of the Yukon delta and that deep parts of the Norton basin end between the western shore of the delta and our easternmost seismic lines in this area.

Contours of offshore free-air gravity data generally mimic structural contours of basement (Figs. 10, 11). The south-boundary fault produces a steep gravity gradient as gravity values decrease by 20 mgal across the fault, and the shallow basement along the west side of the Yukon delta produces relatively high gravity values. Although the basin deep that lies along the south side of the Yukon horst near the Yukon delta has little expression in the gravity data, the deep produces a gravity low of -27 mgal farther west. This gravity value suggests that basement is about 4 km deep, in agreement with the 4 km depth derived from seismic data.

Seismic sections - Seismic line 011 is a regional, north-south section through the western part of the St. Lawrence subbasin (Figs. 10, 12). Basement in the northern part of the line dips gently south from near the Seward Peninsula to where basement is faulted progressively down into a graben, in which basement is at most 4 km below sea level. Faults that bound the graben show a strongly decreasing throw upward. Basement shows considerable relief south of the graben.

Seismic line 009 extends westward from near the Yukon delta through the St. Lawrence subbasin (Figs. 10, 13). Basement is almost 5 km below sea level near the delta. In the west half of the line a lower sequence of rocks that directly overlie basement laps eastward and downward onto basement and then pinches out against basement below the middle of the seismic line. This sequence is overlain by an upper sequence that laps westward and downward onto the lower sequence. Both sequences appear to be parts of fans. Given the predominance of nonmarine rocks at depth in the Anadyr and Hope basins, we believe these sequences to be alluvial deposits. Rocks above about 2 s produce reflections that are essentially parallel and continuous across the section.

The southern part of seismic line 804 (Figs. 10, 14) and the western part of line 813 (Figs. 10, 15) transect the St. Lawrence subbasin. Along line 804, two horsts are evident, and strata that lie over the horsts are arched into structures that show decreasing relief upward. Maximum dip of strata in structures of this type in the basin varies between 2 and 9°. This type of structure is important to the petroleum geology of the Norton basin, as we believe that these structures form likely traps to contain hydrocarbons. These structures could have developed by a combination of two mechanisms: either strata over the horst could be arched by drape across rejuvenated horsts, or the strata could be arched by differential compaction. Consequently, we refer to these structures as "drape or compaction structures." The west end of line 813 (Fig. 15) transects the St. Lawrence subbasin. Drape or compaction structures are evident over the Yukon horst and over another horst to the east.

A seismic section across the south-boundary fault shows the fault to have a throw that exceeds 2.5 km locally (Figs. 10, 16a). The fault has caused major offset of the basement, but offset is barely perceptible in strata that lie over the fault. This pattern is common to nearly all major faults in the basin: major movement along these faults occurred early in the basin history; subsequent fault movement was minor, and the basin deepened by regional subsidence. Reflections from deep strata deposited on the downthrown side of the fault angle down from the fault plane to converge with the basement reflection. We believe that these strata were deposited in an alluvial fan on the downthrown block of the fault.

What we interpret as alluvial deposits are also evident along the west flank of the Yukon horst, shown in the middle of seismic line 8131 (Figs. 10, 16b). Deep reflections there dip downward, away from the horst, and then converge with and terminate against basement. Strata over this horst are arched into a drape or compaction structure. Faults that bound the horst offset basement by about 2 km, yet strata over the horst are essentially unfaulted. On the west side of the horst, the updip ends of some alluvial strata terminate at a subhorizontal horizon reflection that probably stems from an unconformity. This unconformity also forms the nearly flat summit of the horst. Almost every horst in the Norton basin, especially in the Stuart subbasin to the east, also has a nearly flat summit, and all the summits are at about the same depth. These observations suggest that the accordant horst summits were beveled at an unconformity, and, as faults with large throws do not disrupt the unconformity, major faulting preceded the erosion that produced the unconformity.

A band of moderately strong parallel reflections lie just under horizon D (Figs. 10, 16c). The reflections appear at first glance to be highly discontinuous; this appearance, however, is the result of closely spaced normal faults with minor offsets. Expression of these faults die out a short distance above horizon D. That the resolution of seismic data decreases with depth may explain why the faults appear to die out above horizon B.

Many seismic lines in the St. Lawrence subbasin show discontinuous, strong reflections from rocks deep in the basin (Fig. 16c). The high reflection strength means that the discontinuous rocks which cause the strong reflections differ considerably in acoustic impedance from their encasing rocks. Coal (low density and velocity), or crystalline volcanic rock and conglomerate (high density and velocity), could be the cause of the reflections. Some strong reflections have a positive polarity, indicating that volcanic rock or conglomerate is the cause for these reflections, and some positive reflections come from rocks in the distal parts of what we believe are alluvial deposits. As this distal area is an unlikely position for conglomerate to be present, we believe that some of the strong positive reflections are probably due to volcanic rocks. We believe that alluvial fans are common deep in the basin, hence the possibility cannot be excluded that coal could cause other strong reflections.

In the St. Lawrence subbasin, rocks are present in mounds that lie directly on basement (Figs. 10, 16d). The presence of faint reflections from rocks within the mound show that these rocks are poorly stratified. Strata that overlie the mound are arched, probably by differential compaction. We believe that the mound does not comprise basement rocks, rather, the mound is most likely made up of volcanic rocks.

Yukon Horst

The Yukon horst separates the St. Lawrence and the Stuart subbasins and extends northwestward from the Yukon delta towards the Seward Peninsula (Fig. 10). The horst separates the basin into two areas characterized by different strikes of major structural features. During the early history of the basin, the horst extended completely across the basin, so that the horst could also separate the basin into areas that differed in the types of sediment that was deposited. Strata over the horst are arched, forming a drape-or-compaction structure (Fig. 17). Where best developed, the horst is bounded on the east by a precipitous drop across a fault into a deep part of the Norton basin. Maximum relief measured from the top of the horst to the bottom of the flanking deep is almost 3 km. Faults along the west flank of the horst are discontinuous and show smaller throws than the fault along the east flank. The seismic line in Figure 17 shows that strata in alluvial fans lie along the west flank of the horst. The fault that bounds the horst on the northeast offsets strata up to the seafloor and is one of the few major faults that shows relatively recent activity. The horst is expressed well in the gravity data (Fig. 11).

Stuart Subbasin

Structure and gravity maps- The third structural area of the northern Bering Sea is the Stuart subbasin, the eastern part of the Norton basin (Figs. 1, 10). This subbasin is bounded on the west by the Yukon horst and on the north and east by a shallow basement platform. The northern platform extends southward from the Seward Peninsula and in most places the platform terminates at a major east-trending normal fault, called here "the north-boundary fault." Scattered geophysical data obtained over the eastern basement platform suggests that this shallow platform extends east without major structural disruption from the Stuart subbasin to the eastern shore of Norton Sound. Shallow water prevented our collecting data near the Yukon delta; hence, the southern boundary of the Stuart subbasin is not definitely located. However, seismic reflection data from near the delta show that the Stuart subbasin shoals sharply toward the Yukon delta, and as described above, gravity data suggest that only about 1 km of strata overlie basement in the area of the north lobe of the delta. Moreover, east of this lobe, near the southern shoreline of Norton Sound, strongly deformed Cretaceous volcanic and sedimentary rocks of the Yukon-Koyukuk province crop out (Fig. 11). Hence, the Norton basin appears to end between the south shore of Norton Sound and our southmost tracklines.

The structure of the Stuart subbasin is more complex than that of the St. Lawrence subbasin. In the northern part of the Stuart subbasin lies an east-striking horst, informally named the "Nome horst." Faults and small anticlines near the Nome horst, strike nearly east. East and south of this horst, major structures trend northeast. Although seismic reflection data do not show clearly the bottom of the basin deep that lies between the north-boundary fault and the horst, gravity values over this low are about -35 mgal, some of the lowest gravity values recorded over the Norton basin. Hence, the throw of the north-boundary fault may locally exceed 4 km. The north-boundary fault dies out to the west, toward the Yukon horst. To the east, this fault terminates at an intersection with a northeast-trending fault that is down on the west. The intersection of these faults forms a sharp corner in the Norton basin.

Southeast of the Nome horst lies the main and deepest known part of Norton basin. Depths measured there are as great as 6.5 km (Fig. 10), and gravity values there are as low as -35 mgal (Fig. 11). This main part is subcircular in outline and connects across a shallow saddle with the 5-km-deep part of the subbasin that is adjacent to the Yukon horst.

North and east of the deepest part of the subbasin, major faults trend northeast. In places, structural highs are not clearly fault bounded; seismic reflection data show that steep slopes lead from the structural highs to the lows, yet no diffractions are evident. The lack of clear evidence for faults could be due to the presence of alluvial deposits along the basement highs. Where these deposits are poorly sorted and bedded, they can obscure deep geologic structure. Also, basement highs were subaerial when alluvial fans were deposited during the early history of the basin, and fault scarps may have been modified by erosion. We believe that the steep slopes are most likely buried normal faults. The normal faults form a series of narrow northeast-striking structural highs and lows (Fig. 10). Strata that fill the lows are as much as 3.5 km thick, and the lows open to the south into the main and deepest part of the Stuart subbasin.

Magnetic data (Scholl and Hopkins, 1969) show that a prominent magnetic anomaly extends southward from the Darby Peninsula. As mentioned above, Cretaceous quartz monzonite is the source of an aeromagnetic anomaly over the peninsula. Consequently, the offshore magnetic anomaly most likely marks the offshore location of these plutonic rocks. In the eastern Stuart subbasin, northeast-striking normal faults are on line with this magnetic anomaly, and with north-striking normal faults in the Darby Mountains. Hudson and Plafker (1978) could find no evidence for Quaternary offset along major normal faults in the Darby Mountains, and offshore faults show little evidence of offset of shallow rocks. This approximate correspondence in structural trends is the only evidence we have found to suggest that onshore structural trends extend offshore into Norton basin.

Seismic lines- The eastern part of seismic line 813 (Fig. 15) shows that the fault that bounds the east side of the Yukon horst has a throw as large as 2 km, and the basin deep on the downthrown side of the fault is about 4 km deep. Numerous small faults breach the top of the horst and extend upward to the sea floor. Strata thin onto the east flank of the horst. The main part of the basin lies east of the Yukon horst and is filled with as much as 6.5 km of strata.

Seismic line 007 (Fig. 18) extends north from the main part of the basin, across the Nome horst and north-boundary fault to the shallow basement platform that extends south from the Seward Peninsula. At the south end of the line, strong reflections lying over the basement horizon are similar in appearance to the strong reflection that lies at about 3 s on the south side of the Nome horst. These strong reflections in the deep strata could be volcanic rocks or conglomerate interbedded with alluvial deposits. Strata that overlie the alluvial deposits lap onto these deposits and are offset slightly by normal faults that bound the Nome horst on the south. These bounding faults have an aggregate throw on basement of between 3 and 4 km, as shown by seismic-reflection data and by gravity data, which increase by 34 mgal from south to north across these faults. The north-boundary fault shows at least 3 km of offset of the basement on this seismic section, whereas gravity values suggest about 4 km of throw along this fault. Strata thicken from the Nome horst toward this fault, indicating that synsedimentary fault movement occurred. Shallow basement on the north side of the north-boundary fault extends up to the exposed basement rocks on the Seward Peninsula.

Summary of Offshore Structure

To summarize the structure of the northern Bering Sea, we note first that few onshore structures extend offshore. Offshore structures show no obvious strike-slip offset, and structures typical of strike-slip faults, such as anticlines in echelon, are absent. Hence, the offshore location of the strike-slip Kaltag fault is unknown. In the area north of St. Lawrence Island onshore and offshore areas are structurally separated by a zone of anticlines and relatively high gravity values. Two possible extensions of onshore structure into the offshore are: 1) the approximate lineation formed by north-striking normal faults of the Darby Peninsula and by northeast-striking normal faults in eastern Norton basin, and 2) the zone of rifting of possible late Cenozoic age that trends west through the center of the Seward peninsula and that appears to extend into the offshore in the extreme northwest part of the study area. The complex fault patterns of the Seward Peninsula, evident in rose diagrams (Fig. 5), are similar to the complex patterns in the Stuart subbasin.

The Norton basin lies under the eastern half of the northern Bering Sea, east of 168° W. The structure of the westernmost part of Norton basin is that of a crustal downwarp, complicated by the presence of a graben. The intensity of normal faulting increases from the westernmost Norton basin to the Yukon delta. Adjacent to the delta, northwest-trending normal faults formed isolated structural lows as much as 5.0 km deep. The major faults were active early in the history of the basin, then they largely ceased activity. As fault activity diminished, the basin deepened as a result of regional subsidence. Minor reactivation of these faults, or differential compaction of stata over the horst and adjacent grabens, caused strata over horsts to arch into drape or compaction structures. The Yukon horst divides the basin into two structural areas, and during the early history of the basin, the horst was a barrier that could have prevented mixing of sediment transported to the two subbasins. In the northeastern part of the basin, major faults strike east; others in the southeastern part strike northeast. Strata 6.5 km thick fill the deepest part of the Norton basin, adjacent to the north side of the Yukon delta, but deep parts of the basin do not lie under the subaerial part of the delta. Deep strata in the basin were deposited in alluvial fans that are adjacent to basement fault blocks. Discontinuous, strong reflections at depth in the basin could be caused by coal, or crystalline volcanic rocks, or both, that are interbedded with clastic sedimentary rocks.

SEISMIC HORIZONS

Four seismic reflections present on seismic data from large areas of Norton basin were traced through the seismic data. These reflections generally mark significant changes in the reflective character of rocks in the basin, and from deep to shallow, they are designated with letters A through D (Fig. 16c). Horizon A, the deepest reflection that can be correlated throughout the basin, is the basement reflection. Few reflections, if any, are derived from rocks deeper than this horizon. Where horizon A is less than about 2 km deep, it produces a strong primary reflection, multiples of itself, and water-layer reverberations, suggesting that this horizon separates rocks that contrast strongly in acoustic impedence. This horizon also consistently produces refracted arrivals in sonobuoy data.

Horizon B is present only in the deep parts of the Norton basin. This horizon terminates on the flanks of the Yukon horst in both subbasins; hence, we are unsure of the correlation of this horizon across the horst. Reflections between horizons A and B vary considerably in appearance. Some reflections dip down, away from high-standing basement areas; we believe that these reflections derive from alluvial deposits. Other reflections have high amplitudes, are discontinuous, and are locally abundant, especially within the St. Lawrence subbasin. These reflections may be caused by coal or volcanic rocks. In general reflections between horizons A and B are of highly variable strength and in places are nonparallel or discontinuous, or both.

Horizon C separates generally weak and discontinuous reflections below it from generally moderate-amplitude and continuous reflections above. Reflections between horizons B and C overlie the alluvial deposits and lap onto these deposits or onto basement rocks in fault blocks. Considerable subjectivity was used in tracing this horizon; nonetheless, this horizon figures prominently in the discussion of the geologic history of the basin.

Horizon D is the top of a thin rock sequence that produces a distinctive band of strong, parallel reflections. In places, underlying reflections terminate at this horizon, suggesting that at least locally this horizon is an unconformity. However, as we discuss below, this horizon could also result from a boundary caused by the diagensis of silica. Horizon D more consistently produces refracted arrivals than does any other horizon in the basin fill.

Above horizon D, reflections are mostly parallel and continuous over large distances, but they have lower relative amplitudes than do reflections that underlie horizon D. Zones of poorly reflective rocks locally overlie horizon D.

BASIN STRATIGRAPHY

The following description of the stratigraphy of the Norton basin is based on the charater of seismic reflections, on regional geology, and on the velocities measured in basin fill. Cenozoic strata crop out around the periphery of the Norton basin only in scattered, local outcrops, which yield information of doubtful regional significance. Consequently, we can present only a speculative description of the basin stratigraphy.

In the region including the Norton basin, nonmarine rocks are common, and they occur around the basin and deep in the Anadyr and Hope basins, whereas marine rocks are present in the Anadyr basin mainly at shallow depths. On St. Lawrence Island and near Unalakleet (on the east shore of Norton Sound) nonmarine Oligocene sedimentary rocks contain interbedded coal beds and abundant plant debris. Wells drilled in the Hope basin, north of the Seward Peninsula, penetrated 1900 to 2600 m of interbedded sandstone and shale, and conglomerate of probable Cenozoic age. Plant debris are abundant and coal is common in these rocks (American Stratigraphic Co., 1977a,b), suggesting that the rocks were deposited in a nonmarine environment. In the Anadyr basin, Cretaceous, Paleocene, and lower Eocene rocks are chiefly volcanic. However, upper Eocene and Oligocene rocks are predominantly nonmarine, and Neogene rocks were deposited in both shallow marine and nonmarine environments. From these regional geologic relations, we expect nonmarine rocks to be present deep in Norton basin.

The character of reflections in seismic data from the Norton basin suggests that strata deep in the basin were deposited in a nonmarine environment and that shallow strata were deposited in a marine environment. This interpretation is based on the assumption that strata deposited under open-marine conditions produce parallel reflections that are continuous over large distances, whereas strata deposited in a nonmarine environment produce discontinuous, possibly nonparallel reflections. If this assumption is correct, then parallel, continuous reflections between horizons C and D give the deepest indications of a marine environment (Fig. 16c). Rocks above horizon D appear to be largely marine, but some nonmarine rocks may overlie this horizon because reflections are locally discontinous and weak. Below horizon C, reflections are discontinuous, and below horizon B, reflections are nonparallel. These observations suggest that rocks below horizon C were deposited mostly in a nonmarine environment. A transition in environments of deposition is thus inferred from seismic data to be present in rocks of the Norton basin. If the stratigraphy of the Norton basin is similar to that of the Anadyr basin, then rocks below horizon C in the Norton basin would be predominantly nonmarine and of probable Late Cretaceous and Paleogene age, whereas strata above horizon C would be predominantly marine and possibly of Neogene and Quaternary age.

Horizon D may result from either of two fundamentally different geologic boundaries: a diagenetic front or an unconformity. The abrupt diagenetic conversion of the silica of diatom frustules (opal-A) to siliceous cement (opal-CT) produces a reflector that in some areas of the Bering Sea parallels or simulates the sea bottom and is locally discordant with strata (Creager and Scholl, et al., 1973; Hein et al., 1978). The diagenetic reflector simulates the sea bottom because the silica conversion is strongly temperature dependant. On seismic sections from regional outer-shelf areas of the Bering Sea, a bottom-simulating reflection (BSR) occurs between 1.0 and 2.0s, and the BSR is interpreted to be due to the diagenesis of diatomaceous rocks (Hammond and Gaither, 1981).

In the St. Lawrence subbasin, horizon D may be a BSR produced by the diagenesis of silica for the following reasons: 1) the flatness of horizon D conflicts locally with the gentle dip of over- and underlying reflections, 2) on seismic sections, the horizon occurs between 1.0 to 1.5 s, within the 1.0 to 2.0s zone noted for other BSR's under the shelf, 3) the predominant frequency of this horizon is about 10Hz whereas that of adjacent reflections is 25 to 30 Hz, so that locally the horizon appears to overprint the higher-frequency reflections, and 4) this horizon produces refracted arrivals in sonobuoy data more consistently than does any other horizon in the basin fill; acoustic velocities increase by about 35% across this horizon (Fig. 19b). The major problem in the interpretation of horizon D as a BSR is that we expect that the influx of terrigenous debris from the Yukon River would have so reduced the proportion of diatoms in basin sediment that no pronounced diagenetic boundary would have formed.

Alternatively, if horizon D is not a BSR, then it is an unconformity because of the discordance of reflections mentioned above. In this case, the horizon may be at the base of Pliocene rocks. The presence of latest Miocene and Pliocene flood basalts on the Seward Peninsula and their close spatial association with an east-trending zone of rifting along the axis of the peninsula suggest that the peninsula underwent a period of extension that began in the latest Miocene or Pliocene (Barnes and Hudson, 1977). This extension of rocks under the peninsula may have been recorded in the Norton basin by the renewed subsidence that resulted in burial of horizon D, which is at least locally an unconformity. If so, then rocks above this horizon would be of Pliocene and Quaternary age.

Until lithologic data are available from offshore wells, our interpretation of the geologic cause of horizon D must remain ambiguous. However, we prefer the interpretation that this horizon is a BSR that results from diagenesis of diatomaceous rocks.

Acoustic velocities measured in rocks in and below the Norton basin can be used to assign preliminary ages to these rocks. Acoustic velocity in sedimentary rocks is a function of both geologic age and depth of burial (Faust, 1951; Lang, 1980). Therefore, in Figures 19a and b, velocity is plotted against depth to show the variation of velocity with depth among rocks of the same age and to determine whether age causes data from particular rock units to cluster on the velocity-depth graph.

The oldest rocks exposed in the area of the Norton basin are Precambrian and Paleozoic rocks on the Seward Peninsula and on St. Lawrence Island. Greene (1970) measured near-surface refraction velocities in these rocks on the Seward Peninsula near Nome. Sonic logs from the Nimiuk Point No. 1 and Cape Espenberg No. 1 wells (Fig. 2), which bottomed in Precambrian(?) schist and Paleozoic(?) carbonate rocks, give the acoustic velocities in such rocks at depths of 2 to 3 km (Fig. 19a).

Middle Cretaceous rocks crop out in the Yukon-Koyukuk province, and sonic-log data from the one well drilled in these rocks (Benedum and Associates, Nulato No. 1; Fig. 2) show the variation of velocity with depth in these rocks. Refraction velocities measured in Mesozoic rocks in the Anadyr basin (Dolzhanskiy and others, 1966) are close to the velocities measured in the middle Cretaceous rocks of the Yukon-Koyukuk province.

The Nimiuk Point No. 1 and Cape Espenberg No. 1 wells penetrated isolated layers of crystalline volcanic rocks (American Stratigraphic Co., 1977 a, b). This type of rock probably causes the high acoustic velocities (4.5-5.0 km/s) measured above basement. These rocks have acoustic velocities that are similar to acoustic velocities in Cretaceous rocks of the Yukon-Koyukuk province. Some velocities measured deep in these wells, above basement, are the same as refraction velocities measured in Paleogene sedimentary rocks in Anadyr basin (Dolzhansky and others, 1966).

These data on age, depth, and acoustic velocity of rocks in the region of the northern Bering Sea suggest that three groups of rocks can be distinguished on the basis of their depth and acoustic velocity. Velocities over about 5.0 km/s are indicative of Precambrian and Paleozoic rocks. The velocity-depth zone of rocks in the Yukon-Koyukuk province is characteristic either of those sedimentary rocks or of crystalline volcanic rocks. And the velocity-depth trend from the Nimiuk Point and Cape Espenberg wells is characteristic of Cenozoic sedimentary rocks.

When refraction velocities that were measured along interpreted horizons A, B, C, and D and along other horizons in the Norton basin are compared to velocity-depth criteria for the three rock groups described above, a good case can be made that horizon A, the basement horizon, is the top of Precambrian and Paleozoic rocks (Fig. 19b). Only three of 29 velocities recorded along this horizon are characteristic of Cretaceous sedimentary rocks. As described previously, inference from regional geology suggests that Precambrian and Paleozoic rocks lie at some depth under the basin, and velocity data suggest that these rock lie directly under the basin fill.

Horizon B presents the most ambiguous data; some refraction velocities measured on this horizon are similar to acoustic velocities of Cenozoic sedimentary rocks, others to velocities of crystalline volcanic or Cretaceous sedimentary rocks. If as we suggested above, rocks between horizons A and B are interbedded coal, volcanic, and sedimentary rocks, the high velocities measured on horizon B indicate crystalline volcanic rocks, whereas the lower velocities indicate the interbedded sedimentary rocks. As coal has a lower acoustic velocity than encasing rocks, refracted waves from a coal bed are not measured at the surface.

Acoustic velocities measured on horizons C and D are similar to velocities that are characteristic of Cenozoic sedimentary rocks. This result suggests that most of the basin fill is of Cenozoic age. As mentioned by Scholl and Hopkins (1969), the presence of Oligocene sedimentary rocks around the Norton basin suggests that some fill in the basin is at least that old.

An estimate of the maximum probable age of rocks in Norton basin comes from the direction of sediment transport observed in middle Cretaceous (Albian and Cenomanian) rocks of the Yukon-Koyukuk province. Along the east coast of Norton Sound, middle Cretaceous sediment was transported from the Seward Peninsula and from part of the area now submerged beneath Norton Sound (Patton, 1973). The direction of sediment transport suggests that the area of what is now the Norton basin was exposed during the Albian and Cenomanian; hence, the oldest strata in the basin would be post-Cenomanian in age.

Another estimate of the age of the oldest basin fill stems from the possibility that the Norton basin formed because of extensional stress that developed along the Kaltag fault, or along a splay of this fault. The Kaltag fault is a major right-lateral, strike-slip fault that shows between 60 and 130 km of separation of onshore geologic features. The projected location of the fault offshore, southwest of Unalakleet (Fig. 2), is near the southern limit of the Norton basin. Also, the area of most intense faulting in, and the deepest parts of the basin are adjacent to this projected trend. The time when major movement occurred along the fault is not well established, but it probably was middle Late Cretaceous through early Tertiary (Patton and Hoare, 1968), the time during which we believe the Norton basin began to form.

In some extensional basins, the chemical composition of volcanic rocks becomes markedly alkaline when rifting begins (Neumann and Ramberg, 1978). For example, in the Great Basin of the western United States, mainly calc-alkaline volcanic rocks were extruded before rifting began, whereas afterward, mainly a bimodal suite of alkaline basaltic and rhyolitic rocks were extruded

(Christiansen and Lipman, 1972). Best et al. (1980) describe the problems they encountered while trying to deduce the sequence of tectonic events in the Great Basin from the composition of volcanic rocks. Although Paleogene volcanic rocks on St. Lawrence Island include basalt and soda rhyolite, these rocks are not a true alkaline suite. However, calc-alkaline volcanic rocks with K/Ar dates of 70 to 55 m.y. fill grabens or half grabens near and east of Unalakleet (Patton et al., 1980; W. W. Patton, Jr., unpub. data, 1981). We believe that the Norton basin began to form contemporaneously with this latest Cretaceous and early Paleogene extension that formed the onshore grabens.

In summary, we infer from geophysical data and regional geology that the Norton basin is floored by Precambrian and Paleozoic rocks similar to the diverse rocks that are exposed on the Seward Peninsula and on St. Lawrence Island. A thick section of Cretaceous rocks, like those in the Yukon-Koyukuk province, most likely does not lie under the basin. The fill in the Norton basin may be as old as early Late Cretaceous, but in our opinion, the oldest rocks above basement are latest Cretaceous or Paleogene interbedded coal, and volcanic and nonmarine clastic rocks that form alluvial fans. Further, we believe that the basin fill below horizon C is composed of Paleogene, mainly nonmarine deposits, and that the fill above that horizon is Neogene, mainly marine rocks (Fig. 4). We state tentatively that the cause for horizon D in the St. Lawrence subbasin is a diagenetic front that is produced by conversion of silica in diatom frustules to siliceous cement.

GEOLOGIC HISTORY

The geologic history of the area of the Norton basin includes a complex series of Late Jurassic and Cretaceous events that metamorphosed and deformed basement rocks (Patton and Tailleur, 1977; Patton et al., 1977; Roeder and Mull, 1978). The high degree of tectonic activity in this area is suggested by the episodic Cretaceous regional magmatism (Fig. 20). As described in the section concerning regional geology, a crustal suture is present along the eastern and somewhere near the southern shore of Norton Sound. This suture separates Precambrian and Paleozoic rocks that overlie Precambrian crystalline continental basement on the north and west from Cretaceous volcanogenic rocks that are thought to overlie late Paleozoic and early Mesozoic oceanic crust on the south and east (Patton et al., 1977). The suture may be a relic of geologic events that took place in the Late Jurassic and Early Cretaceous when the continental block that includes the Brooks Range and the Seward Peninsula collided with a subduction zone and an oceanic island arc.

During the collision, the Seward Peninsula had a different orientation, relative to the Brooks Range, than the peninsula does now. Presently, rocks in the central Brooks Range trend west; at the west end of the range, the rocks change trend from west to south; and the rocks then trend south through the Seward Peninsula (Fig. 3). The peninsula must be rotated 90° to the east to restore its Late Jurassic and Early Cretaceous position relative to the Brooks Range (Patton and Tailleur, 1977).

During the Late Jurassic and Early Cretaceous (about 160 to 120 m.y.) the rocks of the Brooks Range and the Seward Peninsula formed a continental block that was partly subducted to the south beneath an oceanic plate that supported a magmatic arc. The marine calc-alkaline volcanic rocks, chiefly of Neocomian age, in the Yukon-Koyukuk province are thought to have been produced by that magmatic arc. Evidence that oceanic crust was thrust to the north over rocks now exposed in the Brooks Range includes: 1) the klippen of ophiolite that overlie rocks near the crest of the Brooks Range, and 2) the lower units of Albian and Cenomanian conglomerate along the north margin of the Yukon-Koyukuk province that are rich in ophiolite debris. Younger units of the marginal conglomerate contain mainly debris from Precambrian and Paleozoic metamorphic rocks. This depositional sequence in the conglomerate shows that the ophiolite was on top of rocks in the Brooks Range and was stripped off first. Middle and Late Jurassic ages on layered gabbros indicate the time when the ophiolite was emplaced over the continental rocks (Patton et al., 1977).

The continental block was subducted until the subduction zone ceased to function, perhaps during the Early Cretaceous (Fig. 20). While the continental crust was depressed beneath the obducted oceanic crust, the continental rocks were metamorphosed to blueschist facies. Evidence for the regional metamorphism comes from the polymetamorphic history of rocks in the southern Brooks Range and on the Seward Peninsula. Petrographic examination of schists from the southern Brooks Range and the Seward Peninsula reveals that the schists were first blueschists and then were partly overprinted by greenschist facies metamorphism (R. B. Forbes, oral commun., 1981). A histogram of the number of K/Ar ages versus age for micas in schists from the southern Brooks Range shows three peaks: late Precambrian, Devonian, and Early Cretaceous (130 to 100 m.y., Turner et al., 1979). The peak of Early Cretaceous ages contains most of the measured dates and reflects the regional metamorphism that may have been caused by burial of continental crust beneath the obducted oceanic crust. In the southern Brooks Range, plutonic rocks yield Early Cretaceous, and some give Late Cretaceous K/Ar dates; however, the rocks also give Devonian, and possibly Precambrian, U/Pb and Pb/Pb ages (Dillion et al., 1979, 1980). Thus, these plutonic rocks underwent the same Early Cretaceous heating as the schists. Metamorphic rocks from the Seward Peninsula, yield Cretaceous K/Ar dates and Precambrian Rb/Sr dates (Sainsbury, 1975; R. B. Forbes, oral commun., 1981). However, some Late Cretaceous ages from high-grade metamorphic rocks reflect heating caused by nearby intrusives (Bunker et al., 1977). The Early Cretaceous K/Ar dates mark the end of the regional metamorphic event; the beginning of metamorphism probably coincided with the Late Jurassic beginning of thrusting in the Brooks Range. This thrusting reached peak intensity as early as the end of the Neocomian (Crane, 1980) or as late as the Albian (Mull, 1979). In summary, radiometric-age data show that during the Late Jurassic and Early Cretaceous, rocks in large areas of the Brooks Range and the Seward Peninsula were metamorphosed. Also, structural and stratigraphic data show that, mainly during the Early Cretaceous, these rocks were thrust to the north and strongly deformed. As we believe that basement rocks under the Norton basin are similar to rocks exposed on the Seward Peninsula, the Early Cretaceous heating and thrusting also affected basement rocks under the basin and probably destroyed the capability of these rocks to generate hydrocarbons about 50 m.y. before the basin began to form.

The presence of abundant ophiolite debris in conglomerate in the Yukon-Koyukuk province shows that oceanic crust was uplifted on top of the Brooks Range. The oceanic crust rose partly by thrusting, but mainly by isostatic rebound of the relatively low-density subducted continental crust; this rebound began once subduction ceased. Erosion of the uplifted ophiolite progressively removed overburden from the subducted continental crust and caused continued uplift of the ophiolite and underlying crust. While isostatic rebound and erosion progressed, overburden pressure in the subducted continental crust would be reduced, and as thermal equilibrium was reestablished after subduction ceased, the temperature of the subducted crust would rise. Decreasing pressure and increasing temperature could have caused the blueschist to convert partly to greenschist.

During the Albian and Cenomanian (about 108 to 92 m.y.; time scale from Lanphere and Jones, 1978; van Hinte, 1978), elevation of the Brooks Range, Seward Peninsula, and part of the area under the Norton Sound provided abundant debris to the Yukon-Koyukuk province (Patton, 1973). Hence, the area of the Norton basin was exposed and deeply eroded at this time. During this period, volcanism occurred throughout the region from west-central Alaska to eastern Siberia. Volcanism was active concurrently with deposition in the Yukon-Koyukuk province, so that rocks in the province are mainly volcanogenic.

During the middle Cretaceous (110 to 85 m.y.) granitic plutons intruded rocks of the Yukon-Koyukuk province, the eastern Seward Peninsula, St. Lawrence Island and the Chukotsk Peninsula. This plutonic episode includes potassium-rich, silica-poor rocks (107 to 105 m.y.) that lie close to the suture between continental and oceanic crust. The unusual composition of these rocks suggests that they were intruded along a conduit to the deep mantle (Miller, 1972).

In the Late Cretaceous (about 85 to 70 m.y.), during a time of east-west compression, the Seward Peninsula was rotated 90° counterclockwise to its present position relative to the Brooks Range (Patton and Tailleur, 1977). Rotation of the peninsula caused major deformation of Cretaceous rocks in the Yukon-Koyukuk province, and some evidence suggests that Paleozoic rocks of the peninsula were thrust eastward over Neocomian volcanic rocks of the province. Uplift of these Cretaceous rocks and removal of a thick overburden (about 3 to 5 km) is suggested by the high vitrinite reflectances (2.5 to 3.5%) measured in samples of these rocks from along the eastern shore of Norton Sound (Nos. 15 to 23, Table 1, Fig. 21). During this Late Cretaceous time, a zone of eastward thrusting extended south from near Cape Lisburne (Fig. 2) through the eastern Seward Peninsula and along the eastern shore of Norton Sound (Patton and Tailleur, 1977). The eastward thrusting may have been accompanied by movement along the strike-slip Kaltag fault. If the Norton basin formed as a pull-apart basin along this fault, then the earliest time the basin could have formed is between 85 and 70 m.y. ago. The east-west compression occurred contemporaneously with plutonism and volcanism in the region including the Yukon-Koyukuk province and Siberia.

During the latest Cretaceous and early Paleogene (70 to 55 m.y.) regional extension occurred in west-central Alaska, forming northeast-trending grabens and half grabens that are filled with calc-alkaline volcanic rocks. The regional extension probably caused the Norton basin to form; however, some mechanism caused major extension to be concentrated in the small area of the basin. The mechanism may have involved reactivation of the Kaltag fault.

The Norton basin initially subsided by block faulting along major normal faults. The presence of alluvial fans in the deep parts of the basin suggests that considerable relief attended the fault-controlled subsidence and that the basement fault blocks were subaerially eroded. Deposition of sediment in fans suggests that as relief developed the rate of subsidence at least temporarily exceeded the rate of sedimentation. If the west-flowing drainage of the middle Cretaceous that delivered sediment to the Yukon-Koyukuk province still existed at the time when the basin relief formed, then the northeast-trending structural lows in the east part of the Norton basin, could have disrupted this antecedent drainage, so that locally closed drainage systems could have developed, and lacustrine deposits could have been laid down.

The Nunivak arch, a basement high beneath the southern Bering Sea (Scholl and Hopkins, 1969; Marlow et al., 1976; Fig. 2), could have been part of the cause of the nonmarine environment of deposition in Norton basin by forming a barrier to a transgressive southern ocean until the late Cenozoic. The crest of the arch extends from near Nunivak to St. Matthew Island and thence to the Chukotsk Peninsula. The arch formed during the Late Cretaceous or early Tertiary and was subaerially exposed at times during the Cenozoic (M. S. Marlow, oral commun., 1981). Presently, much of the crestal area of the arch is buried by less than 0.25 km of late Cenozoic rocks.

Major fault movement in the Norton basin ceased before erosion that cut the accordant summits of the horsts and before deposition of rocks over horizon C, the presumed base of Neogene rocks. After fault-controlled subsidence ceased, subsidence of the basin became regional. An arm of the ocean entered the Norton basin for the first time, perhaps during the early Neogene. Neogene marine rocks were deposited throughout the basin, and a predominantly marine environment has existed in the basin ever since. Herman and Hopkins (1980) reported that the Bering Sea land bridge separated the Arctic from the Pacific Ocean during the late Neogene and that the bridge was finally breached by the ocean about 3.5 m.y. ago. Hence, some late Neogene rocks in the basin could be nonmarine. Because of the shallowness and flatness of the seafloor beneath Norton Sound, minor fluctuations of sea level cause exposure or inundation of large areas, as happened repeatedly during the Pleistocene. The most recent rise in sea level inundated the area of Norton Sound about 9500 years ago, and the presently active north lobe of the Yukon delta formed about 5000 years ago (Nelson and Creager, 1975).

During the latest Miocene, Pliocene, and Quaternary, basaltic volcanism occurred in the region of the northern Bering Sea, and locally abundant volcanic rocks were extruded onto land areas around the Norton basin (Hoare and Coonrad, 1980). Seismic-reflection data show no evidence that these volcanic rock are present extensively under the northern Bering Sea. Latest Miocene and Pliocene flood basalts are present on the Seward Peninsula close to an east-trending zone of rifting along the axis of the peninsula, suggesting that the peninsula underwent a period of extension that began in the latest Miocene or earliest Pliocene (Barnes and Hudson, 1977). This extension may have caused reinvigorated subsidence in the Norton basin. During the Quaternary, offset streams and disrupted alluvial deposits show that the Kaltag fault was active. This reactivation of the Kaltag fault, however, has not resulted in recurrent major activity along large normal faults in the Norton basin.

PETROLEUM GEOLOGY

As shown in the preceding sections, rocks that fill the Norton basin are as much as 6.5 km thick and are of probable Cenozoic age, although some uppermost Cretaceous rocks could be present locally at depth. The basin formed as a rift. Klemme (1980) has stated that rifted basins tend to have high geothermal gradients and large traps for hydrocarbons and that 35% of rifted basins contain giant oil fields. These general characteristics of rifted basins, together with the thickness and probable age of rocks in the Norton basin, suggest that this basin could contain hydrocarbon resources. The U.S. Geological Survey (Dolton and others, 1981) reports that in the statistical mean of its basin assessment, the Norton basin could contain 0.2 billion barrels of oil and 1.0 trillion cubic feet of gas. The proposed date for a lease sale in the area of the Norton basin is November, 1982; outlines of the proposed sale areas are shown in Figure 21.

The purpose of this section is to describe the petroleum geology of the Norton basin as that geology is understood in advance of drilling. Only three wells from which public data can be obtained have been drilled near the Norton basin. Two lie north of the Seward Peninsula, in Hope basin; the third penetrated Cretaceous rocks east of the Norton basin (Fig. 2). A continental offshore stratigraphic test (COST) well was drilled in the basin in 1980 (Fig. 21); however, information from that well is not yet public. The paucity of well data and of information from small, widely scattered exposures of Tertiary rocks around the basin makes it necessary to infer the petroleum geology by indirect methods. Here, we briefly describe organic-geochemical and reservoir-property data from some onshore rocks, and then we discuss the inferred characteristics of basin rocks.

Source-Rock Data

To determine whether rocks exposed around the Norton basin could be sources for hydrocarbons, outcrop samples were collected from St. Lawrence Island, from the Seward Peninsula, and from the Yukon-Koyukuk geologic province. These samples were analyzed for source richness by means of solvent extraction of C_{15+} hydrocarbons and determination of the amount of organic carbon and for thermal maturity by means of vitrinite reflectance and thermal alteration index (TAI).

Criteria for evaluating the ability of rocks to produce hydrocarbons (Tissot and Welte, 1978; Hunt, 1979; GeoChem Laboratories, Inc., 1980) are that clastic rocks that are source rocks for liquid hydrocarbons generally contain at least 0.5% organic carbon and that good source rocks contain about 2%, whereas carbonates that are sources for liquid hydrocarbons contain at vitrinite attains values between 0.5 and 0.6%, or when the TAI is 2.2. Oil generation ends when vitrinite reflectance is between 1.35 and 1.50%, or when the TAI is 3.4.

Samples of Paleozoic and lower Mesozoic carbonate rocks were collected from St. Lawrence Island and from the eastern shore of Norton Sound. Three samples from the island (Nos. 7, 9, and 10, Table 1 and Fig. 21) contain between 0.16 and 0.41% organic carbon, and herbaceous and woody kerogen predominate in the samples. TAI values show that organic matter in these samples is thermally immature. This result accords with field observations that these rocks are not metamorphosed. One sample from carbonaceous streaks in carbonates from the eastern shore of Norton Sound (No. 24, Table 1 and Fig. 21) contains over 1% organic carbon, and only coaly kerogen is present. In contrast to the low degree of thermal alteration of carbonate rocks on St. Lawrence Island, vitrinite- reflectance values from the eastern shore are high enough that organic matter there could produce only gas, and the TAI suggests that the matter is too highly thermally altered to produce any hydrocarbons.

Samples of upper Paleozoic and Mesozoic clastic rocks were obtained from St. Lawrence Island and from the Yukon-Koyukuk geologic province. The samples of Permian and Triassic shale and Triassic shale from the island (Nos. 5 and 7) contain about 2.1% organic carbon. Herbaceous and coaly types of kerogen predominate in these samples. TAI values show that organic matter in the sample of Permian and Triassic shale is too highly thermally mature to produce oil, whereas organic matter in the Triassic shale is immature for oil. This difference in the level of thermal alteration may be the effect of local heating by Cretaceous plutonic rocks that intruded rocks now exposed on St. Lawrence Island; thermal metamorphism caused by the plutons extends as much as 1.5 km into the country rocks (Csejtey et al., 1971).

Clastic rocks in the Yukon-Koyukuk province are mainly of late Early and early Late Cretaceous (Albian and Cenomanian) age (Patton, 1973). In outcrop samples of these rocks (Nos. 15 to 23), amounts of organic carbon range from 0.31 to 1.87% (excluding coal and coaly shale), with a mean value of 0.88%. Herbaceous and woody kerogen predominate in the non-coal samples. Along the eastern shore of Norton Sound, vitrinite reflectance values range from 1.88 to 3.45%, with a mean of 2.51%. TAI values are broadly scattered between 2.2 and 4.2, with a small majority of values in the range of 3.0 to 4.2. Two outcrop samples from along the Yukon River (No. 23) show vitrinite reflectances of 1.15 and 1.19% and TAI values of 1.8 to 2.2. Both types of measurements indicate that at least locally, rocks along the river are less altered thermally than rocks along the eastern shore of Norton Sound. However, data are too sparse to determine whether rocks of the province manifest a regional, eastward-decreasing gradient in thermal alteration.

A problem in determining the level of thermal alteration of the middle Cretaceous clastic rocks is that TAI values from these rocks suggest a consistently lower level of thermal alteration than do vitrinite-reflectance values (Fig. 22). In most cases a first peak in the histograms of vitrinite reflectance is clearly expressed, suggesting that the reflectances were not measured on reworked material. To resolve the conflict between the TAI and vitrinite-reflectance data, seven samples of the Cretaceous rocks were analyzed by Rock-Eval pyrolysis (G. E. Claypool, written commun., 1981; Table

2). Only 0.015 to 0.045 mg/g of hydrocarbons already present in the rock samples were evolved under the S_1 peak, and the hydrogen indices of these samples are very low. Furthermore, most hydrocarbons produced by the thermal cracking of kerogen (S_2) evolved only when the samples were heated to temperatures as high as 475 to 530°C. Thus, although the samples contain 0.74 to 1.87% organic carbon, they can produce only meager amounts of hydrocarbons. These pyrolitic data agree with the vitrinite-reflectance data (Table 2) that the Cretaceous rocks have already produced hydrocarbons. Hence, we use values of reflectance to indicate the level of thermal alteration of these clastic rocks. Values of vitrinite reflectance indicate that the organic matter in the Cretaceous rocks is too highly thermally altered to generate oil, but that the organic matter is capable of producing hydrocarbon gas. The Benedum and Associates Nulato No. 1 well (location shown in Fig. 2) penetrated 3663 m of these Cretaceous rocks and yielded no oil or gas shows (Hite and Nakayama, 1980).

Samples of Tertiary rocks were collected from St. Lawrence Island, from the Seward Peninsula, and from the Yukon-Koyukuk province. Tertiary rocks on St. Lawrence Island include Paleocene volcanogenic and Oligocene non-volcanic and volcanic rocks that are exposed in local outcrops. Organic-geochemical data are available only from the Oligocene rocks (Nos. 1 to 4, Table 1, Fig. 21) and the samples are mainly coal. Vitrinite-reflectance values range from 0.22 to 0.39%, with a mean value of 0.31%. These values and the TAI values, which are in the range of 1.4 to 2.2 suggest that organic matter in Oligocene rocks on the island is thermally immature. On the Seward Peninsula, thin, locally derived deposits of probable Tertiary age overlie Precambrian and Paleozoic metamorphic rocks. The one non-coal sample (No. 11) is a sandstone that contains 0.37% organic carbon in mainly herbaceous kerogen. Vitrinite reflectances from this sandstone and from a sample of coal are near 0.9% and indicate that organic matter in the samples is mature for oil. This conclusion is supported in part by TAI values that range from 1.4 to 3.0. In the Yukon-Koyukuk geologic province, Oligocene and Oligocene(?) deposits occur in badly slumped exposures of clay and coal (Nos. 12 to 14). Vitrinite reflectances average 0.31% and agree with TAI values of 1.0 to 1.4, which indicate that organic matter in these rocks is immature. One sample contains large amounts of extractable C_{15+} material, although less than 10% of that material is hydrocarbons.

The only organic-geochemical data from the offshore area show the composition of gases in near bottom sediment (Kvenvolden et al., 1979, 1981; Kvenvolden and Claypool, 1980). Gas from the largest known offshore seep is mainly CO_2 (98%), and the gas there contains only 0.1% of hydrocarbon compounds. Kvenvolden and Claypool (1980) reported that the CO_2 is most likely derived from the thermal decarbonation of basement carbonate rocks and that the hydrocarbons are probably the result of low-temperature diagenesis of immature organic matter in the basin fill. These conclusions followed from an analysis of gaseous and gasoline-range hydrocarbons and of carbon-isotopic data. Hydrocarbon gases from sites away from the main seep are mainly of biogenic origin, and the gases are thought to be derived from peat buried in the upper 4 m of sediment (Kvenvolden and others, 1979).

The main gas seep described above has clear expression in multifold seismic data, including the downward bending and complete disruption of reflections (Fig. 23). The seep lies under an area of 30 km^2 where basement is about 2 km deep, so that 60 km^3 of basin fill is gas charged to varying degrees, mainly by CO_2. At two places on the seismic section, disruptions of reflections extend nearly to the seafloor, suggesting that gas seeps from the seafloor. Seepage is shown by gas bubbles that rise from the seafloor, as seen with the aid of underwater television (Kvenvolden et al., 1979). Gas may rise through the basin fill along a fault. When basement reflections on opposite sides of the seep are projected to the center of the seep, the projected reflections are offset vertically by about 0.8 km.

Multifold-seismic data show features that suggest that gas is present commonly in near-surface sediment (Fig. 24). These features include local bright spots, downward sagging of reflections, and a strong low-frequencey reflection. These seismic data show only large gas zones; small shallow zones probably exist, but high-resolution seismic systems (3.5 and 12 kHz) give generally poor penetration into near-bottom sediment. That the area of the Norton basin was repeatedly a subaerial deltaic plain during the Pleistocene poses problems in determining which acoustic anomalies result from gas and which from complex near-bottom stratigraphy. Upward bending of reflections under many acoustic anomalies indicates that the anomalies derive from local course-grained deposits that are interbedded with mud and silt. These anomalies are not shown on Figure 24. The most abundant evidence for shallow gas is found in a strong, low-frequency reflection and accompanying local downward sag of underlying reflections that are evident in unfiltered and undeconvolved seismic data obtained throughout a large area north of the Yukon delta. This possibly gas-charged area lies directly over the deepest known part of the Norton basin, suggesting that some hydrocarbon gas may have been produced thermally, deep in the basin. However, carbon-isotopic analyses have shown that all hydrocarbon gas is biogenic in samples from shallow cores obtained away from the site of the main seep (Kvenvolden et al., 1981). Also, Marlow and Cooper (1980) describe a similar correspondence between deep-basin and gas-charged areas in St. George basin. They proposed that during Pleistocene times of low sea level, basin areas were topographic lows and, hence, were possible sites for swamps or lagoons. The subsequent shallow burial of deposits rich in organic carbon could cause biogenic gas to evolve. Consequently, the near-surface acoustic anomalies in the Norton basin are most likely indications of biogenic gas. Nearly all acoustic anomalies that can be attributed to gas are from shallow features. No deep anomalies, such as bright spots with negative reflection polarity or flat spots, are evident.

In summary, although in most cases organic-geochemical data from onshore rocks are too sparse to allow firm conclusions, these data suggest that Paleozoic and lower Mesozoic rocks along the western flank of the Norton basin contain sufficient organic carbon to be considered potential sources for hydrocarbons. The mainly herbaceous and woody kerogen suggests that hydrocarbon gas or condensate would be derived from these rocks. The low level of thermal alteration of these rocks contrasts strongly with the high degree of metamorphism of coeval rocks that lie under much of the Seward Peninsula and that are exposed locally along the eastern shore of Norton Sound. Over large areas, these latter rocks are metamorphosed to blueschist or greenschist and to marble. Cretaceous rocks of the Yukon-Koyukuk province that are exposed along the eastern shore of Norton Sound are overmature for oil and contain predominantly herbaceous, woody, and coaly kerogen; hence these rocks are possible sources for hydrocarbon gas. However, evidence from seismic-refraction data presented in the preceding paper, suggests that these Cretaceous rocks are not present offshore, below the Norton basin. With few exceptions, Paleogene rocks that are exposed around the basin are thermally immature. These rocks were deposited around the periphery of the basin and probably have never been deeply buried. They contain herbaceous and woody kerogen; and if deeply buried, they could be sources for hydrocarbon gas or condensate.

Reservoir-property Data

Levorsen and Berry (1967) state that fair reservoirs have porosities of from 10 to 15% and permeabilities of from 1 to 10 md and that poor reservoirs have porosities of from 5 to 10% and permeabilities of less than 1 md. According to these criteria, the values of porosity and permeability of outcrop samples from St. Lawrence Island and from the Yukon-Koyukuk province (Table 3) show that most of the outcrop samples from around Norton Sound have poor reservoir properties. A single sample of Permian and Triassic graywacke from St. Lawrence Island (No. 8, Table 3 and Fig. 21) has very low porosity and permeability. Most of the data are from Cretaceous sandstone in the Yukon-Koyukuk province. These rocks have porosities in the range of 0.6 to 10.2%, with a mean value of 3.4%, and their permeabilities are between 0.01 and 2.79 md, with a mean value of 0.25 md. These results from outcrop samples of Cretaceous rocks agree with results from the only well drilled nearby: middle Cretaceous rocks in the Nulato No. 1 well contained no porous zones (Hite and Nakayama, 1980). If the high values of vitrinite reflectance that have been measured in samples of these rocks are correct, these values indicate that the rocks were once deeply buried and that they probably lost porosity by compaction. Another possible cause for the poor reservoir properties of these rocks is the laumontite, reported by Hoare, Condon, and Patton (1964), that cements the nonporous sandstone that is exposed in an area of about 5200 km^2 in the province. These authors observed that the laumontite occurs mainly in sandstone that is rich in volcanic detritus. Hence, because of compaction, partial zeolization, and the resulting low porosities and very low permeabilities observed in them, these rocks would be poor reservoirs for hydrocarbons.

Only three samples of Tertiary rocks were analyzed; all samples are of Oligocene age and are from St. Lawrence Island (Nos. 1 to 4). Porosities of the samples average 9.1%, and permeabilities averge 1.1 md. Thus, because of poor permeabilities the Oligocene rocks that we sampled would make poor reservoirs.

Discussion of Petroleum Geology

The hydrocarbon-source and reservoir properties of rocks exposed around the Norton basin are known in a cursory way from the discussion in the preceding sections. The inferred source and reservoir properties both of rocks in the basement beneath the Norton basin and of rocks in the basin are discussed next. This discussion will be based on geologic relations in the region that extends from Anadyr Basin to the southern Brooks Range.

Source Rocks-- Organic-geochemical data from Paleozoic and lower Mesozoic rocks suggests that these rocks could be sources for hydrocarbons under some parts of the Norton basin. West of the basin, most Paleozoic and lower Mesozoic rocks are thermally immature, whereas east and north of the basin, Paleozoic rocks are too highly thermally altered to be sources for hydrocarbons. Gradation or abrupt transition between these levels of thermal alteration may take place beneath the Norton basin, in such a way that source rocks for hydrocarbons may be present locally beneath the basin. This possibility is intriguing because organic-carbon-rich Triassic rocks on St. Lawrence Island are lithologically similar to the Triassic Shublik Formation under the North Slope of Alaska, where this formation is a potential source rock for hydrocarbons (L. B. Magoon, oral commun., 1981).

The regional trend and the metamorphic history of Precambrian and Paleozoic rocks in the southern Brooks Range and on the Seward Peninsula suggest that this gradation may occur beneath the westernmost part of the Norton basin, in the vicinity of St. Lawrence Island. Regionally, the Precambrian and Paleozoic rocks trend west through the Brooks Range, bend sharply to the south at the west end of the range, and trend south through the Seward Peninsula. This regional southward trend combines with evidence from seismic-refraction data to suggest that the Precambrian and Paleozoic rocks continue southward from the Seward Peninsula to underlie the Norton basin. Evidence presented above suggests that rocks exposed on the Seward Peninsula were heated, thrust, and eroded during the Late Jurassic and Early Cretaceous and suggests that rocks in the basement beneath the Norton basin underwent similar events. Over large areas of the Seward Peninsula, Precambrian and Paleozoic rocks are metamorphosed to blueschist or greenschist, except in the westernmost part of the peninsula, west of long. 166°W, where unmetamorphosed Paleozoic carbonate rocks crop out (Sainsbury, 1972, 1975). Thus, the metamorphic grade of rocks on the peninsula decreases to the west, in a direction perpendicular to the regional southward trend. St. Lawrence Island lies to the west (and to the south along the regional trend) of the unmetamorphosed carbonate rocks on the peninsula, and except locally, Paleozoic rocks on the island are thermally immature for oil. These regional relations suggest that east of about long. 166°W basement rocks beneath the Norton basin are metamorphosed to blueschist or greenshist. From 166°W to about 169°W the grade may decrease and east of about 169°W, the grade may be low (immature for oil generation). West of 166°W, then, source rocks for hydrocarbons may be present in the basement, and the type of kerogen in Paleozoic rocks on St. Lawrence Island suggests that these rocks could be sources for gas or for condensate. Isolated basin deeps are present between 166° and 168°W, such that hydrocarbons could be locally generated from basement rocks and trapped in the basin fill. West of 168°W, however, the Norton basin is shallower than 2 km, and potential traps for hydrocarbons there are few and small. The presence of potential source rocks in the basement, then, may have little practical effect on the hydrocarbon resources of the area north of St. Lawrence Island.

Plutonism occurred about 100 m.y. and again about 80 m.y. ago (Miller et al., 1966; Patton, 1973) and affected large areas in the northern Bering Sea region. Some plutons intruded pre-Cretaceous rocks now exposed on St. Lawrence Island, yet most of these rocks are thermally immature for oil generation; hence, heating of pre-Cretaceous rocks by the late Early and Late Cretaceous plutonism was probably restricted to local areas, in thermal aureoles around the plutons.

The main consequence of these Cretaceous regional and local thermal events is that basement rocks older than about 100 m.y. beneath the main part of the Norton basin generated hydrocarbons before the basin began to form, and if hydrocarbons are trapped in the main part of the basin, source rocks for the hydrocarbons are most likely to be within the basin fill.

Superimposed upon the metamorphosed basement rocks below the Norton basin are as much as 6.5 km of mainly Cenozoic rocks for which no source-rock data are available. On the basis of the appearance of reflections in seismic data, rocks deep in the Norton basin are predominantly nonmarine, whereas marine rocks make up the upper third of the basin fill. Nonmarine rocks may be poorer sources for oil than marine rocks because hydrogen-poor kerogen is typically deposited in nonmarine environments. Some nonmarine rocks, however, are thought to produce two types of condensate and high-wax oil from the exinite-rich kerogen that is derived from algae and lipid-rich plant debris (Connan and Casson, 1980). One type of condensate can be generated from such kerogen when the vitrinite reflectance is in the range of 0.39 to 0.6%. These "immature condensates" are mainly dry gas with a gas-oil ratio greater than 20,000 (m^3/m^3) and are chemically distinct from the second type of condensate, which is produced by thermal cracking of hydrocarbons when vitrinite reflectance is in the range of 0.95 to 2.0%. When vitrinite reflectance is in the range of 0.5 to 1.35%, exinite-rich kerogen also produces wet gas that contains appreciable quantities of high-wax crude oil. Immature condensates and wet gas are hydrocarbon resources in basins in New Zealand, Colombia, Australia, and Indonesia, according to Connan and Casson (1980). These authors emphasized that the exinite-rich kerogen is of high quality; that is, the kerogen does not contain large amounts of low-hydrogen, woody or coaly kerogen. Around the Norton basin, kerogen in samples from scattered, local outcrops is predominantly woody and coaly. The type of kerogen in offshore rocks, however, may be more condensate- or oil-prone than is the type in onshore rocks: Kvenvolden and Claypool (1980) stated that hydrocarbons from the main offshore gas seep are possibly an immature condensate. Hence, nonmarine source rocks for oil could conceivably be found in the Norton basin. Also, during the early history of the Norton basin, when subsidence was most rapid, lakes may have formed so that lacustrine deposits could be source rocks for oil.

Potential source rocks for oil may be in the Neogene, possibly marine rocks. We used a method described by Lopatin (1971) and by Waples (1980) to calculate the thermal maturity of these rocks in the Norton basin. The accuracy of these calculations are affected by three main assumptions --1) the basin began to form 65 m.y. ago, 2) the basement has subsided at a constant rate since then, and 3) the geothermal gradient through the basin fill has been in the range of 35 to 45 °C/km. The last two assumptions are discussed next.

A constant rate of subsidence undoubtedly does not describe the true subsidence history of the Norton basin. As described above subsidence during the early basin history was controlled by major normal faults and was probably more rapid than later subsidence, which was due to thermal contraction of the crust and to isostasy. No evidence from seismic data suggests that rocks in the Norton basin underwent major uplift; basin fill, therefore, is now at its maximum depth of burial. An undated unconformity truncates rocks in the basin and was apparently the only major interruption of continuous subsidence. A subsidence curve more realistic than a straight line would show rapid deepening of the basin while rifting occurred during the latest Cretaceous or early Paleogene, and the curve would show progressive slowing of the rate after rifting, during the late Paleogene and Neogene. Angevine and Turcotte (1981) provided a method to calculate the thermal and isostatic components of basin subsidence. This method requires knowledge of an exponential relation between porosity and depth; this relation for Norton basin is obtained from porosity-depth data from the Hope and Anadyr basins (Fig. 28). The subsidence curve that is calculated using regional porosity-depth data (curve 1, Fig. 25) differs substantially from the assumed straight line; however, an arbitrary adjustment that slows the calculated rate of porosity reduction with depth yields the correct present depth of the basin (curve 2). The regional porosity data and a 50 m.y. assumed time for the beginning of rifting yields a subsidence curve (curve 3) that accords with the present basin depth and approximates the straight-line subsidence curve. We proceed on the assumption that Norton basin subsided at a constant rate because we have insufficient biostratigraphic and porosity data to show the form of a more realistic curve. The only test of this assumption is that horizon C, inferred to be at the base of the Neogene, is at a mean depth of about 2 km, and the linear subsidence curve predicts that this horizon should be at 2.3 km depth (line 5, Fig. 25).

Theoretical studies show that heat flow through extensional basins varies considerably through time (McKenzie, 1978; Royden et al., 1980; Sclater and Christie, 1980). Under tensile stress, the lower crust of the earth elongates viscously and the upper crust fails in brittle fracture (Bott, 1976). Both processes result in overall thinning of the crust, with the consequence that after extension, hot mantle material is closer to the Earth's surface than before. Some heat may be carried upward along faults or other conduits that allow magma to intrude upper levels of the crust or to extrude into the basin. Typically, fault-controlled subsidence of extensional basins diminishes in importance through time, and basin subsidence becomes more regional in scale, being controlled by thermal contraction and by sediment loading. Once regional subsidence begins, heat flow through the basin is theoretically predictable. Calculations (McKenzie, 1978; Royden et al., 1980; Sclater and Christie, 1980) show that heat flow is at a peak value when rifting ends, that heat flow decreases rapidly with time during the succeeding 60 m.y., and that during another 40 to 60 m.y., heat flow decreases slowly to average values for continental areas. According to this theory, heat flow through the Norton basin has been and still is higher than the continental average because rifting ceased less than 60 m.y. ago. Furthermore, the calculations for rifted basins in general suggest that heat flow through the Norton basin would have varied considerably with time as the basin formed; consequently, a range of geothermal gradients must be used to calculate the thermal maturity of basin rocks.

We derive an estimate for the range of the geothermal gradient that has existed in the Norton basin through time from gradients through other extensional basins, from bottom-hole temperatures in wells in the region around the basin, and from the depth to a possible diagenetic front in the basin. Because the geothermal gradient in extensional basins can vary strongly with location, as is true in the North Sea basin (Evans and Coleman, 1974), we refer to geographic-average gradients. Table 4 shows values of geothermal gradient through several extensional basins. Because of the temporal variation of heat flow through extensional basins, the geothermal gradient through the Norton basin may be intermediate in value between the gradient in the North Sea basin, which is considerably older than the Norton basin, and the gradient in the Great Basin, the Red Sea, and the Rhine graben, which are younger.

Corrected bottom-hole temperatures (Table 5) from wells drilled in west-central Alaska suggest that the mean regional geothermal gradient is about 40° C/km, which is higher than the average gradient in continental areas (25° C/km). The gradient in the Hope basin may be nearly 50° C/km. These data indicate that the average geothermal gradient in the Norton basin is in the range of 40 to 50° C/km.

We tentatively identify horizon D as a reflection that results from the diagenesis of silica. Hein et al. (1978) have shown that this reaction occurs mainly at temperatures between 35 and 50°C. Hence, as horizon D is about 1.2 km deep, the shallow geothermal gradient is about 29-42° C/km.

From these three types of data we believe that the average geothermal gradient in the Norton basin has varied between 35 and 45° C/km since the basin formed. The average gradient may well have been toward the upper end of this range when the basin began to form and toward the lower end in the recent past.

With these assumptions about basin age, subsidence history, and geothermal gradient, we computed the thermal maturity of organic matter in the rocks that are in the deepest part of the Norton basin. The assumptions about the value of the geothermal gradient in the past are so uncertain that gradient is plotted along an axis in figure 26 to show the variation in calculated maturity caused by the assumption of different gradients. Rocks that are presently in the oil window (Ro between 0.65 and 1.30; Waples, 1980) are 45 to 28 m.y. old (middle Eocene to late Oligocene) and 2.8 to 4.5 km deep. The organic geochemistry of hydrocarbon gases at the main offshore seep suggests that these gases are from low-temperature diagenesis of immature organic matter (Kvenvolden and Claypool, 1980) and in the area of the seep, the Norton basin is at most 2 km deep. Hence, carbon dioxide migrating upward through the section has encountered only immature rocks. This observation is consistent with the calculated minimum depth of 2.8 km for the upper limit of the oil window. Rocks in the peak phase of oil generation (Ro is 1.0; Waples, 1980) are 42 to 34 m.y. old (late Eocene to middle Oligocene). Paleocene rocks, by assumption in this analysis the oldest rocks in the Norton basin, generated oil between about 35 and 28 m.y. ago, and since then the oil window has moved steadily upward through the basin fill. This analysis of thermal maturity suggests that the Neogene, possibly marine rocks are not mature for oil, and would not be even if the geothermal gradient had been as high as 50°C/km for the past 20 m.y. Consequently, any source rocks for oil must be found in the nonmarine rocks that lie under the Neogene section.

The relative timing of oil generation and of the growth of the drape or compaction structures that lie over horsts shows that oil could have been generated before and during structural growth. The analysis above suggests that oil could have begun to form between 35 and 28 m.y. ago, and the structures involve rocks mainly of Neogene age. As mentioned above, no bright or flat spots have been observed in seismic data obtained over any of these structures.

Because numerous faults and fault blocks are present, migration paths to the drape or compaction structures are broken repeatedly over short distances, and only strata in isolated, fault-bounded basin lows can charge an individual structure. The low volume of possible source rocks is shown by the calculated depth limits of the oil window, which are great enough that only a small proportion of basin fill has been or is within the window. The graph of cumulative volume in the basin shows that less than 2% of the fill is below 4 km, whereas 74% of the fill is shallower than 2 km (Fig. 27). The restricted volume of basin deeps is due to the formation of deeps as isolated, fault-bounded structures. The basin volume shown is a minimum value because we do not know the extent of the deep-basin areas under shallow water near the north lobe of the Yukon delta. The calculations of thermal maturity of the basin fill suggest that at most 11% of the fill has been or is capable of generating oil and that at most 5% of the fill is in the peak phase of oil generation (Fig. 27).

Reservoirs--No public data are available to show the reservoir properties of offshore rocks. Paleozoic carbonate rocks, coeval with reservoir rocks in the Lisburne Group of the North Slope, crop out on the western Seward Peninsula and on St. Lawrence Island; however, data from onshore rocks suggest that Paleozoic and lower Mesozoic rocks in the basement of the Norton basin have poor intergranular-reservoir properties, even in those areas where the thermal alteration of such rocks is relatively low. If metamorphosed rocks like those on the Seward Peninsula lie under the basin, then reservoirs of the intergranular type are not likely to be present in the basement. However, fractures could provide reservoir space in these rocks. Also, in many Chinese oil fields reservoir space is provided by karst features, including caverns, weathered fractures, and regolith, that formed when Paleozoic carbonate rocks were elevated in horsts and then eroded. The oil was generated in Tertiary lacustrine deposits that overlie or abut high-standing karst features (Yan and Zhia, 1980; Chang et al., 1980). On the Seward Peninsula and on St. Lawrence Island, Paleozoic carbonate rocks crop out, and thus, they may form part of the basement complex under the Norton basin. Furthermore, the presence of alluvial fans along the flanks of the horsts in this basin provides evidence that these horsts were eroded early in the history of the basin. Some features of karst topography may have formed during the time of erosion, and these may provide reservoir space in basement rocks.

The reservoir properties of rocks deep in the Norton basin could have been adversely affected by compaction and diagenetic alteration of volcanic detritus that was laid down during the rifting phase of the basin's formation. These deep rocks could contain local quartz-rich deposits in alluvial fans formed by erosion of high-standing fault blocks. These blocks may have exposed quartzose rocks like some of the metamorphic rocks on the Seward Peninsula.

The provenance of sediment deposited in Norton basin is underlain by a diverse assemblage of volcanic, plutonic, metamorphic, and sedimentary rocks; consequently, during the early history of the basin, the northwest-striking Yukon horst could have divided the basin sedimentologically. Deep rocks west of the horst were most likely derived from the horst and from the area that includes St. Lawrence Island, Siberia, and the western Seward Peninsula. This area is underlain chiefly by carbonate, acidic to basic volcanic, and plutonic rocks. In contrast, deep rocks east of the horst were most likely derived from local high-standing areas in the basin, the central and eastern Seward peninsula, and the Yukon-Koyukuk province. This area is underlain mainly by andesitic volcanic, plutonic, metamorphic, and quartz-poor volcaniclastic rocks. The differing rock types in the two provenances could cause basic differences in composition and reservoir properties of sandstone in the two areas of the basin. Once basin deposits overtopped the Yukon horst, perhaps during the early Neogene, the composition of the basin fill could have become more uniform than before.

Present-day rivers that drain the Seward Peninsula and debouch into Norton Sound are not large, and there is no evidence to suggest that large rivers drained the peninsula to the south in the past. Accordingly, the eastern and deepest part of Norton basin would probably have been filled from the larger and closer land areas, to the east and south, which are underlain by rocks that contain an average of only 8% quartz (Patton, 1973).

The reservoir properties of late Miocene and younger rocks are likely to be better than the properties of older basin rocks because of tectonic events that occured at a distance from the Norton basin and that resulted in uplift of the Alaska Range in south-central Alaska (Nelson and others, 1974). Evidence for this late Miocene uplift includes sedimentologic relations among rocks on the north side of the range (Wahrhafting, 1968; Wahrhafting and others,1971) and the mineralogy and sedimentology of rocks in Cook Inlet (Kirschner, Christiansen, and Wesendunk, unpub. data, 1978). These relations suggest that in the pre-late Miocene, the upper Yukon River flowed through Cook Inlet and that uplift of the Alaska Range in the late Miocene diverted the river to near its present course. If the lower part of the Yukon emptied into the Norton basin throughout much of the Cenozoic, sediment delivered to the main part of the basin would have been derived mainly from quartz-poor rocks that crop out near the Norton basin, whereas after the diversion of the upper part of the Yukon, quartzose rocks in the upper reaches of the river drainage could have been sources for sediment in the basin. Modern sediment from the Yukon River contains an average of 25% quartz (VenkataRathnam, 1970).

Porosity-depth data from sandstone in the Anadyr and Hope basins suggest that on a regional basis, sandstone porosity decreases rapidly with depth, so that mean porosities below 3 km in these basins are less than 5% (Fig. 28). In the Anadyr basin, Miocene sandstone has fair to very good porosities, but pre-Miocene sandstone has only poor to fair reservoir properties (Ivanov et al., 1974). Although the age of rocks in the Hope basin penetrated by the Cape Espenberg No. 1 and the Nimiuk Point No. 1 wells is not known in detail, the rocks are most likely Cenozoic. As determined from compensated gamma-gamma formation density logs, porosites in these rocks range from 40% near the top of the well to 5% near the bottom. The Hope and Anadyr basins have different tectonic histories, different types of basement, and possibly different structure, yet the porosity reduction with depth is similar in both basins. That similarity suggests that such reduction follows a regional pattern. If the porosities of rocks in the Norton basin also follow this pattern, then rocks in the drape or compaction structures, at a depth of 2 to 3 km, would have mean porosities of around 10%.

Traps--The types of hydrocarbon traps that are present in petroliferous, extensional basins suggest that potential traps in the Norton basin could be of four main types (Fig. 29) : 1) traps within horsts, 2) traps in drape or compaction structures, 3) traps in structures that develop along faults, and 4) stratigraphic traps along the flanks of horsts. We do not believe that traps that depend on the presence of evaporites are present in the Norton basin. Some petroliferous basins that contain a given type of trap are mentioned below in the description of that type.

Examples of the first type of potential trap, in which hydrocarbons are contained inside horsts, are present in: 1) the Sirte basin, where petroleum is contained in fractured granite and quartzite (Conant and Goudarzi, 1967); 2) in Chinese oil fields, where oil is contained in voids that formed as horsts were eroded and karst topography formed; and 3) in the North Sea Basin, where oil is contained in tilted, eroded strata within horsts (Blair, 1975; Watson and Swanson, 1975; Williams et al., 1975). In the Norton basin, traps in tilted strata within horsts are unlikely because seismic-refraction data and regional geology indicate that the horsts are composed of indurated Paleozoic and Precambrian rocks. These rocks were heated during the Late Jurassic and Early Cretaceous, such that reservoirs of the intergranular type probably are not present in the basement.

The second type of potential trap, in which hydrocarbons are contained in drape or compaction structures over deep horsts, is present in the North Sea Basin (Walmsley, 1975; Heritier et al., 1979), in the Sirte basin (Conant and Goudarzi, 1964) and in the Reconcavo basin of Brazil (Ghignone and DeAndrade, 1970). In the Norton basin, numerous potential traps of this type exist, (see preceding paper), and we believe that these traps are the most likely to contain hydrocarbon reserves in the basin.

The third type of potential trap is formed by structures that formed along faults in the basin. Such structures tend to be of small size and to include local monoclines and anticlines on the downthrown side of faults. The monoclines may be sealed at their updip end by the fault plane or by the juxtaposition of sandstone against shale along the fault.

The fourth type of potential trap is the stratigraphic trap that forms on the periphery of a horst. Stratigraphic traps formed in the Sirte basin where carbonate and quartzose sandstones lap onto Precambrian and Paleozoic basement rocks (Conant and Goudarzi, 1967; Bebout and Pendexter, 1975). These sand bodies occur where basement highs have an arrangement such that local traps for sand have formed, and hence the presence of these traps may depend on fortuitous basement morphology. In Norton basin, however, a considerable amount of basin fill laps either onto basement horsts or onto alluvial fans that were deposited along the blocks; stratigraphic traps may form in these onlapping strata. In the North Sea, alluvial fans that were deposited during the rifting of the basin are reservoirs for oil and gas (Harms and others, 1980); such traps could occur in the Norton basin, where deep alluvial fans are common.

SUMMARY AND CONCLUSIONS

The northwest Bering Sea, west of the Norton basin, is underlain by a shallow basement, that is composed mainly of Precambrian through lower Mesozoic rocks. Magnetic data suggest that isolated Cretaceous silicic plutons intruded basement rocks in this area; nonmagnetic Cretaceous alkaline plutons could also be present. Gravity, single-channel seismic, and scant multifold seismic data show that the basement is overlain by an average of 1 km of rocks of probable late Neogene and Quaternary age and that local structural lows exist in which rocks are at most 2 km deep. These data also show that a northwest-striking zone of anticlines with high free-air-gravity values marks the boundary between the western Seward Peninsula, where two major normal faults strike west, and the continental shelf north of St. Lawrence Island, under which normal faults strike northwest.

The rocks in Norton basin overlie basement rocks of probable Precambrian and Paleozoic rocks like those exposed on the Seward Peninsula. We do not believe that a thick sequence of middle Cretaceous rocks, coeval with rocks in the Yukon-Koyukuk province, underlie the basin. The basin is divided by the Yukon horst, which strikes northwestward from the Yukon delta toward the Seward Peninsula. Rocks in the St. Lawrence subbasin, west of the horst, are locally as thick as 5.0 km. Major normal faults there strike northwest. The Stuart subbasin, which lies east of the Yukon horst, contains basin fill that is locally as thick as 6.5 km. Major normal faults there strike east in the northern part of the subbasin and northeast in the southern and eastern part. The horst also could have divided Norton basin in such a way that rocks of different composition would have been deposited on opposite sides of the horst.

We believe that basement rocks beneath Norton basin were heated, thrust, intruded by plutonic rocks, and eroded during the Late Jurassic and Early and early late Cretaceous. During the latest Cretaceous or early Paleogene, Norton basin began to form in response to regional extension. Major subsidence caused by the regional extension affected only a small area to produce Norton basin, suggesting that the strike-slip Kaltag fault played a role in basin formation. Relief among basement horsts and grabens developed so quickly that the rate of sedimentation lagged behind the rate of subsidence, and alluvial fans were deposited along the margins of the horsts. Alluvial deposits are locally interbedded with what we believe to be coal or volcanic rocks. An unconformity in the uppermost part of these nonmarine deposits represents a time when basement rocks in horsts were eroded and many horst summits bevelled flat. Nonmarine deposition continued in the basin until the end of the Paleogene, and during the Neogene and Quaternary, mainly marine rocks were deposited.

Precambrian and Paleozoic basement rocks beneath the main part of the Norton basin are thought to be metamorphosed to such an extent that these rocks generated hydrocarbons before the basin formed, but they have been incapable of producing any hydrocarbons since then. Potential basement source rocks exist near St. Lawrence Island, where rocks in the Norton basin are generally thinner than 2 km and where few traps are present. In the main part of the basin, potential source rocks for hydrocarbons exist only in the basin fill. The assumptions that the Norton basin underwent a constant subsidence rate since 65 m.y. ago and that the average geothermal gradient has been between 45 and 35°C/km yield the result that Paleogene rocks between 45 and 28 m.y. old are now in the oil window. These rocks, however, were deposited in a nonmarine environment, judging from the appearance of seismic reflections from deep rocks. As the Neogene, possibly marine rocks are unlikely to be mature in any part of the basin, the most likely hydrocarbons to be found in the basin are gas and condensate.

Because the deep parts of the Norton basin are confined to fault-bounded lows, the fill that is or has been in the oil window is at most 11% of the total basin volume. The isolated basin lows and the numerous faults and fault blocks mean that migration paths are disrupted over short distances.

Potential traps for hydrocarbons are common in the Norton basin. They could be of four main types: 1) fractures or weathered zones in basement rocks within horsts, 2) drape or compaction structures that form in basin fill over horsts, 3) small structures that develop along faults, and 4) strata that lap onto basement fault blocks or that are in alluvial fans adjacent to the horsts. We believe that the drape or compaction structures are the most likely traps to contain hydrocarbons. These traps formed mainly during the Neogene, and oil began to be generated in deep rocks before these structures began to form. No bright or flat spots are evident in seismic data collected over any of these structures.

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FIGURE CAPTIONS

Figure 1. Geography, bathymetry, and structural subdivisions of northern Bering Sea.

Figure 2. Tracklines of geophysical data.

Figure 3. Regional geology around northern Bering Sea.

Figure 4. Stratigraphic correlation chart of basement rocks and basin strata in the region of northern Bering Sea.

Figure 5. Rose diagrams of high-angle faults on Seward Peninsula, as mapped by various authors. For each rose diagram, the lengths of faults that strike in a particular direction are summed and then divided by the total length of all faults. The circle in each diagram represents 10 percent of that total length.

Figure 6. Conversion of seismic travel time to depth. Time-depth curves from refraction and reflection data obtained in Norton basin are compared to such curves from sonic logs from wells in Hope basin.

Figure 7. Structure of the area north of St. Lawrence Island as shown by contours on horizon A, which probably lies between Precambrian through lower Mesozoic rocks below and upper Neogene and Quaternary rocks above.

Figure 8. Relation between depth to basement and free-air-gravity value. Values for each point on the figure were averaged over data in a 25 km^2 area.

Figure 9. Gravity map of area north of St. Lawrence Island (free-air data) and of Seward Peninsula (Bouguer data). Free-air and Bouguer data are not directly comparable because of high land elevations on the peninsula, but the general form of the contours can be compared.

Figure 10. Structure contours on horizon A in Norton basin. Horizon A is an unconformity between probable Precambrian and Paleozoic rocks below and uppermost Cretaceous or lowest Paleogene rocks above. Seismic sections that are shown in figures are located here by numbered lines.

Figure 11. Contours of free-air gravity over Norton basin (Fisher and others, 1980) and of Bouguer gravity over the Yukon delta (Barnes, 1977). Low land elevation on delta allow approximate comparison of free-air and Bouguer values.

Figure 12. Line 011 is a north-south, regional seismic section through western Norton basin. Dip of beds indicated. Horizon A at top of basement rock.

Figure 13. Line 009 is an east-west, regional section through western Norton basin. Dip of beds indicated. Horizon A at top of basement rock.

Figure 14. Line 804 is a northeast-southwest seismic section through the central part of Norton basin. Horizon A at top of basement rock.

Figure 15. Line 813 is an east-west seismic section through eastern and central Norton basin. Dip of beds indicated. Horizon A at top of basement rock.

Figure 16. Seismic lines showing details of particular geolgic features. Dip of beds indicated. A, line 8021 shows detailed structure of the south-boundary fault and alluvial fan on downthrown side of fault. B, line 8131 shows details of the Yukon horst which is flanked on the west by an alluvial fan and is overlain by a drape or compaction structure. Some reflections from alluvial deposits on the west are truncated at an unconformity that also forms the nearly flat top of the horst. C, line 8022 shows the abundance of small normal faults that offset strata under horizon D, and the isolated deep reflections that could be due to coal and crystalline volcanic rocks. D, line 0091 shows mound of probable volcanic rocks that rest on basement.

Figure 17. Line 8041 shows the Yukon horst. The fault on the northeast is one of the few major faults that offset shallow strata.

Figure 18. Line 007 is a north-south seismic section through eastern Norton basin. Dip of beds indicated. Horizon A at top of basement rocks.

Figure 19. Velocity-depth-age for rocks in the region around the northern Bering Sea. From these data, three groups of rocks can be distinguished: 1) Precambrian and Paleozoic rocks, 2) crystalline volcanic or Cretaceous sedimentary rocks, and 3) Cenozoic sedimentary rocks. In figure 19b refraction velocities measured in rocks of Norton basin are presented for comparison with velocity-age criteria established in figure 19a.

Figure 20. Geologic history of Norton basin and of the region around the basin.

Figure 21. Geography of Norton Sound, locations of numbered samples (Tables 1 and 2), and proposed lease-sale areas. Samples 14 and 23 were collected along the Yukon River, east of the area shown in this figure. The latitude of these samples is shown correctly.

Figure 22. Comparison of vitrinite-reflectance and TAI values from Cretaceous rocks in the Yukon-Koyukuk province (circled dots) to two proposed relations between reflectance and TAI (solid and dashed lines). TAI values from the province consistently indicate a less intense thermal alteration then does vitrinite reflectance.

Figure 23. Seismic section through main gas seep in Norton basin; location shown in Figure 4. Gas from the seep is 98% CO_2 and 0.1% hydrocarbon gases.

Figure 24. Locations of anomalous reflections, in multifold seismic data, that could be caused by gas in rocks shallower than 0.5 km. High-resolution seismic data typically show poor subbottom penetration, and so acoustic anomalies evident in these data are not plotted here. Three-kilometer structural contour on basement is also shown to compare areas of deep basin and areas of possibly gas-charged sediment. North of the Yukon delta lies an area that is underlain extensively by what may be shallow gas; the deepest part of the Norton basin also lies under this area.

Figure 25. Subsidence curves for the Norton basin. Basin is assumed to have subsided at a constant rate (straight line numbered 4) because of the lack of biostratigraphic data needed to determine the correct subsidence curve. Curves 1 to 3 are calculated by method of Angevine and Turcotte (1981) to show possible magnitudes of the thermal and isostatic components of subsidence; fault-controlled subsidence is not accounted for in these calculations. ϕ_0 porosity at surface; Yp depth at which porosity is 37% of ϕ_0. Values of ϕ_0 and Yp describe exponential curve that relates porosity and depth and were calculated from regional porosity-depth data (Fig. 8). Note that if Norton basin is only 50 m.y. old and if porosity values in basin decrease with depth according to regional data, a straight line (line numbered 4) approximates the calculated subsidence (curve 3). Straight line numbered 5 shows assumed burial history of rocks at base of Neogene section. This line shows these rocks to be at a predicted depth of 2.3 km, whereas average depth to base of Neogene rocks (horizon C of preceding paper) is about 2.0 km.

Figure 26. Thermal maturity of rocks in Norton basin as calculated by method of Lopatic (1971) and Waples (1980), assuming constant rate of basin subsidence since 65 m.y. ago. Values of vitrinite reflectance (Ro) used to define the oil window are from Waples (1980).

Figure 27. Cumulative-volume curve for Norton basin, showing total basin fill below a given depth. Area of basin included in volumetric calcuations is bounded by 162° and 168° W, and 63° and 64° 15' N. At most 11% of basin fill is in or below calculated oil window.

Figure 28. Porosity-depth data from Anadyr and Hope basins. Porosity of sandstones in Anadyr basin (left) from core measurements (Ivanov et al., 1974). Porosities from Hope basin (middle) are calculated from compensated formation density logs (FDC). Right-hand graph shows a comparison of porosity data from Anadyr and Hope basins. Porosity of rocks in Norton basin may decrease according to the regional pattern shown in right hand graph.

Figure 29. Types of hydrocarbon traps in extensional basins. All types, except for the one with porous strata in a horst, are possible in or below Norton basin. Some basins that contain these traps are indicated in parentheses.

Table 1. Organic Geochemical Data

Sample No.[A]	Age	Lithology	Organic carbon (percent)	Average vitrinite reflectance (percent)	Indigenous kerogen		C_{15+} Extraction		
					Type[B]	Thermal alteration index	Extract (ppm)	Hydrocarbon in Extract (ppm)	P-N[C] in extract (percent)
St. Lawrence Island									
1	Tertiary	Limey sandstone	0.44	0.24	H-W-C;-;Am	1.6	670	48	---
2	Tertiary	Coaly siltstone	33.18	0.39	W-C;-;H	2.0	---	---	---
3	Tertiary	Coal	81.8	0.22	W-C;H;Am	1.6	---	---	---
4	Tertiary	Coal	52.6	0.39	W-C;-;Am-H	2.0	---	---	---
5	Triassic	Shale	2.16	---	H-W;-;-	1.6	489	31	---
6	Triassic	Limestone	0.16	---	W-C;-;H	1.6	---	---	---
7	Permian and Triassic	Shale	2.13	---	W-C;H;-	3.6	708	70	---
9	Devonian	Limestone	0.29	---	H;W;-	1.6	---	---	---
10	Devonian	Dolomite	0.41	---	H-W;-;-	2.0	439	29	---
Seward Peninsula									
11	Tertiary(?)	Sandstone	0.37	0.86	H;W;-	1.6	469	76	1.5
11	Tertiary(?)	Coal	29.29	0.92	H-W;C;-	2.8	7,312	862	0.3
Eastern shore Norton Sound									
12	Oligocene	Coal	26.48	0.31	W;H;Am	1.2	1,826	184	0.2
13	Oligocene(?)	Coal	28.14	0.32	W;H;Am	1.2	160	36[D]	---
14	Oligocene	Coal	21.03	0.30	H-W;-;-	1.2	10,826	948	0.3
15	Cretaceous	Shale	0.50	1.96[E]	H-W;C;-	3.2	70	10[D]	---
15	Cretaceous	Shale	1.50	2.63	W-C;H-	2.8	135	32[D]	---
15	Cretaceous	Coaly shale	6.58	2.47	H;C;W	3.6	210	57	5.3
16	Cretaceous	Shale	0.38	2.27[E]	C;H-W;-	3.6	197	38	10.1
16	Cretaceous	Shale	0.31	2.42	W-C;-;H	3.6	138	25	---
18	Cretaceous	Coaly shale	7.37	2.53	H-W;C;-	3.2	228	75	1.8
19	Cretaceous	Siltstone	1.02	2.74	W;H;-	2.4	140	24[D]	---
19	Cretaceous	Shale	0.97	3.22	H;W;-	2.4	110	28[D]	---
19	Cretaceous	Coaly shale	6.01	3.27	H;-;-	3.2	296	44[D]	---
19	Cretaceous	Shale	1.87	3.45	H;-;W	2.4	179	11	1.1
19	Cretaceous	Shale	0.74	1.91	H;-;-	3.2	134	28[D]	---
19	Cretaceous	Coal	14.06	1.92	W-C;-;H	4.0	125	34[D]	---
20	Cretaceous	Shale	1.33	2.24	W-C;H;-	3.2	157	48[D]	---
21	Cretaceous	Coal	56.42	1.88	W;-;H	2.8	3,321	413	0.2
21	Cretaceous	Shale	0.98	2.01	H;W;-	2.8	182	42[D]	---
22	Cretaceous	Shale	0.52	2.00[E]	H-W-C;-;-	3.2	135	42[D]	---
23	Cretaceous	Shale	0.81	1.15	H-W;-;-	2.0	119	26[D]	---
23	Cretaceous	Shale	0.52	1.19	H;-;Am-W	2.0	249	46	7.2
24	Paleozoic	Carbonaceous limestone	1.36	1.86	C;-;-	5	105	18	---

A. For locations see Figure 1.
B. H = Herbaceous, spore/cuticle, C = Coaly, W = Woody, Am = Amorphous
Kerogen types listed in order of abundance: Predominant, 100-60%; Secondary, 40-20%; Trace, 20-0%.
C. P-N = paraffins and naphthenes.
D. Estimated value.
E. Scattered values in histogram.

Table 2. Data from Rock-Eval Pyrolysis of Cretaceous Rocks

Sample No.[A]	TOC[B] (%)	Ro[C] (%)	S_1 (mg/g)	S_2 (mg/g)	S_3 (mg/g)	Hydrogen Index (mgHC/g C)	Oxygen Index ($mgCO_2/gC$)	T_{S_2} (°C)	Transformation Ratio
15	1.50	2.63	0.020	<0.02	0.35	<1	24	530	>0.50
19	1.02	2.74	0.028	<0.02	0.27	<2.7	26	525	>0.58
19	0.97	3.22	0.015	<0.01	0.12	<1	12	530	>0.60
19	1.87	3.45	0.045	<0.02	0.35	<1	19	475	>0.69
19	0.74	1.91	0.035	<0.03	0.10	<4	14	470	>0.54
20	1.33	2.24	0.022	<0.04	0.11	<3	9	525	>0.35
21	0.98	2.01	0.034	<0.04	0.43	<4	44	525	>0.46

A. For locations see Figure 1
B. Total organic carbon
C. Vitrinite reflectance

Table 3. Porosity and Permeability Data

Sample Number	Age	Porosity (percent)	Permeability (Md)
St. Lawrence Island			
1	Tertiary	8.1	0.12
2	Tertiary	7.8	0.67
4	Tertiary	11.3	2.6
8	Permian and Triassic	2.3	0.28
Yukon-Koyukuk province			
15	Cretaceous	1.1	<0.01
15	Cretaceous	1.7	<0.01
16	Cretaceous	0.6	<0.01
17	Cretaceous	1.3	<0.01
19	Cretaceous	7.6	<0.01
19	Cretaceous	6.6	<0.01
19	Cretaceous	6.4	<0.01
20	Cretaceous	2.8	<0.01
21	Cretaceous	2.9	<0.01
21	Cretaceous	2.6	<0.01
22	Cretaceous	2.2	<0.01
22	Cretaceous	7.0	0.033
23	Cretaceous	4.0	<0.01
23	Cretaceous	10.2	1.42

Table 4. Geothermal Gradients of Some Extensional Basins

BASIN	GEOTHERMAL GRADIENT (°C/km)			AGE OF RIFTING
	LOW	HIGH	GEOGRAPHIC AVERAGE	
North Sea	18[A]	44[A]	35[B]	Late Triassic and Late Jurassic to Early Cretaceous
Great Basin	27[C]	57[C]	42[C]	Miocene[D]
Red Sea	28[E]	50+[E]	-	Miocene[D]
Rhine Graben	36[F]	50+[F]	-	late Eocene[G]

A Evans and Coleman (1974), Carstens and Finstad (1979).
B Ziegler (1977).
C Calculated from heat flow values in Lachenbrach and Sass, (1978) by assuming a thermal conductivity of 4 ucal/°C-cm-s (Clark, 1966). Values in "High" and "Low" columns are one standard deviation from the value in the "Average" column.
D Stewart (1978).
E Lowell and others (1975).
F Klemme (1975).
G Illies (1978).

Table 5. Geothermal Gradients[A] From Wells in West-central Alaska

WELL[B]	UNCORRECTED GRADIENT (°C/km)	CORRECTED[C] GRADIENT (°C/km)
Standard Oil of California Nimiuk Point No. 1	33[D]	62[D]
Standard Oil of California Cape Espenberg No. 1	27	48
Benedum and Associates Nulato No. 1	17	32
Pan American Petroluem Co. Napatuk Creek No. 1	27[D]	48[D]

A Assumed surface temperature is 5°C.
B Location shown in figure 2 of preceeding paper.
C Method of correction by Castano and Sparks (1974).
D Straight line fits data poorly; value given is probably too high.

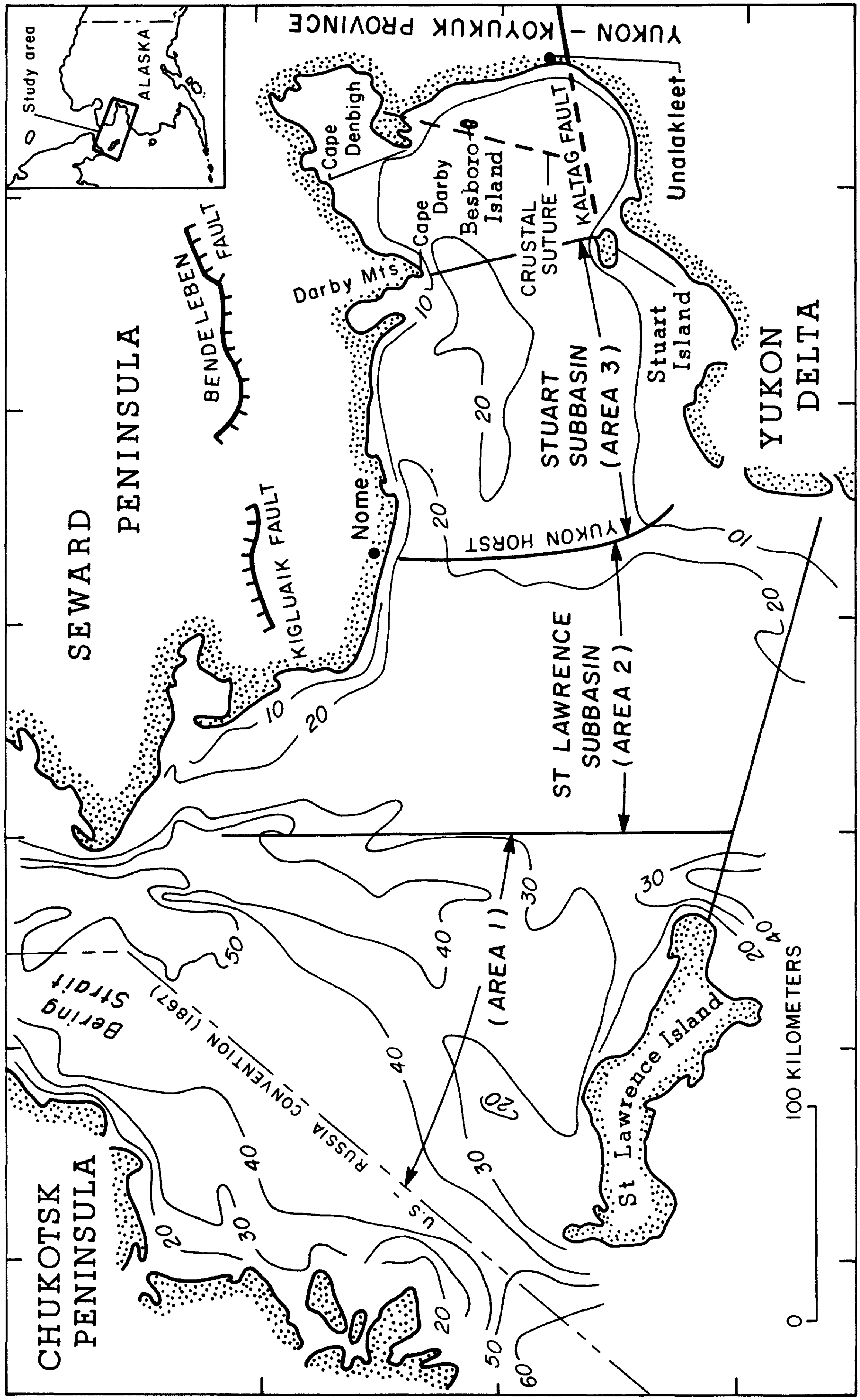
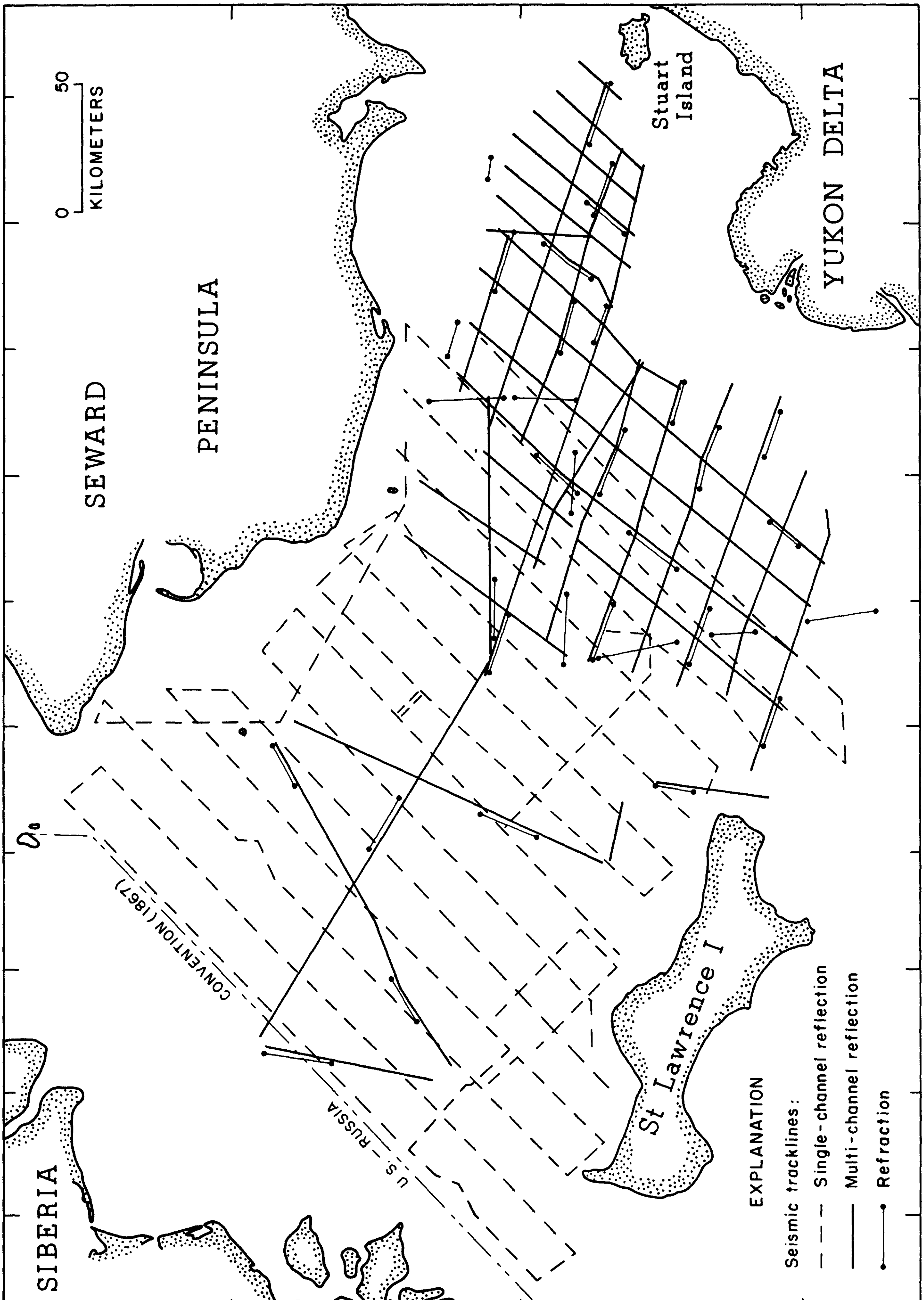

CHUKOTSK PENINSULA
SEWARD PENINSULA
Bering Strait
U.S. RUSSIA CONVENTION (1867)
St Lawrence Island
YUKON DELTA
Stuart Island
STUART SUBBASIN (AREA 3)
ST LAWRENCE SUBBASIN (AREA 2)
(AREA 1)
YUKON HORST
KIGLUAIK FAULT
BENDELEBEN FAULT
Nome
Darby Mts
Cape Darby
Besboro Island
Cape Denbigh
CRUSTAL SUTURE
KALTAG FAULT
Unalakleet
YUKON - KOYUKUK PROVINCE
Study area
ALASKA
0
100 KILOMETERS
162°
164°
166°
168°
170°
172°
65°
63°

FIG. 1



0
50
KILOMETERS
164°
166°
168°
170°
172°
65°
64°
63°
SEWARD
PENINSULA
Stuart
Island
YUKON DELTA
SIBERIA
St Lawrence I
U.S. – RUSSIA
CONVENTION (1867)
EXPLANATION
Seismic tracklines:
Single-channel reflection
Multi-channel reflection
Refraction

FIG. 2


Wrangel Island
Chaun Gulf
Colville Basin
Cape Lisburne
Hope Basin
Brooks Range
Kotzebue Sound
Chukotsk Peninsula
ANADYR R.
Gulf of Anadyr
Anadyr Basin
Koryak Uplands
U.S.–RUSSIA CONVENTION (1867)
Seward Peninsula
Cape Denbigh
Koyukuk Prov.
Kaltag fault
Yukon
Norton Sound
Gas seep
Norton Basin
St. Lawrence Island
BERING SEA
NUNIVAK ARCH
St. Matthew Island
Nunivak Island
Yukon Delta
0 100 200 KILOMETERS
70°
68°
66°
64°
62°
60°
180°
175°
170°
165°
160°

FIG. 3

EXPLANATION

LATE CENOZOIC

- Surficial deposits
- Subaerial volcanic rocks (Chiefly basalt)

LATE MESOZOIC

- Forearc deposits (Chiefly terrigenous sedimentary rocks)
- Volcanic deposits (Locally includes rocks of earliest Cenozoic age, stippled where chiefly terrigenous sedimentary rocks)

PRECAMBRIAN, PALEOZOIC, AND EARLY MESOZOIC

- Miogeoclinal deposits (Wavy lines indicate where rocks metamorphosed to greenschist or amphibolite facies)

TERTIARY

- Coal-bearing deposits (Outcrop too small to be shown on map)

CRETACEOUS

- Granitic rocks

Outline of basin

Exploratory well

1 Pan American Petroleum Corporation Napatuk Creek No. 1

2 Benedum & Associates No. 1 Nulato Unit

3 Standard of California No. 1 Cape Espenberg

4 Standard of California No. 1 Nimiuk Point

Explanation FIG. 3

W — E

SYSTEM	PRE-CENOZOIC BASEMENT ROCKS[1]: CHUKOTSK PENINSULA	EASTERN ST. LAWRENCE ISLAND	SEWARD PENINSULA AND YUKON-KOYUKUK PROV.	WESTERN AND CENTRAL BROOKS RANGE
JURASSIC AND CRETACEOUS	Sandstone and shale, volcanic rocks of acid and intermediate composition.		Graywacke, mudstone and andesitic volcanic rocks in Yukon-Koyukuk province.	Graywacke and mudstone.
TRIASSIC	Shale, siltstone, sandstone, and limestone.	Shale, limestone, and chert. — ? — ? — Siltstone and chert.		Shublik Fm.: Limestone, chert, and shale.
PERMIAN	Sandstone, shale, siltstone, and conglomerate.	Graywacke and mudstone. ? ?		Shale, siltstone, and chert.
MISSISSIPPIAN	Limestone, siltstone, shale, and sandstone. ? ? ?	Limestone and chert.	Limestone near Cape Prince of Wales, west end Seward Peninsula.	Lisburne Group: Limestone, dolomite, and chert. / Shale, limestone, and sandstone.
DEVONIAN	Limestone, dolomite, phyllite, and slate.	Dolomite and dolomitic limestone.	Dolomite, limestone, and black slate near Council and Kougarok Rivers, Seward Peninsula.	Dolomite, dolomitic limestone, and limestone.
PRECAMBRIAN AND E. PALEOZOIC	High-grade, regionally metamorphosed sedimentary and igneous rocks; gneiss; and schist.	Calc-silicate hornfels that crops out in small areas around plutons.	High-grade, regionally metamorphosed sedimentary rocks; metavolcanic rocks (including greenschist); gneiss; and argillaceous limestone.	Metasedimentary and metaigneous (including greenschist) rocks in schist belt along south side of range.

[1]Modified from Patton and Dutro (1969).

W — E

SYSTEM (SERIES)	UPPERMOST MESOZOIC AND CENOZOIC BASIN ROCKS: ANADYR[1] BASIN	HOPE[2] BASIN	NORTON[3] BASIN	SEISMIC HORIZON
NEOGENE AND QUATERNARY	Nonmarine sandstone, shale, and brown coal. Marine and nonmarine sandstone, siltstone, and shale.	Nonmarine, interbedded sandstone, shale, and siltstone that contain abundant	Nonmarine and shallow marine. Predominantly marine	? D; C
PALEOGENE	Interbedded volcanic and nonmarine sedimentary rocks. Local marine rocks. Nonmarine	plant remains and coal stringers. Volcanic rocks locally abundant near base of section. Conglomerate more abundant downward. ? ?	Predominantly nonmarine (undated) — — — Nonmarine, coal- and/or volcanic-rich rocks. Alluvial fans	? B
CRETACEOUS (UPPER CRETACEOUS)	coal-bearing rocks. Flysch-like deposits[4]		common at depth ? ?	A
BASEMENT ROCKS	Upper Jurassic and Lower Cretaceous volcanogenic rocks. / Strongly folded and faulted Mesozoic sedimetary rocks of the Koryak fold belt.	Precambrian(?) quartz-mica schist and phyllite and Paleozoic(?) limestone.	Precambrian metamorphic and Paleozoic carbonate rocks, like those on Seward Peninsula. Local Cretaceous plutonic rocks.	

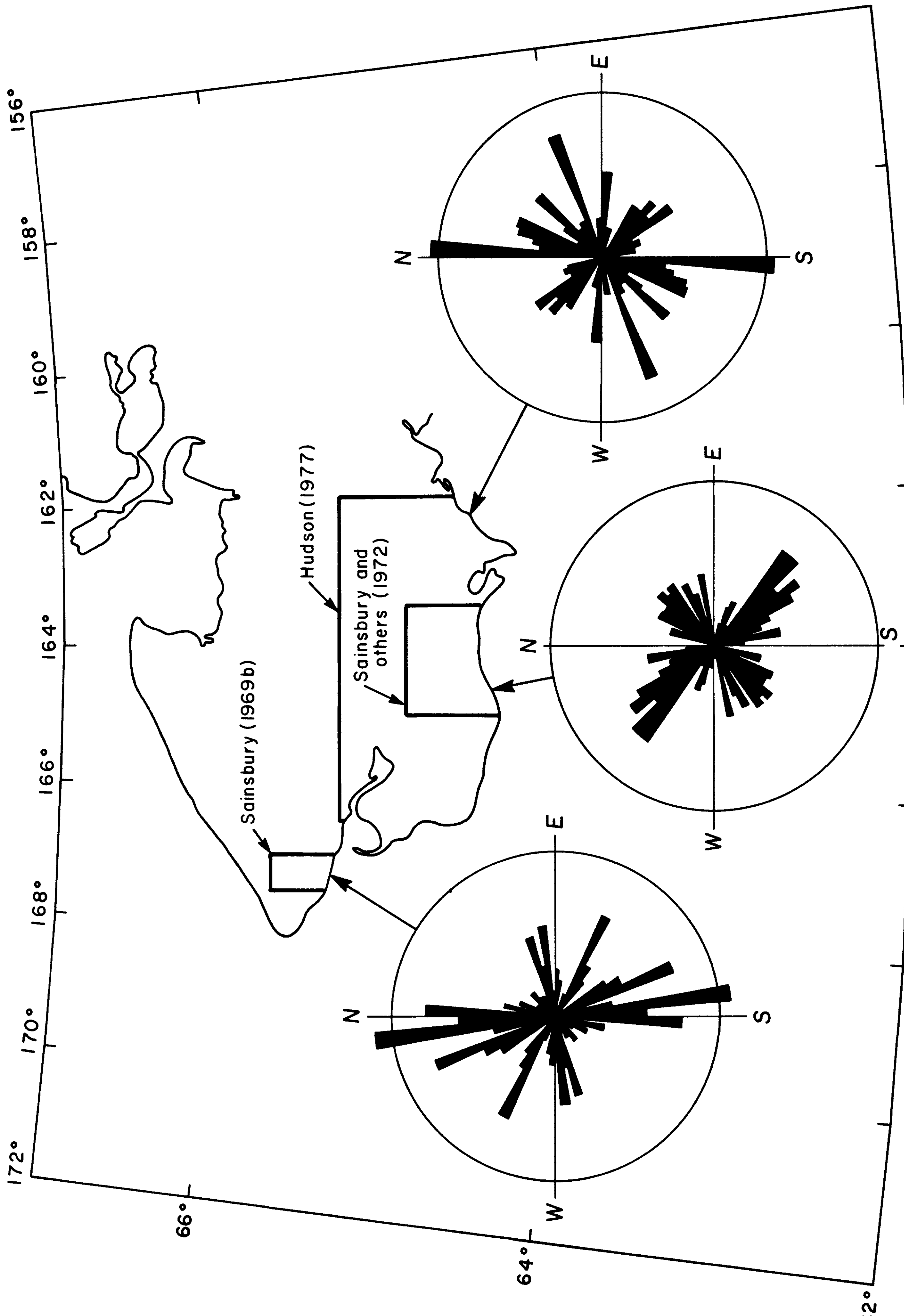
1 Meyerhoff (1972), Agapitov and others (1973), McLean (1979).

2 Age of sedimentary and volcanic rocks in two wells is not known in detail, but is assumed to be Cenozoic. Lithologic data from American Stratigraphic Company (1977 a, b).

3 From seismic stratigraphy explained in this paper.

4 Includes thin Aptian and Albian rocks.

FIG. 4



156°
158°
160°
162°
164°
166°
168°
170°
172°
66°
64°
62°
Hudson (1977)
Sainsbury and others (1972)
Sainsbury (1969b)
Sainsbury
N
E
S
W

FIG. 5

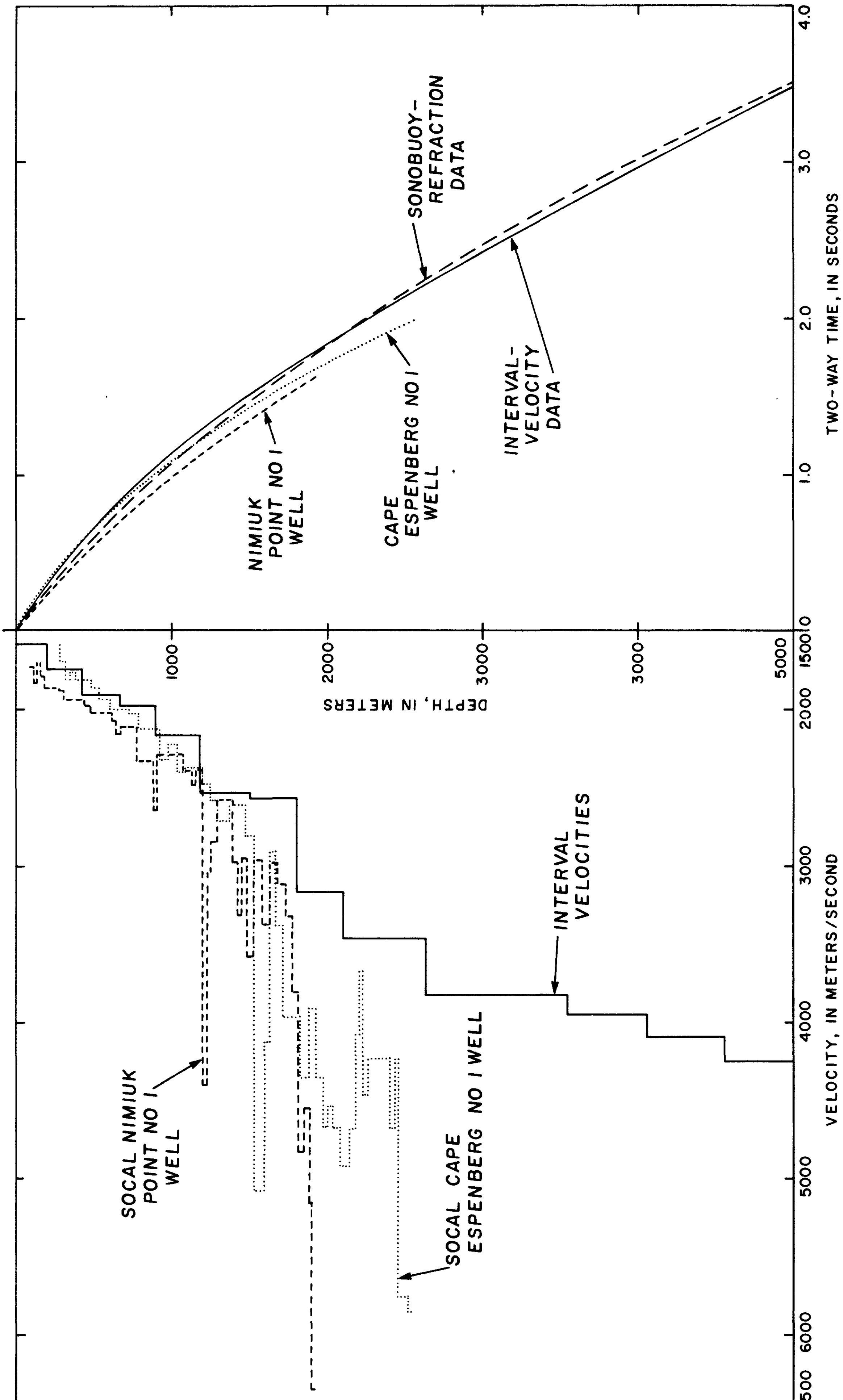
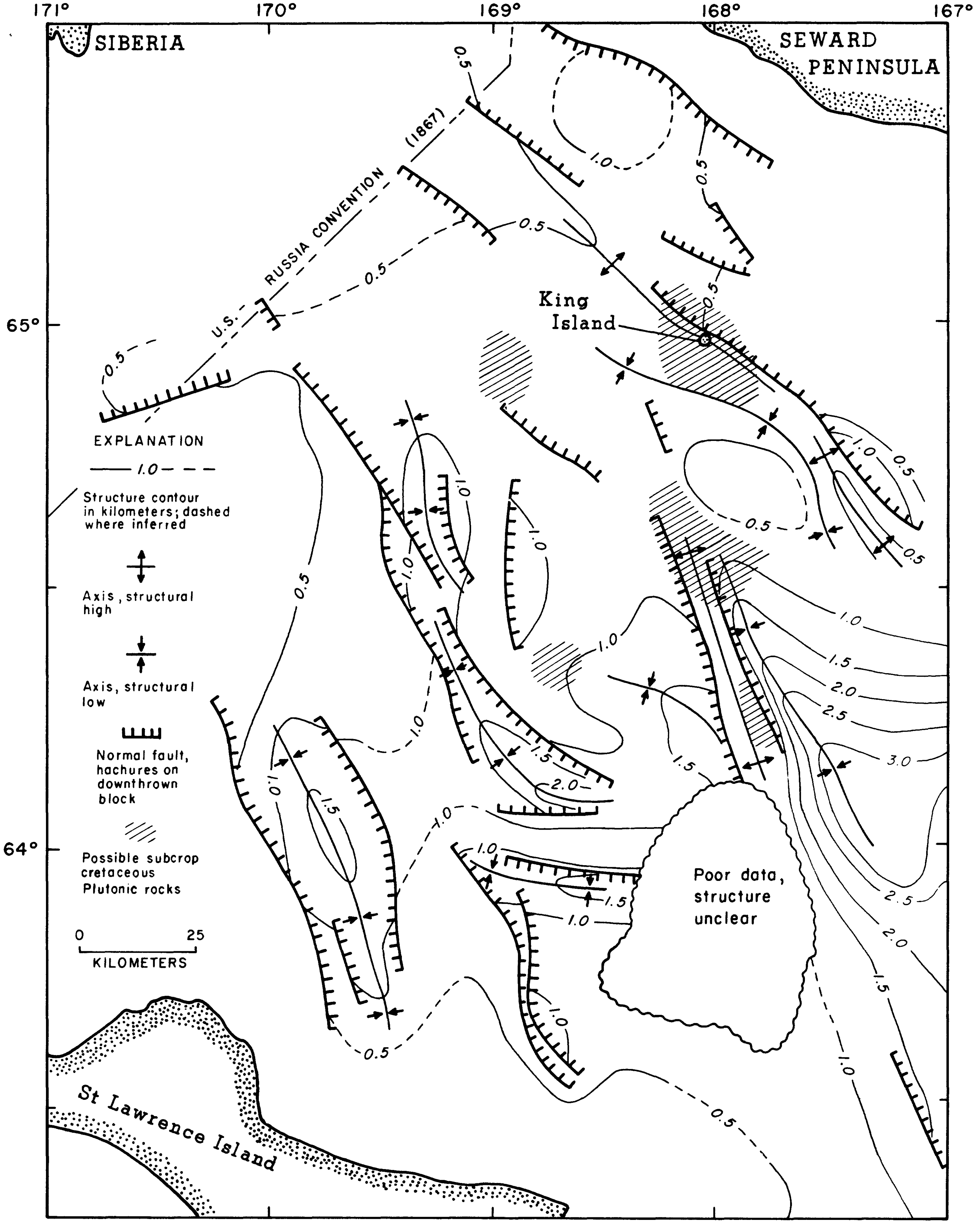
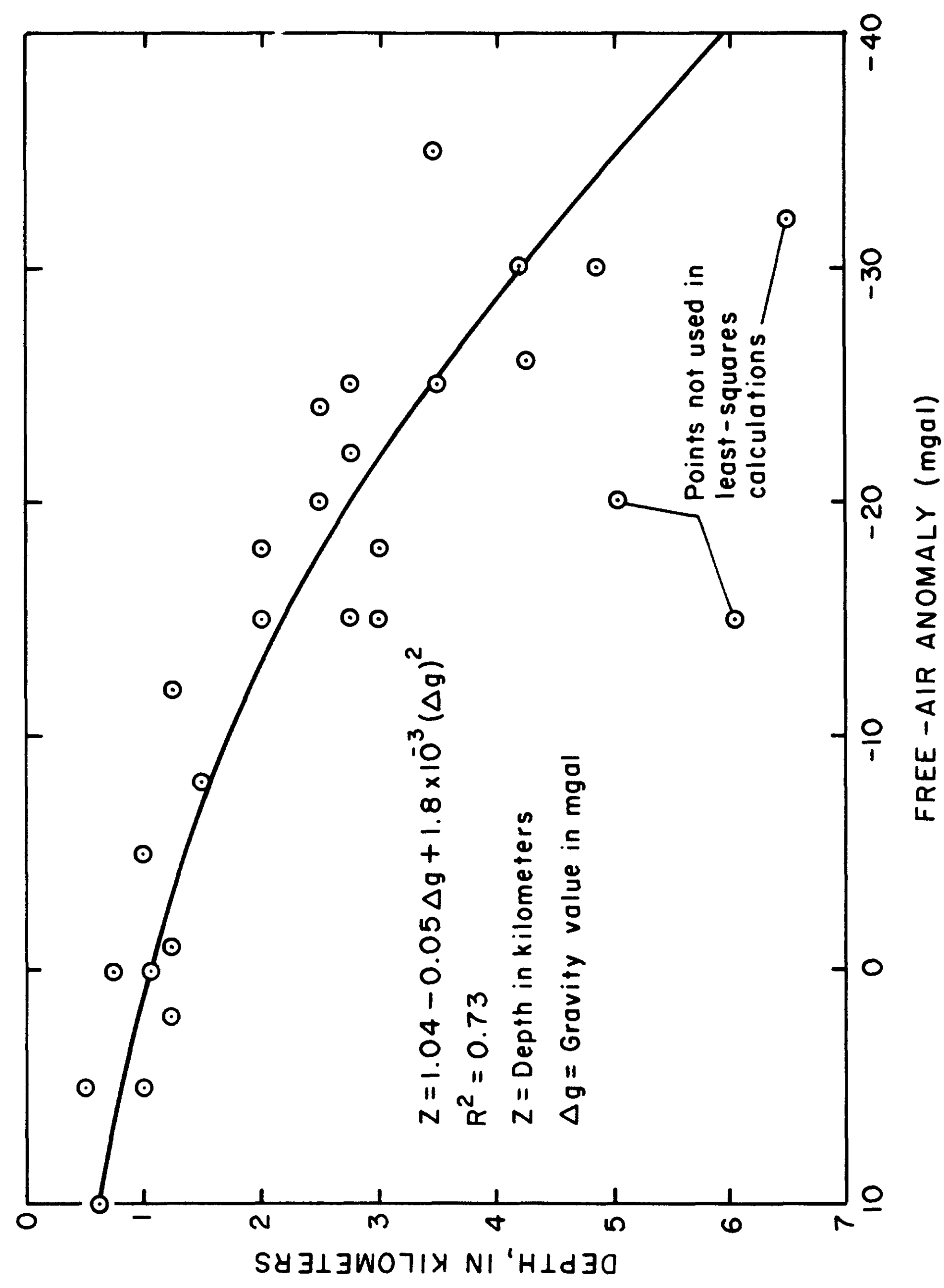

SONOBUOY-REFRACTION DATA
NIMIUK POINT NO I WELL
CAPE ESPENBERG NO I WELL
INTERVAL-VELOCITY DATA
TWO-WAY TIME, IN SECONDS
0
1.0
2.0
3.0
4.0
DEPTH, IN METERS
1000
2000
3000
4000
5000
INTERVAL VELOCITIES
SOCAL NIMIUK POINT NO I WELL
SOCAL CAPE ESPENBERG NO I WELL
VELOCITY, IN METERS/SECOND
1500
2000
3000
4000
5000
6000
6500

FIG. 6



171°
170°
169°
168°
167°
65°
64°
SIBERIA
SEWARD PENINSULA
U.S. - RUSSIA CONVENTION (1867)
King Island
St Lawrence Island
Poor data, structure unclear
EXPLANATION
1.0
Structure contour in kilometers; dashed where inferred
Axis, structural high
Axis, structural low
Normal fault, hachures on downthrown block
Possible subcrop cretaceous Plutonic rocks
0
25
KILOMETERS
0.5
1.0
1.5
2.0
2.5
3.0

FIG. 7



DEPTH, IN KILOMETERS
0
1
2
3
4
5
6
7
FREE -AIR ANOMALY (mgal)
10
0
-10
-20
-30
-40
Z = 1.04 − 0.05 Δg + 1.8 x 10^-3 (Δg)^2
R^2 = 0.73
Z = Depth in kilometers
Δg = Gravity value in mgal
Points not used in least-squares calculations

FIG. 8

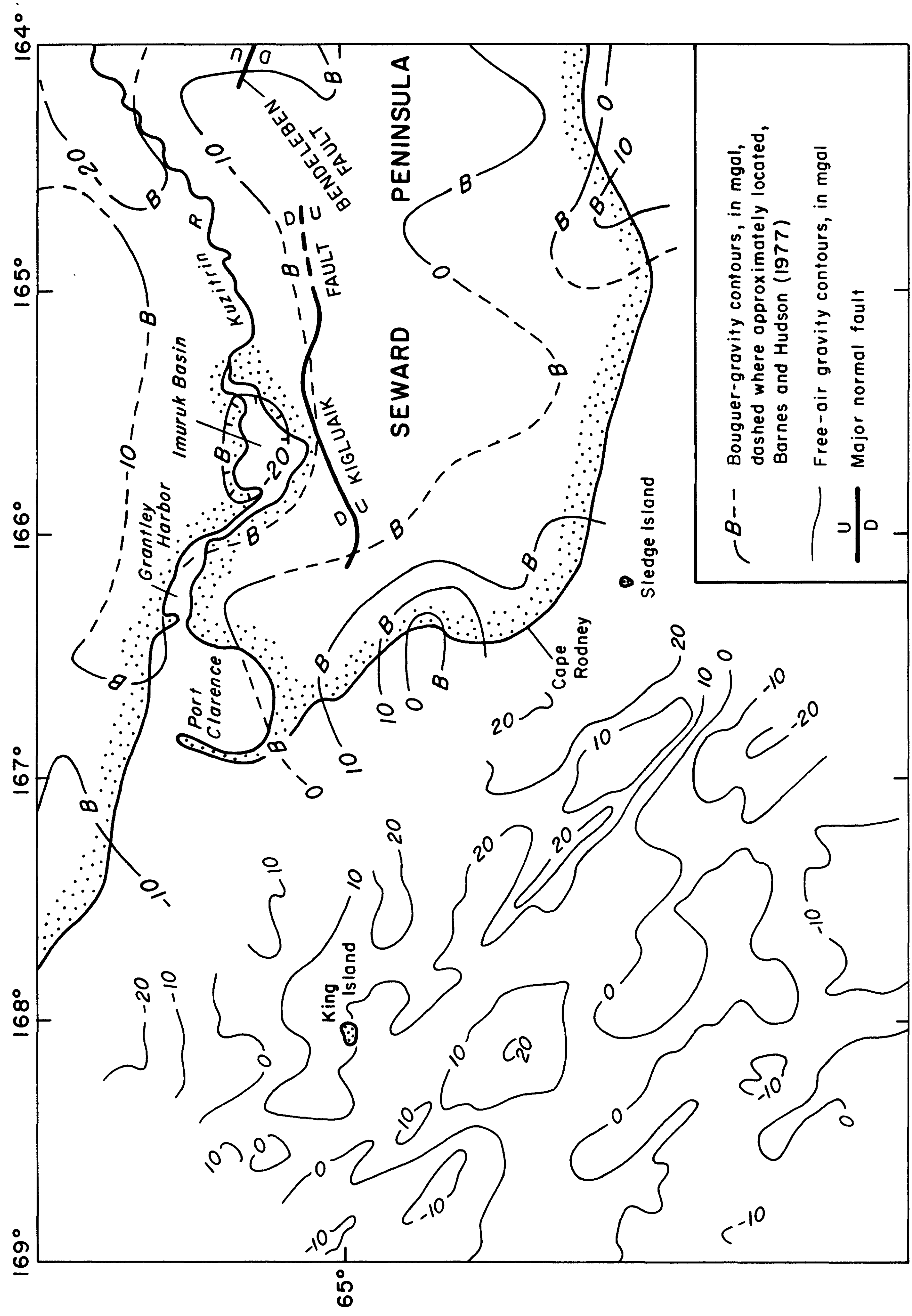

164°
165°
166°
167°
168°
169°
65°
SEWARD
PENINSULA
BENDELEBEN FAULT
KIGLUAIK FAULT
Kuzitrin R
Imuruk Basin
Grantley Harbor
Port Clarence
Cape Rodney
Sledge Island
King Island
Bouguer-gravity contours, in mgal, dashed where approximately located, Barnes and Hudson (1977)
Free-air gravity contours, in mgal
U
D
Major normal fault

FIG. 9

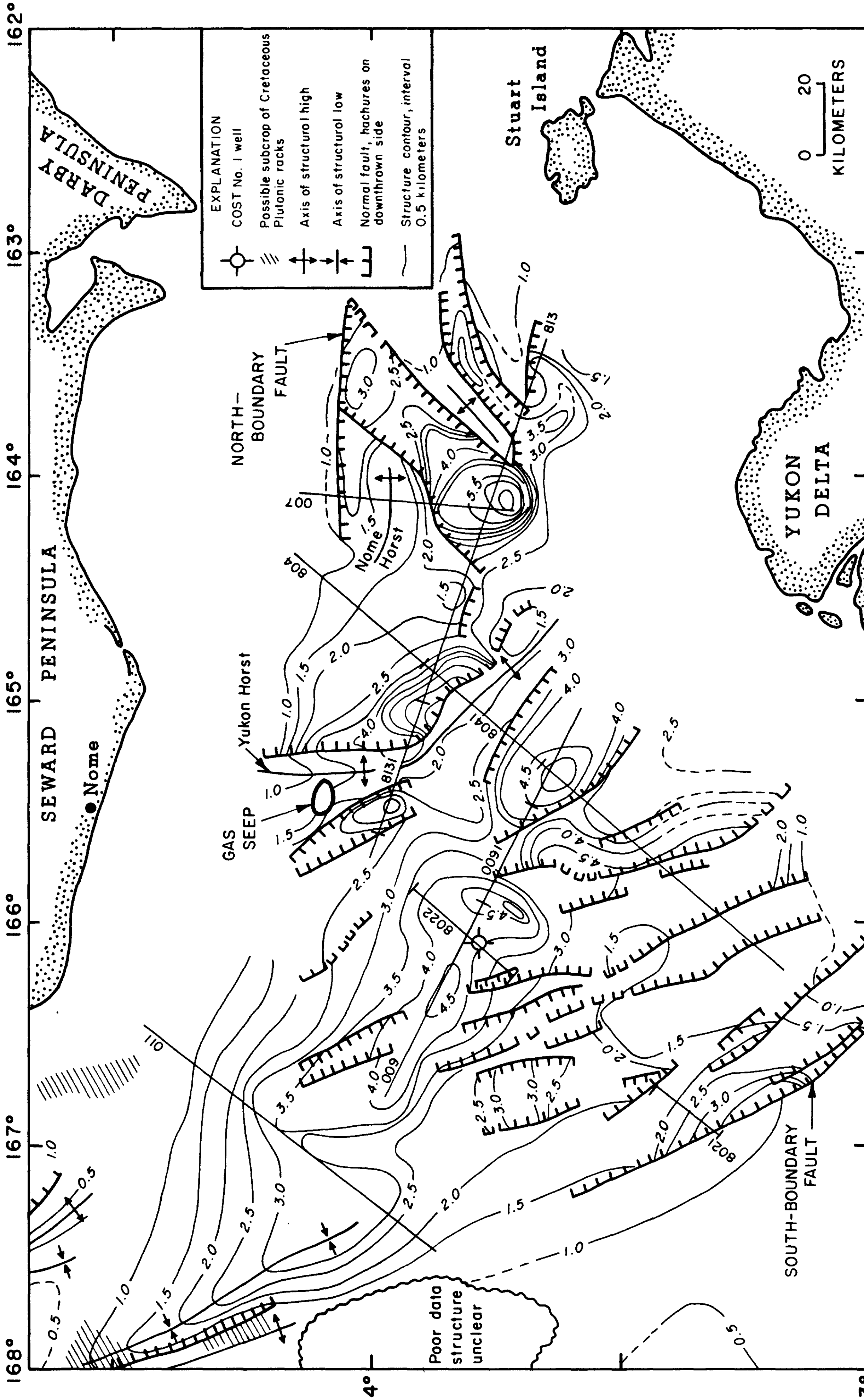

EXPLANATION
COST No. 1 well
Possible subcrop of Cretaceous Plutonic rocks
Axis of structural high
Axis of structural low
Normal fault, hachures on downthrown side
Structure contour, interval 0.5 kilometers
0 20 KILOMETERS
DARBY PENINSULA
SEWARD PENINSULA
Nome
Stuart Island
YUKON DELTA
NORTH-BOUNDARY FAULT
SOUTH-BOUNDARY FAULT
Nome Horst
Yukon Horst
GAS SEEP
Poor data structure unclear
162°
163°
164°
165°
166°
167°
168°
64°
63°

FIG. 10

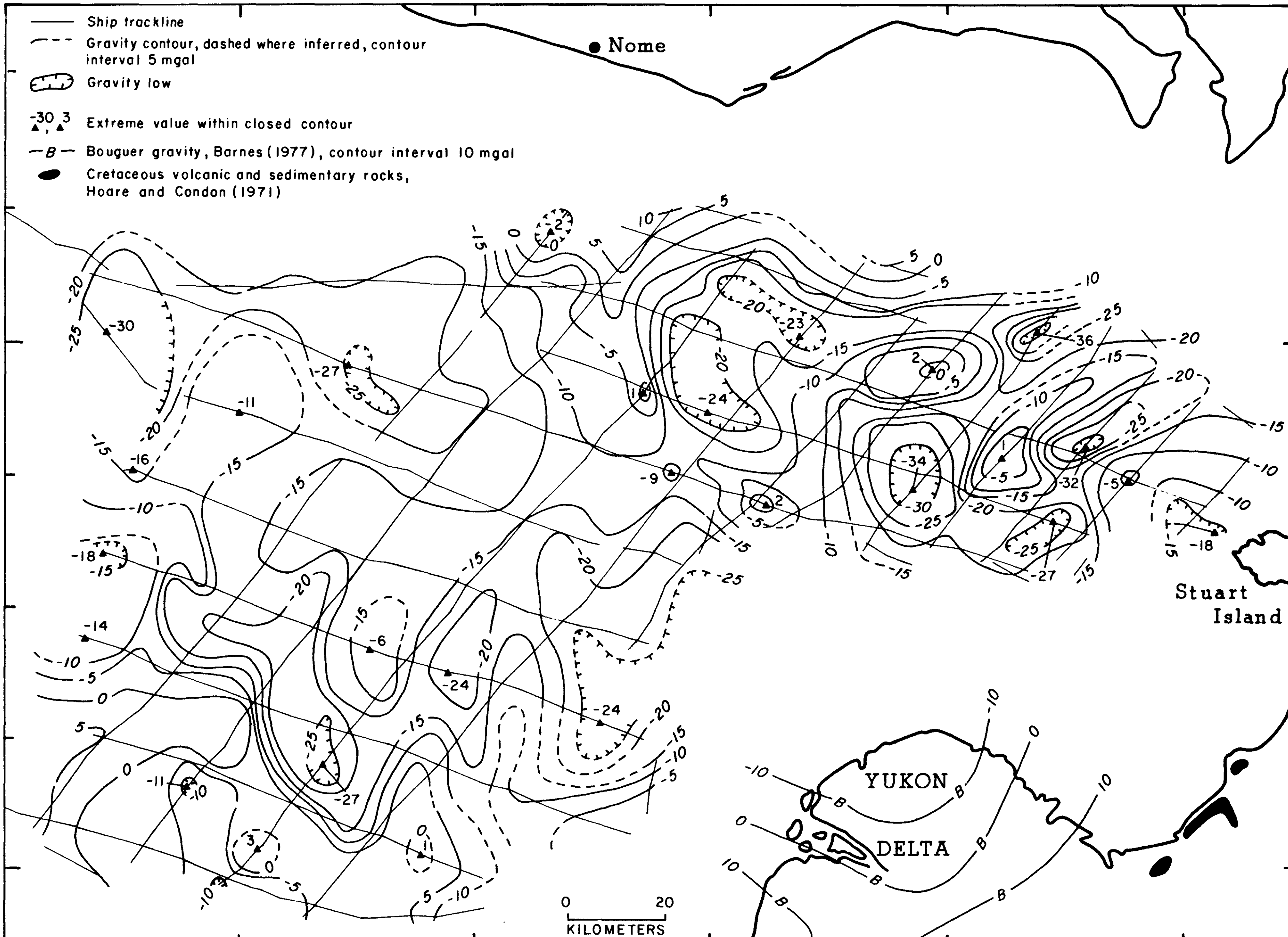

167°
166°
165°
164°
163°
64°
63°
Nome
Stuart Island
YUKON DELTA
Ship trackline
Gravity contour, dashed where inferred, contour interval 5 mgal
Gravity low
Extreme value within closed contour
Bouguer gravity, Barnes (1977), contour interval 10 mgal
Cretaceous volcanic and sedimentary rocks, Hoare and Condon (1971)
0 20
KILOMETERS

FIG. 11

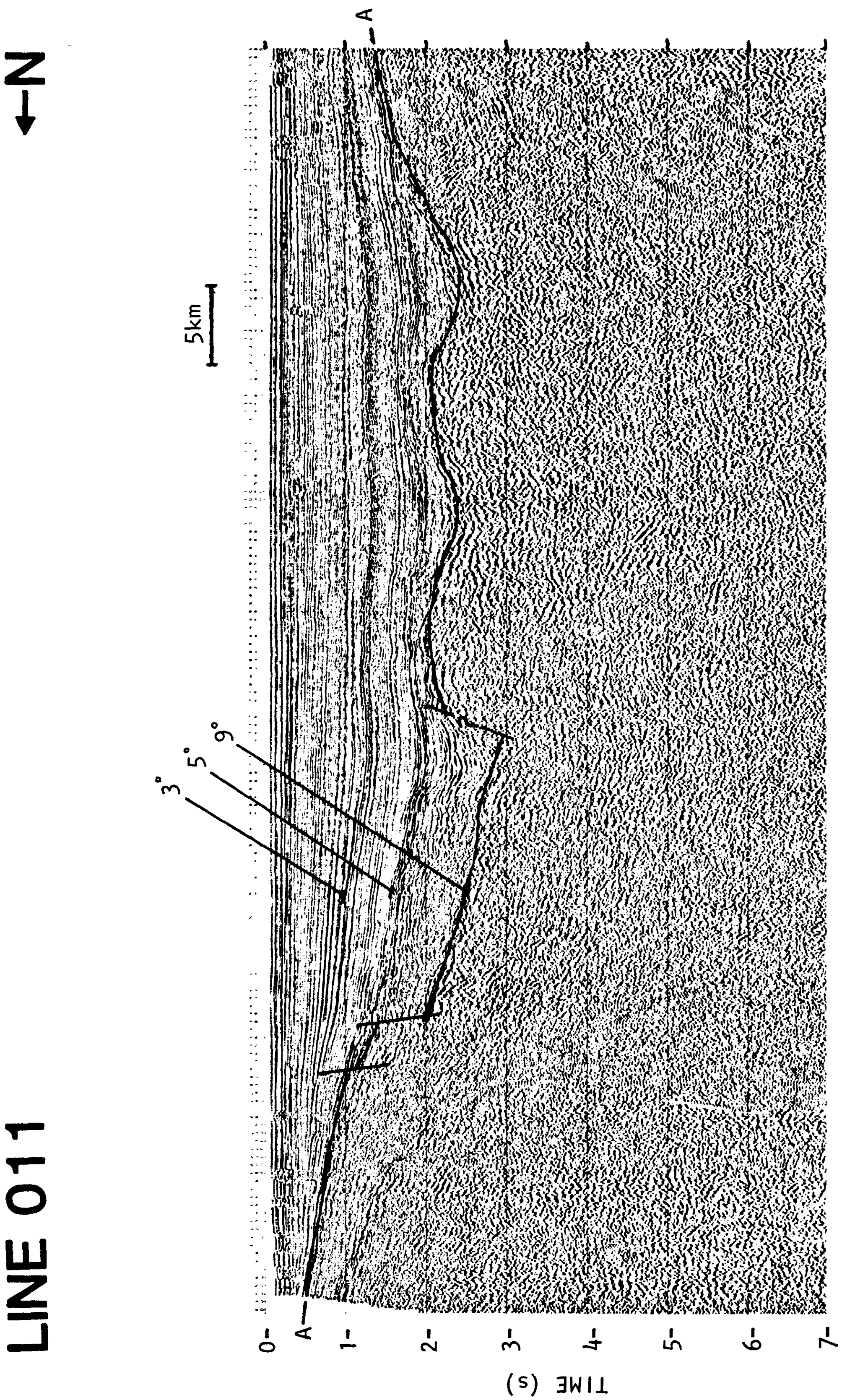


FIG. 12

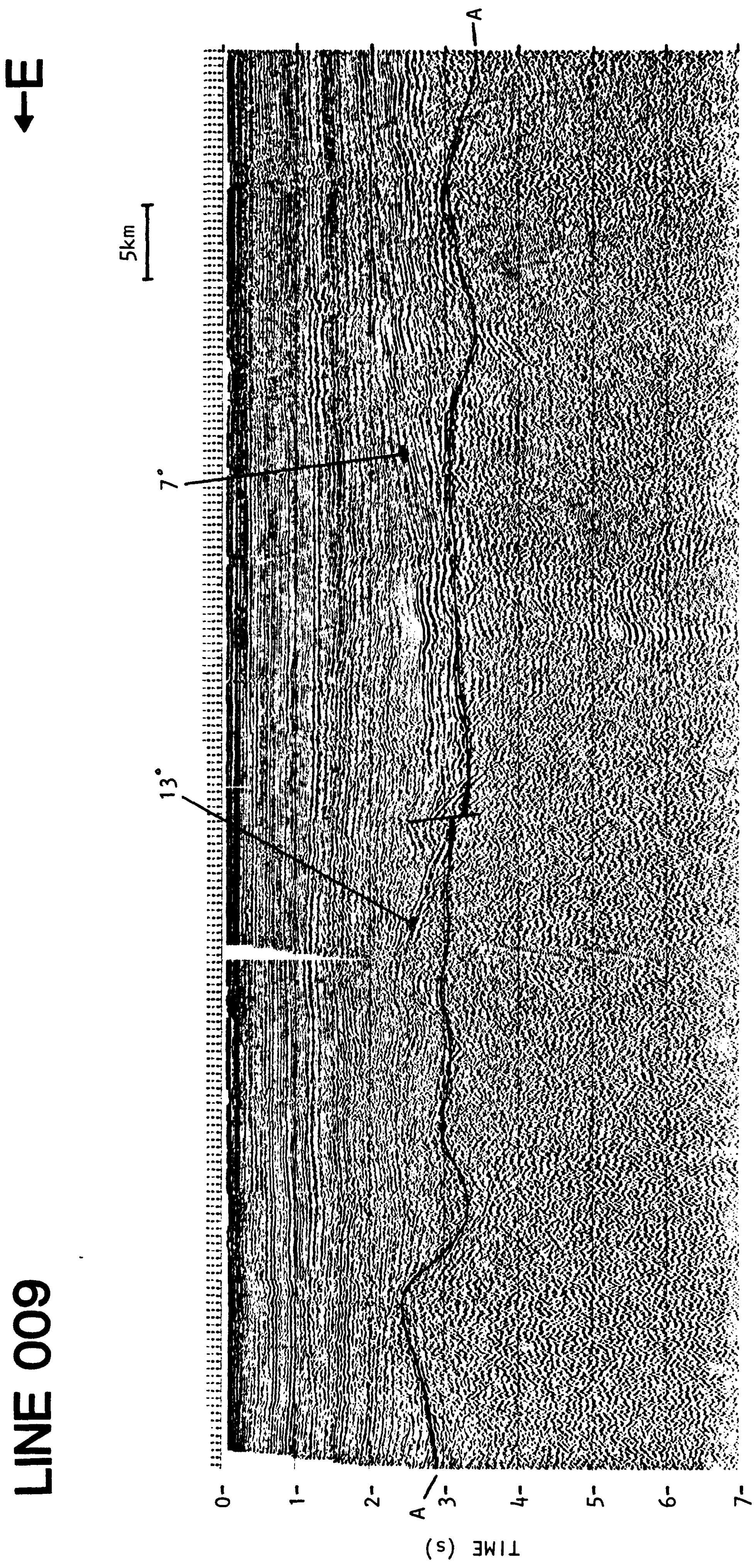
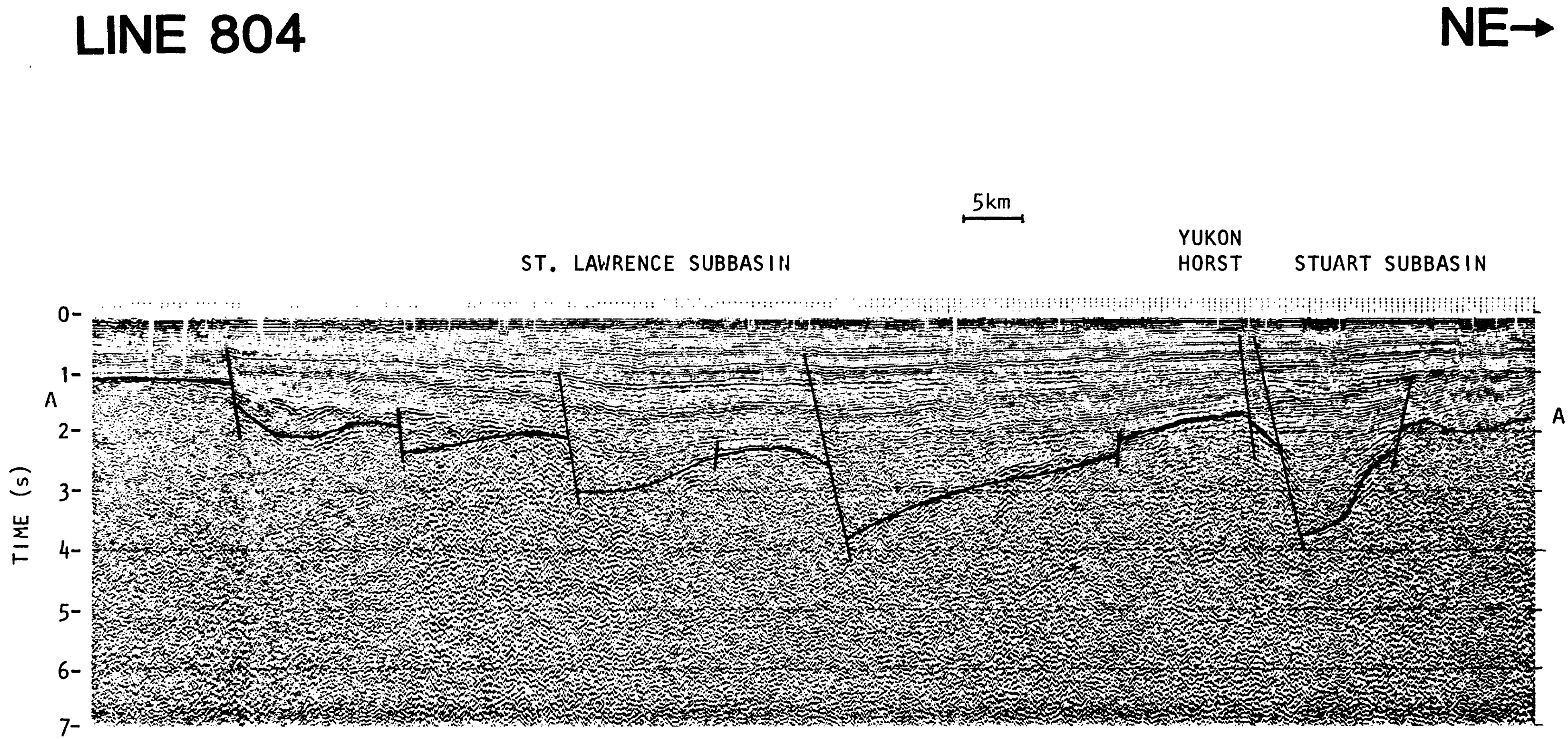
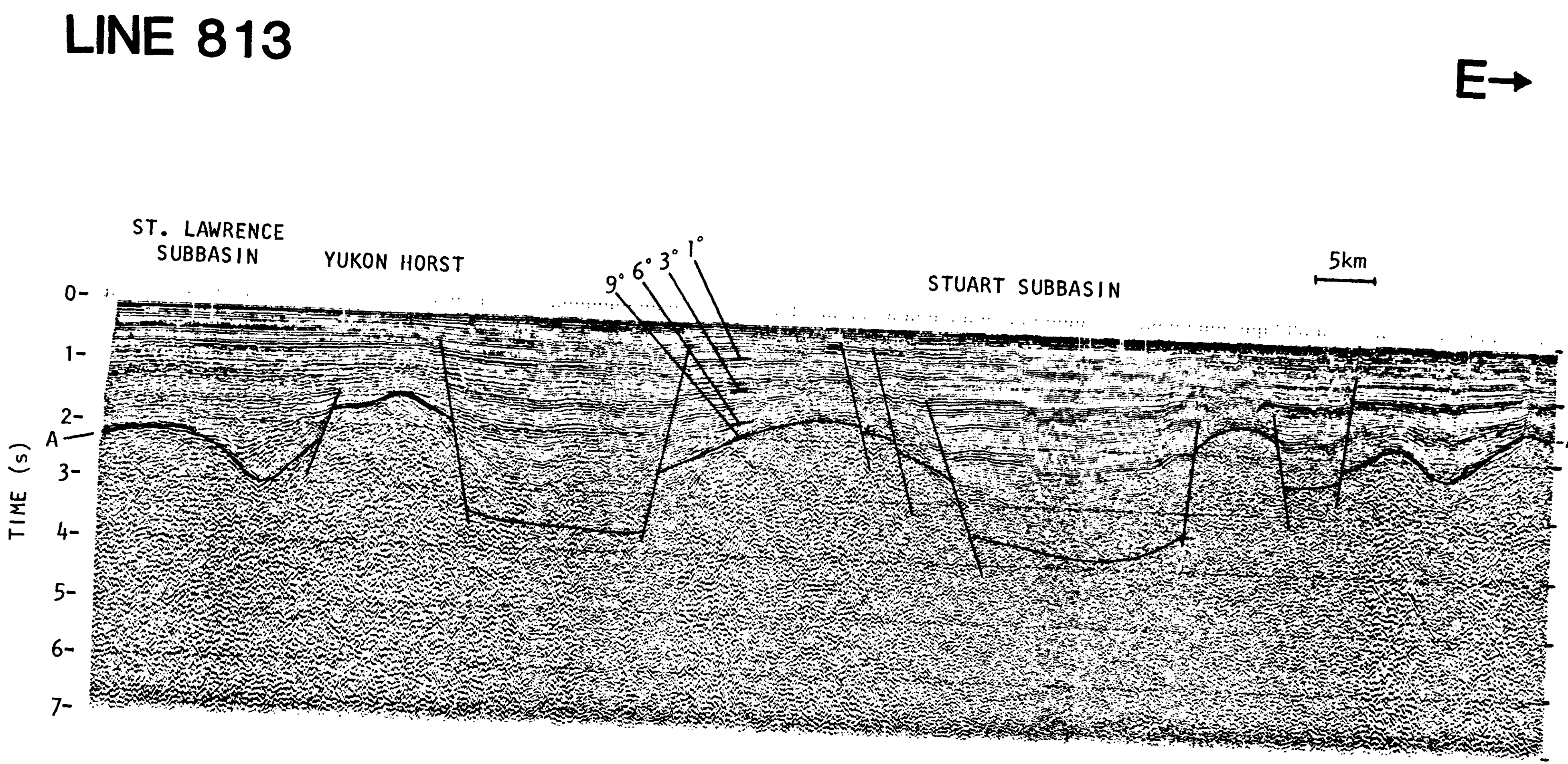


FIG. 13



LINE 804
NE→
5km
ST. LAWRENCE SUBBASIN
YUKON
HORST
STUART SUBBASIN
A
A
TIME (s)
0-
1-
2-
3-
4-
5-
6-
7-

FIG. 14



LINE 813
E→
ST. LAWRENCE SUBBASIN
YUKON HORST
9° 6° 3° 1°
STUART SUBBASIN
5km
0-
1-
2-
3-
4-
5-
6-
7-
TIME (s)
A
A

FIG. 15

LINE 8021

NE→

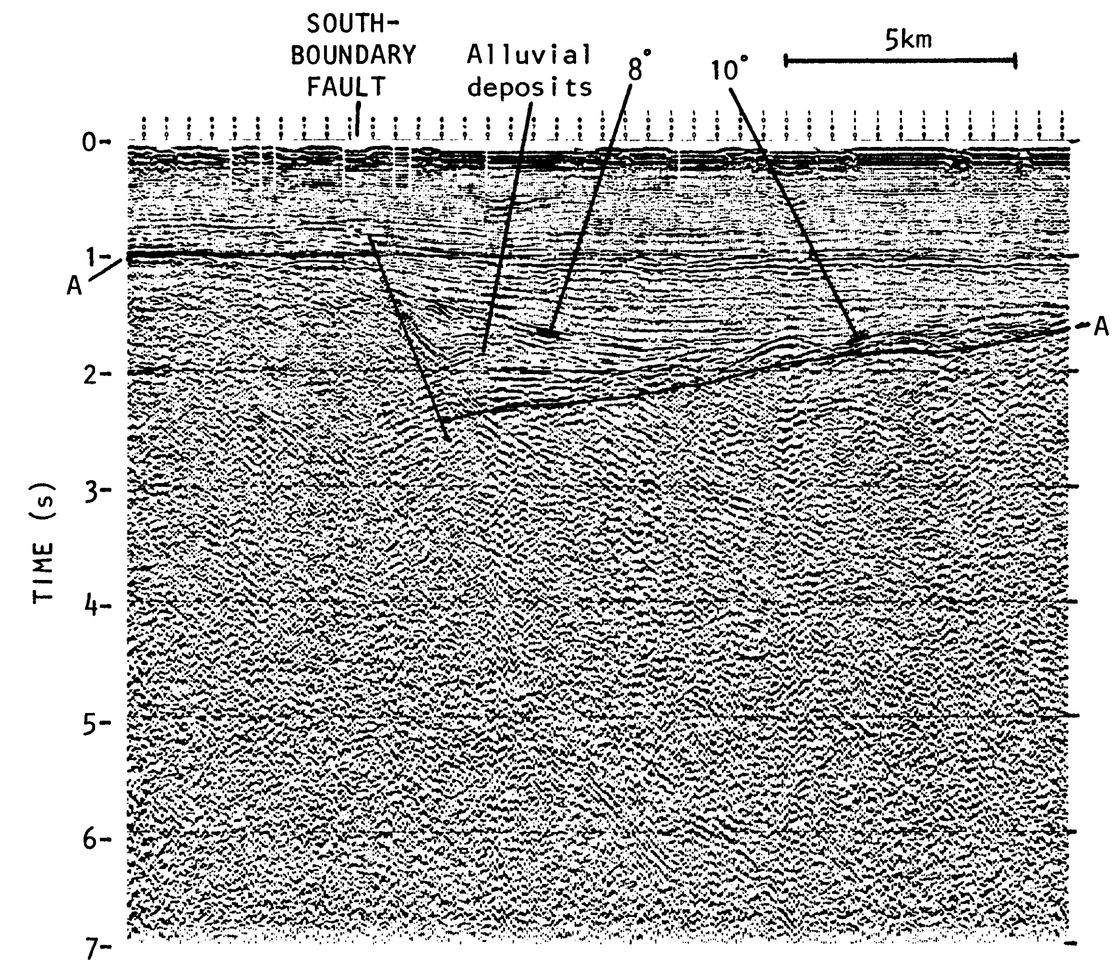
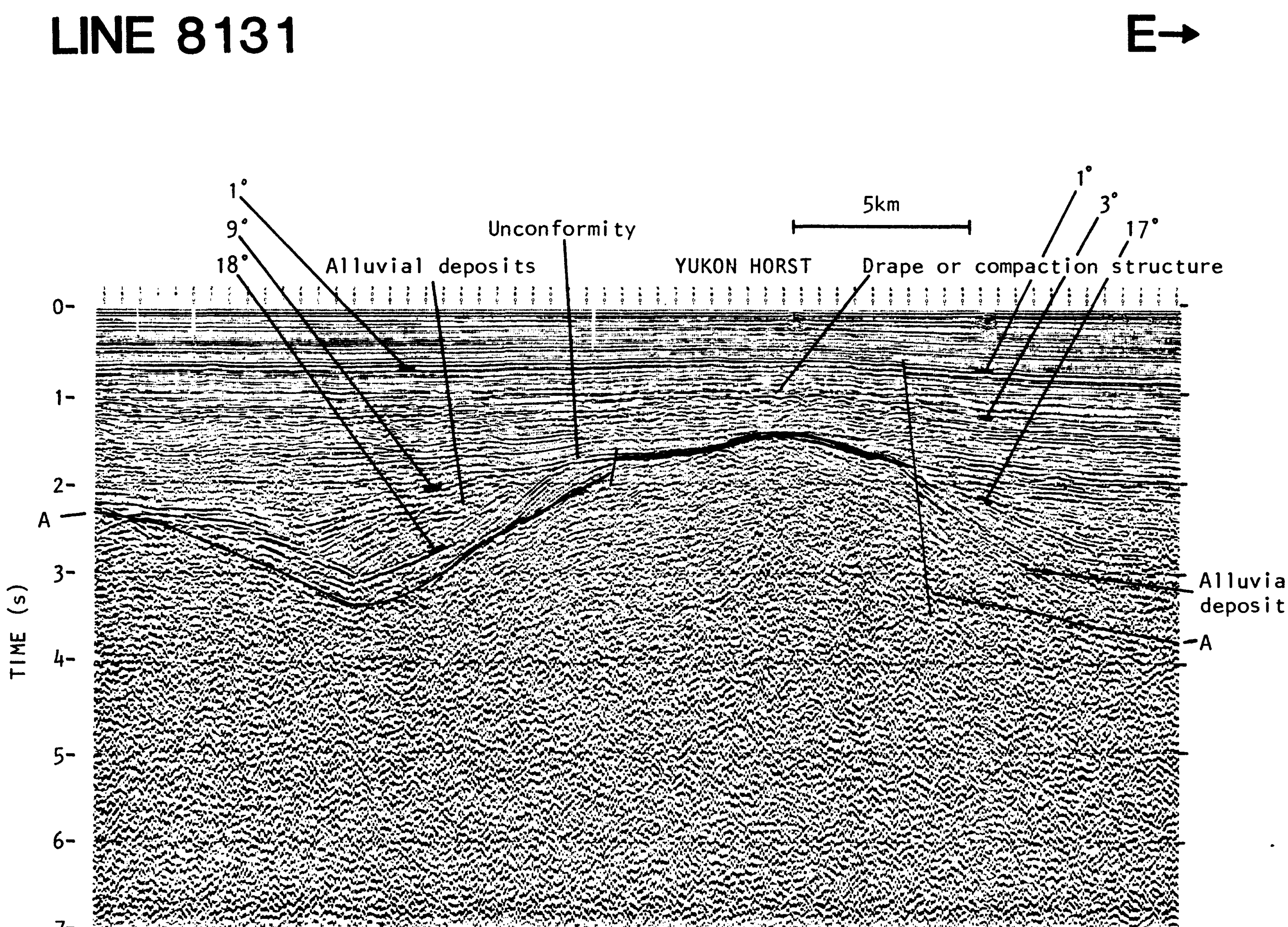


FIG. 16a



LINE 8131
E→
1°
9°
18°
Alluvial deposits
Unconformity
YUKON HORST
5km
Drape or compaction structure
1°
3°
17°
A
A
Alluvial deposits
TIME (s)
0
1
2
3
4
5
6
7

FIG. 16b

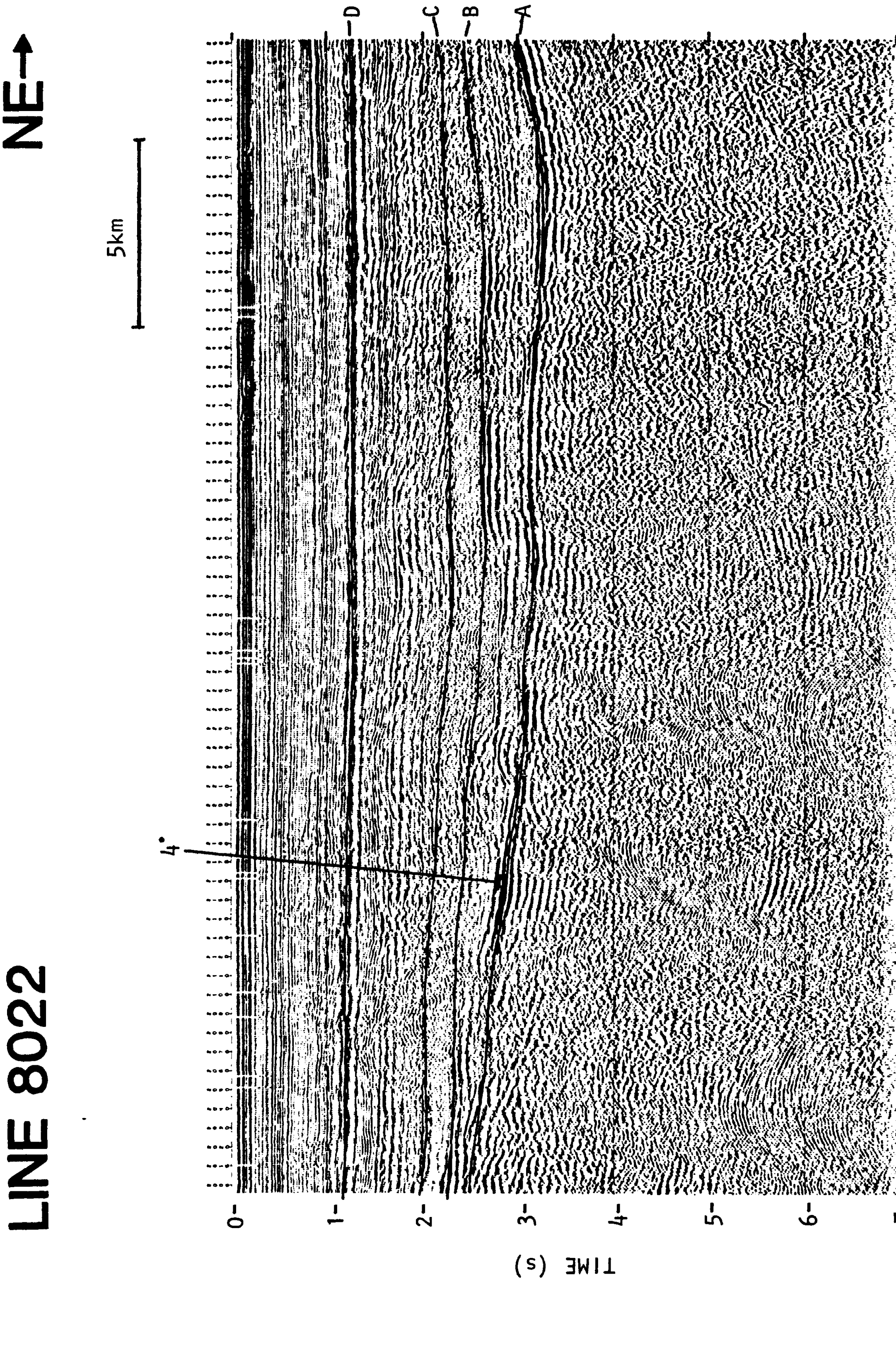


FIG. 16c

LINE 0091

←E

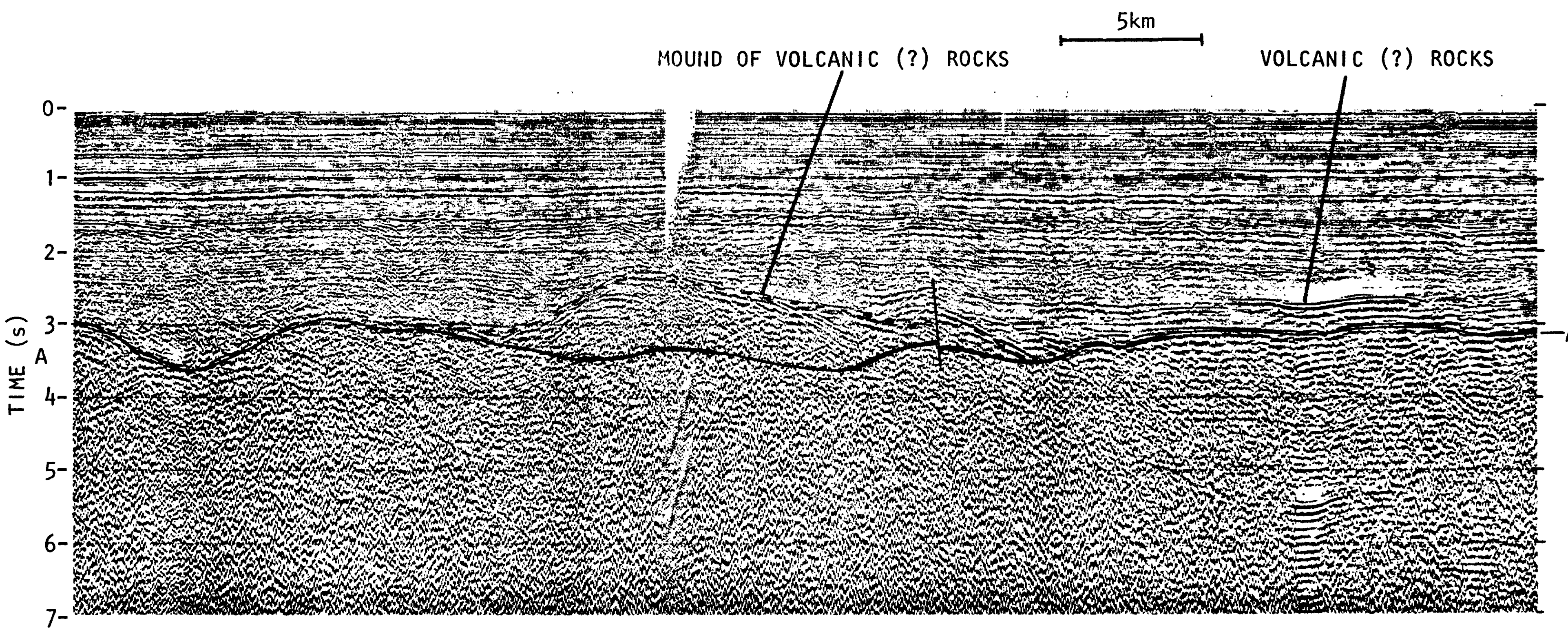


FIG. 16d

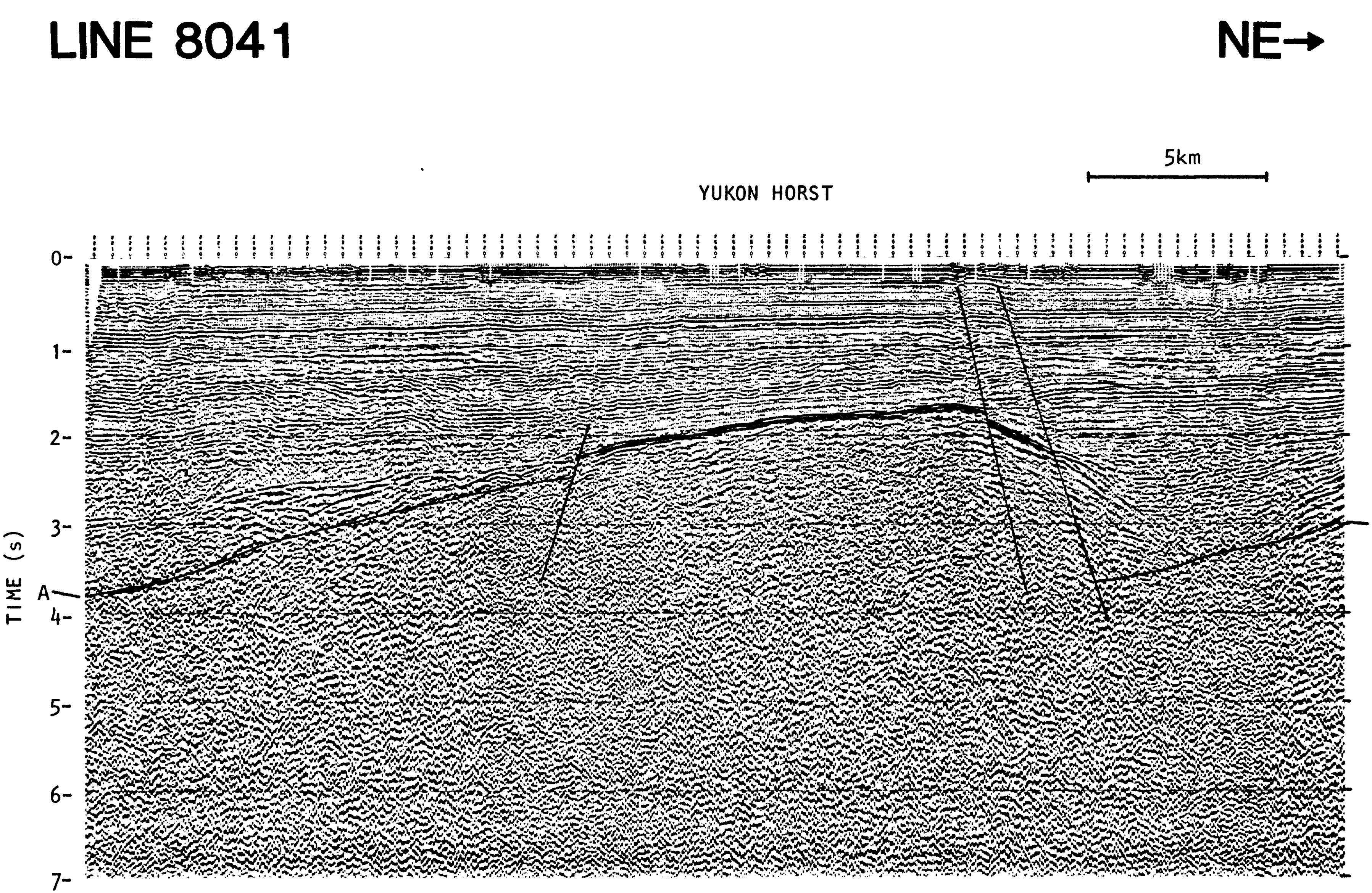


FIG.. 17

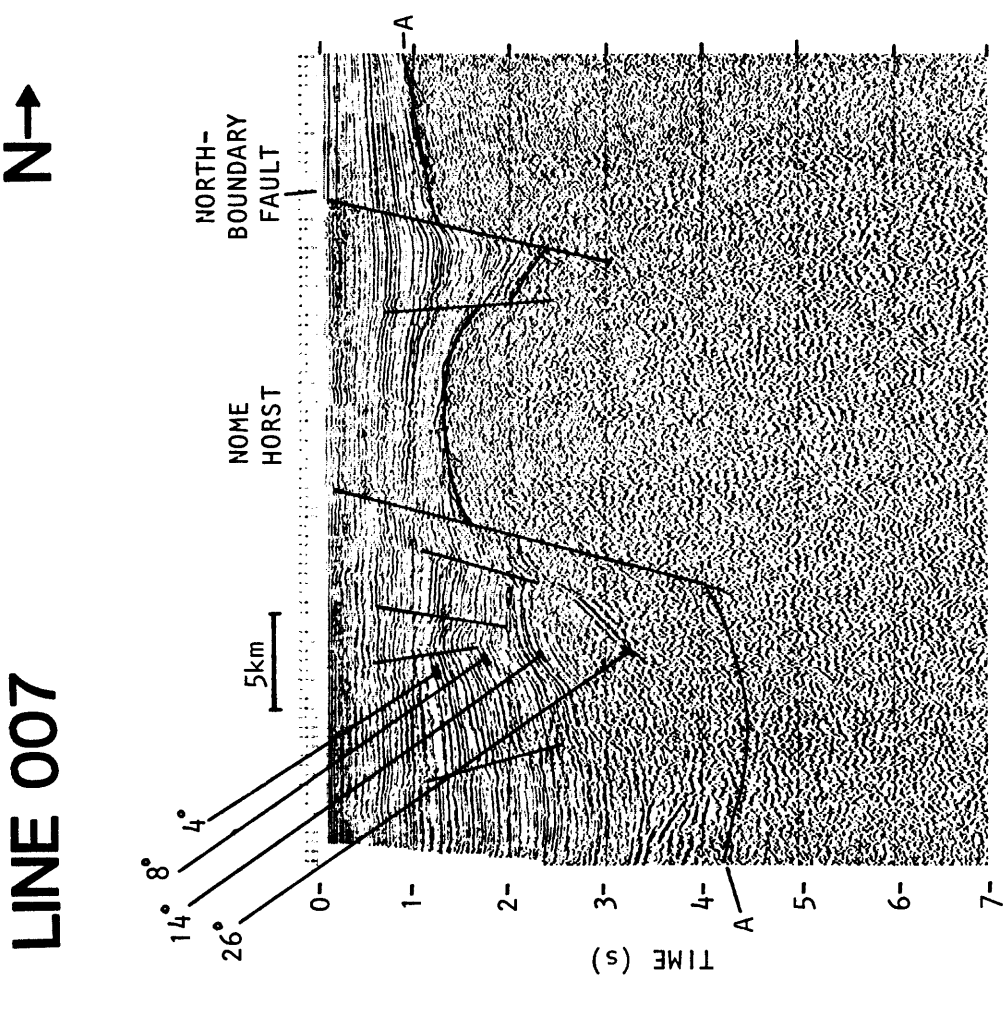

LINE 007
N→
NORTH-
BOUNDARY
FAULT
NOME
HORST
5km
4°
8°
14°
26°
TIME (s)
0-
1-
2-
3-
4-
5-
6-
7-
A
A

FIG. 18

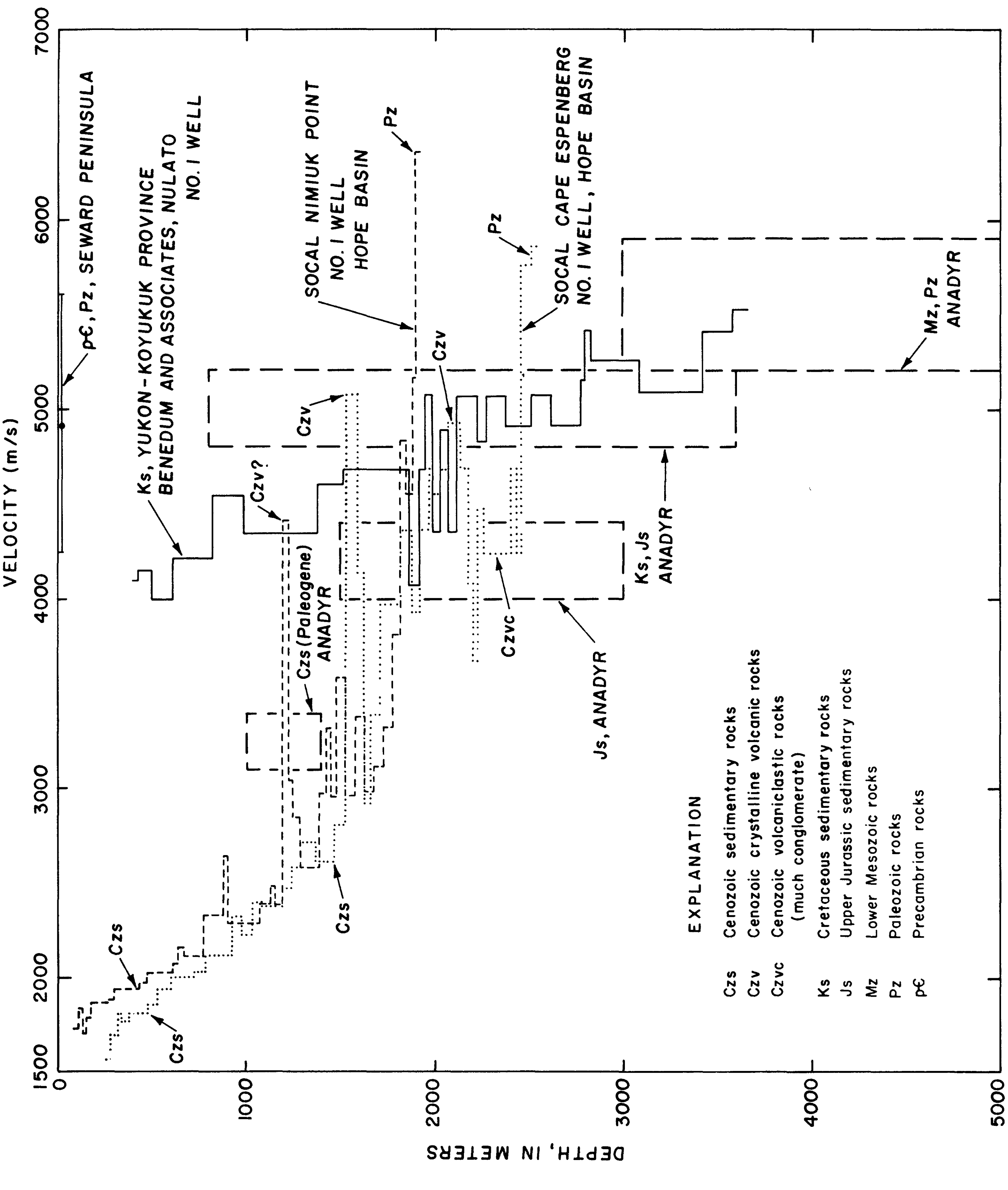

VELOCITY (m/s)
DEPTH, IN METERS
1500
2000
3000
4000
5000
6000
7000
0
1000
2000
3000
4000
5000
p€, Pz, SEWARD PENINSULA
Ks, YUKON-KOYUKUK PROVINCE
BENEDUM AND ASSOCIATES, NULATO
NO. I WELL
SOCAL NIMIUK POINT
NO. I WELL
HOPE BASIN
Pz
SOCAL CAPE ESPENBERG
NO. I WELL, HOPE BASIN
Pz
Mz, Pz
ANADYR
Czv?
Czv
Czv
Czs (Paleogene)
ANADYR
Czvc
Ks, Js
ANADYR
ANADYR
Js, ANADYR
Czs
Czs
Czs
EXPLANATION
Czs Cenozoic sedimentary rocks
Czv Cenozoic crystalline volcanic rocks
Czvc Cenozoic volcaniclastic rocks
(much conglomerate)
Ks Cretaceous sedimentary rocks
Js Upper Jurassic sedimentary rocks
Mz Lower Mesozoic rocks
Pz Paleozoic rocks
p€ Precambrian rocks

FIG. 19a

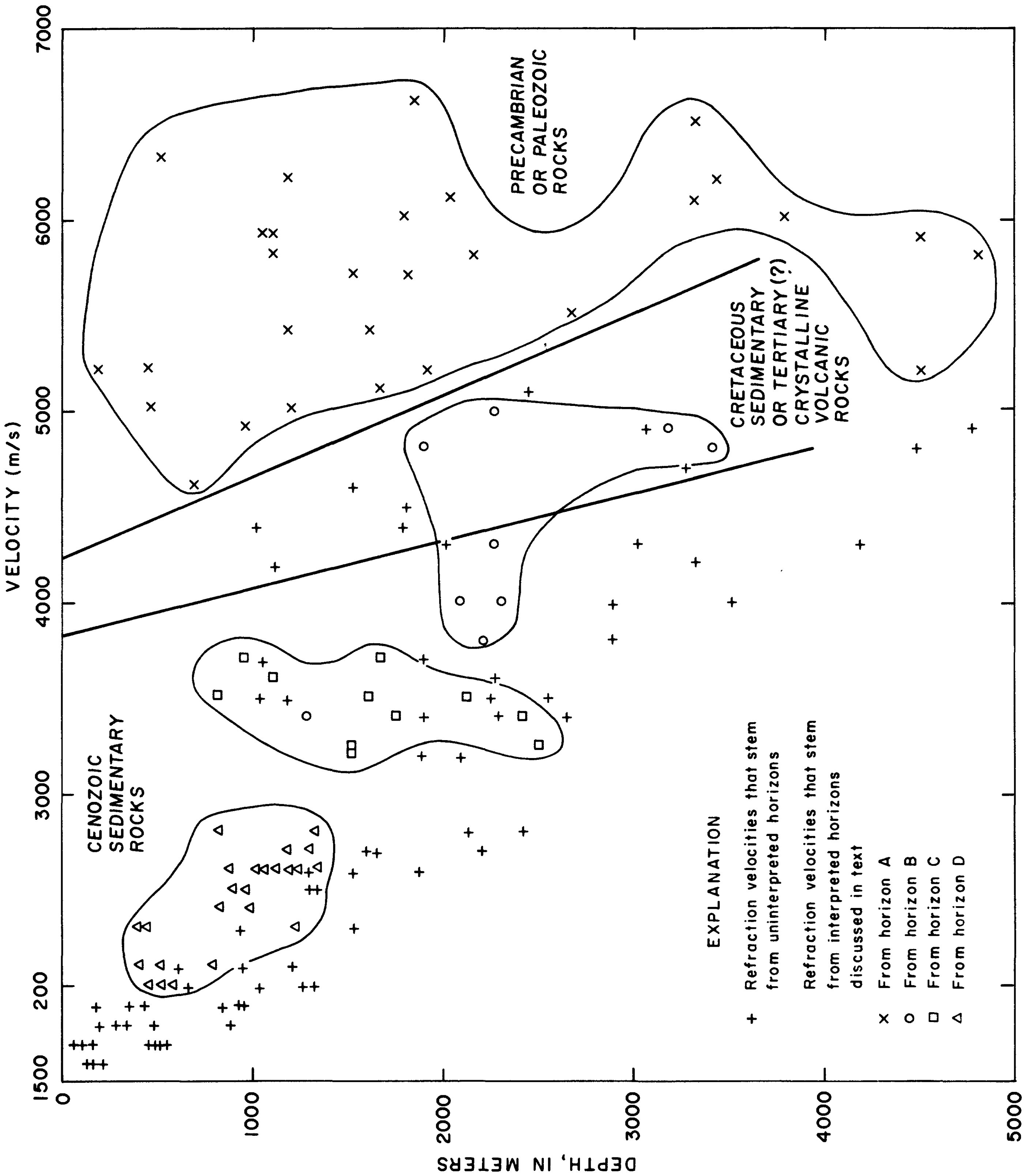

VELOCITY (m/s)
DEPTH, IN METERS
1500
2000
3000
4000
5000
6000
7000
0
1000
2000
3000
4000
5000
PRECAMBRIAN OR PALEOZOIC ROCKS
CRETACEOUS SEDIMENTARY OR TERTIARY (?) CRYSTALLINE VOLCANIC ROCKS
CENOZOIC SEDIMENTARY ROCKS
EXPLANATION
+ Refraction velocities that stem from uninterpreted horizons
Refraction velocities that stem from interpreted horizons discussed in text
× From horizon A
○ From horizon B
□ From horizon C
◁ From horizon D

FIG. 19b

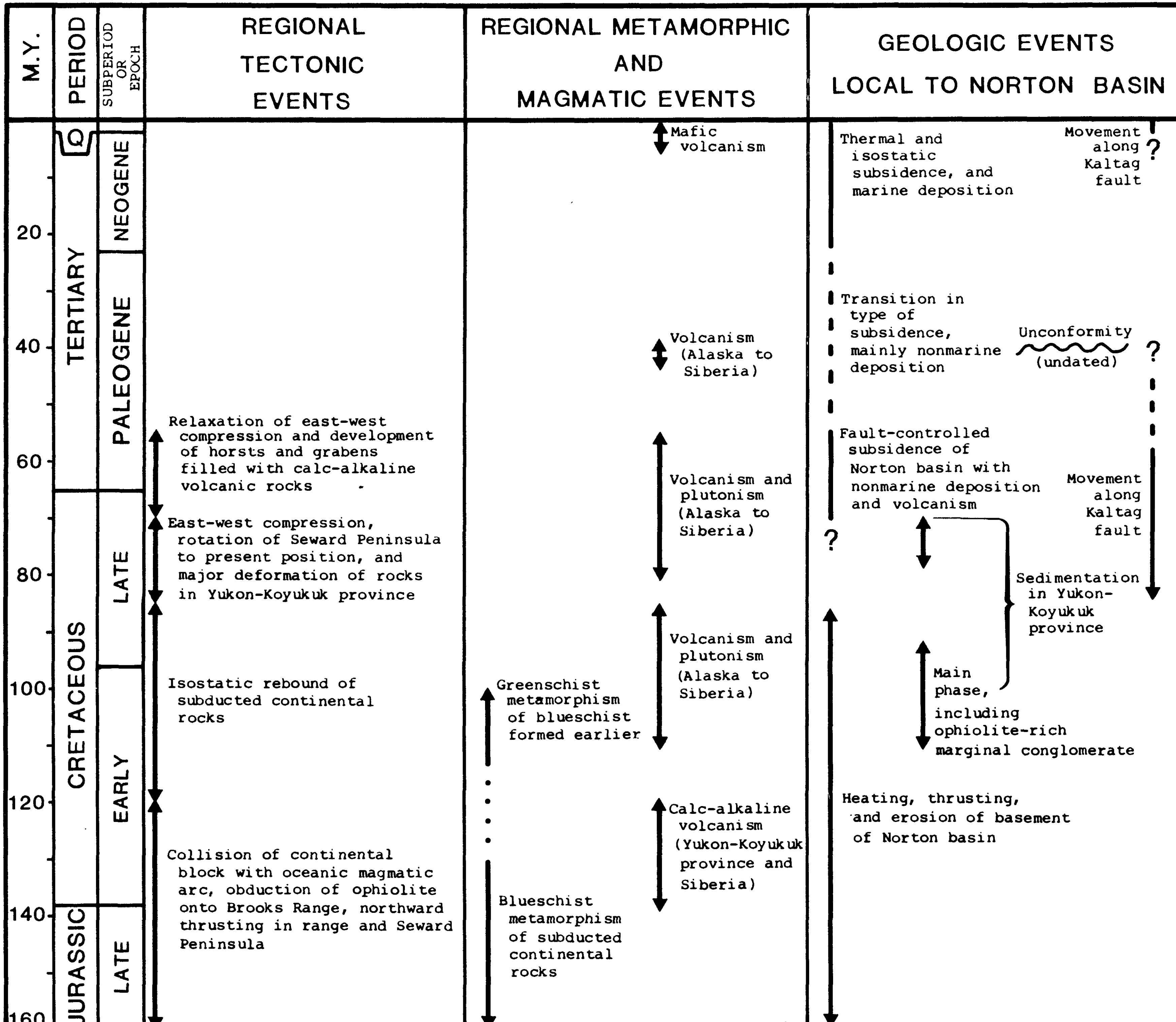

M.Y.
PERIOD
SUBPERIOD OR EPOCH
REGIONAL TECTONIC EVENTS
REGIONAL METAMORPHIC AND MAGMATIC EVENTS
GEOLOGIC EVENTS LOCAL TO NORTON BASIN
20
40
60
80
100
120
140
160
Q
TERTIARY
CRETACEOUS
JURASSIC
NEOGENE
PALEOGENE
LATE
EARLY
LATE
Relaxation of east-west compression and development of horsts and grabens filled with calc-alkaline volcanic rocks
East-west compression, rotation of Seward Peninsula to present position, and major deformation of rocks in Yukon-Koyukuk province
Isostatic rebound of subducted continental rocks
Collision of continental block with oceanic magmatic arc, obduction of ophiolite onto Brooks Range, northward thrusting in range and Seward Peninsula
Mafic volcanism
Volcanism (Alaska to Siberia)
Volcanism and plutonism (Alaska to Siberia)
Volcanism and plutonism (Alaska to Siberia)
Calc-alkaline volcanism (Yukon-Koyukuk province and Siberia)
Greenschist metamorphism of blueschist formed earlier
Blueschist metamorphism of subducted continental rocks
Thermal and isostatic subsidence, and marine deposition
Movement along Kaltag fault
?
Transition in type of subsidence, mainly nonmarine deposition
Unconformity (undated)
?
Fault-controlled subsidence of Norton basin with nonmarine deposition and volcanism
Movement along Kaltag fault
?
Sedimentation in Yukon-Koyukuk province
Main phase, including ophiolite-rich marginal conglomerate
Heating, thrusting, and erosion of basement of Norton basin

FIG. 20

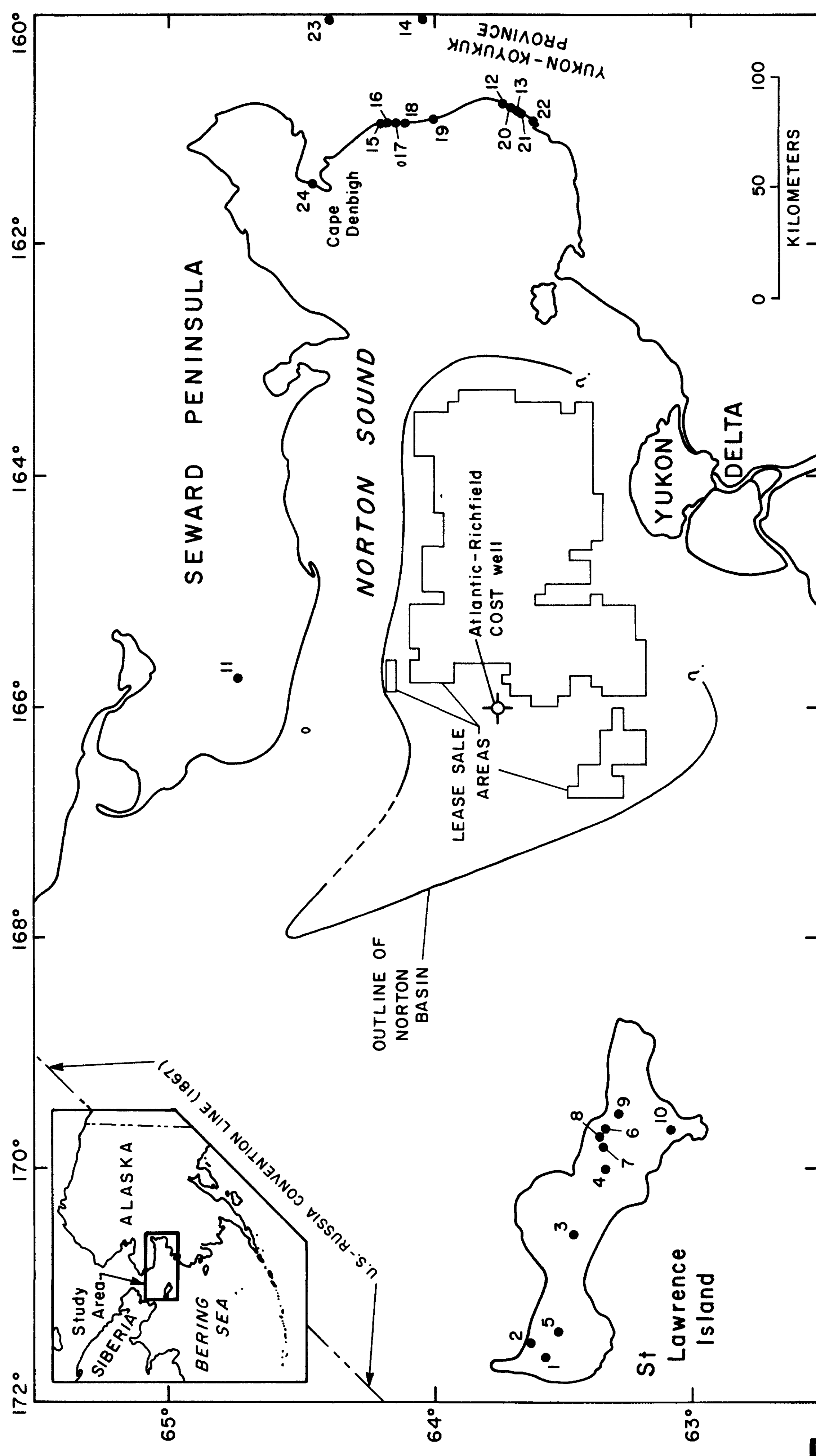

SEWARD PENINSULA
NORTON SOUND
YUKON DELTA
YUKON-KOYUKUK PROVINCE
Cape Denbigh
Atlantic-Richfield COST well
LEASE SALE AREAS
OUTLINE OF NORTON BASIN
St Lawrence Island
U.S.-RUSSIA CONVENTION LINE (1867)
ALASKA
SIBERIA
BERING SEA
Study Area
KILOMETERS
0
50
100
160°
162°
164°
166°
168°
170°
172°
65°
64°
63°
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

FIG. 21

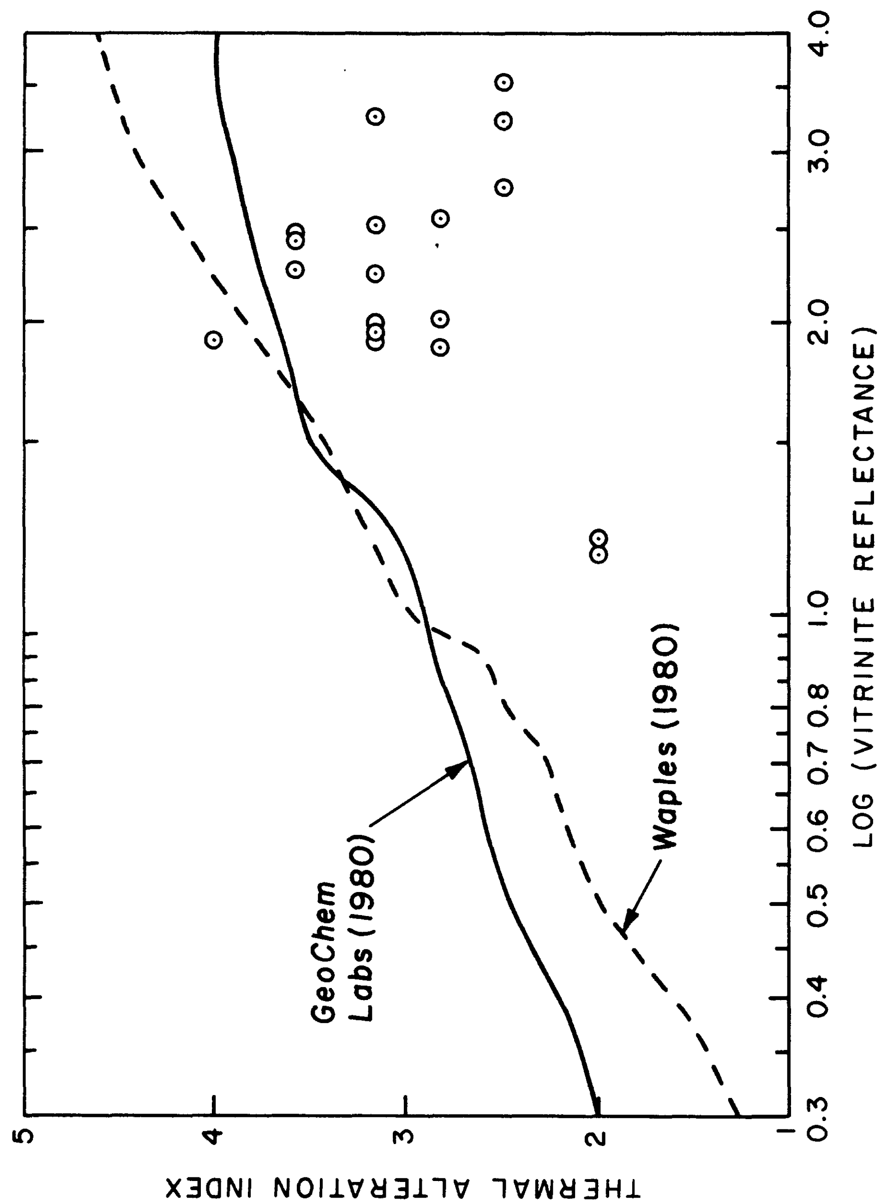

THERMAL ALTERATION INDEX
5
4
3
2
1
0.3
0.4
0.5
0.6
0.7
0.8
1.0
2.0
3.0
4.0
LOG (VITRINITE REFLECTANCE)
GeoChem Labs (1980)
Waples (1980)

FIG. 22

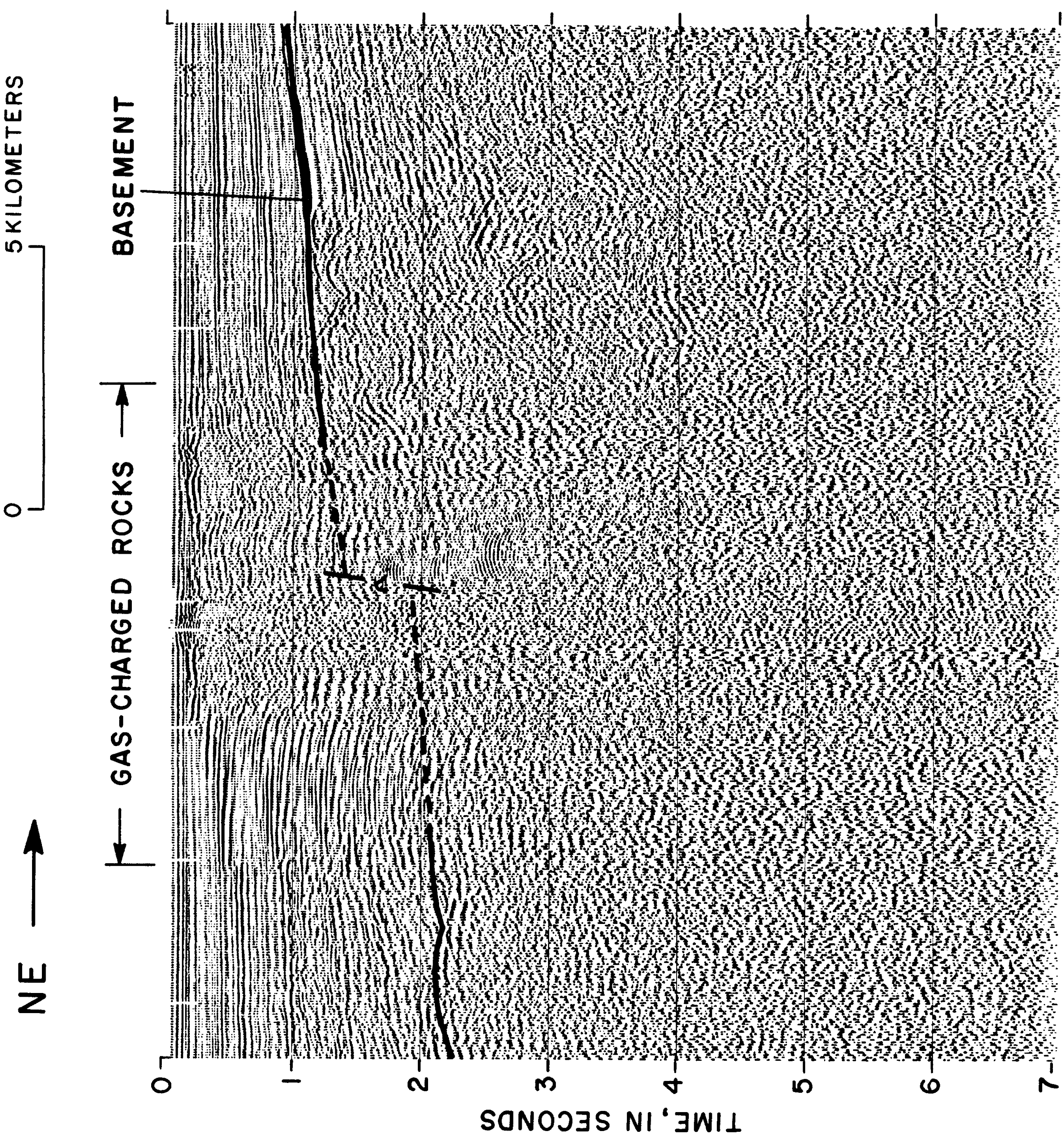

NE
5 KILOMETERS
0
5
GAS-CHARGED ROCKS
BASEMENT
A
TIME, IN SECONDS
0
1
2
3
4
5
6
7

FIG. 23

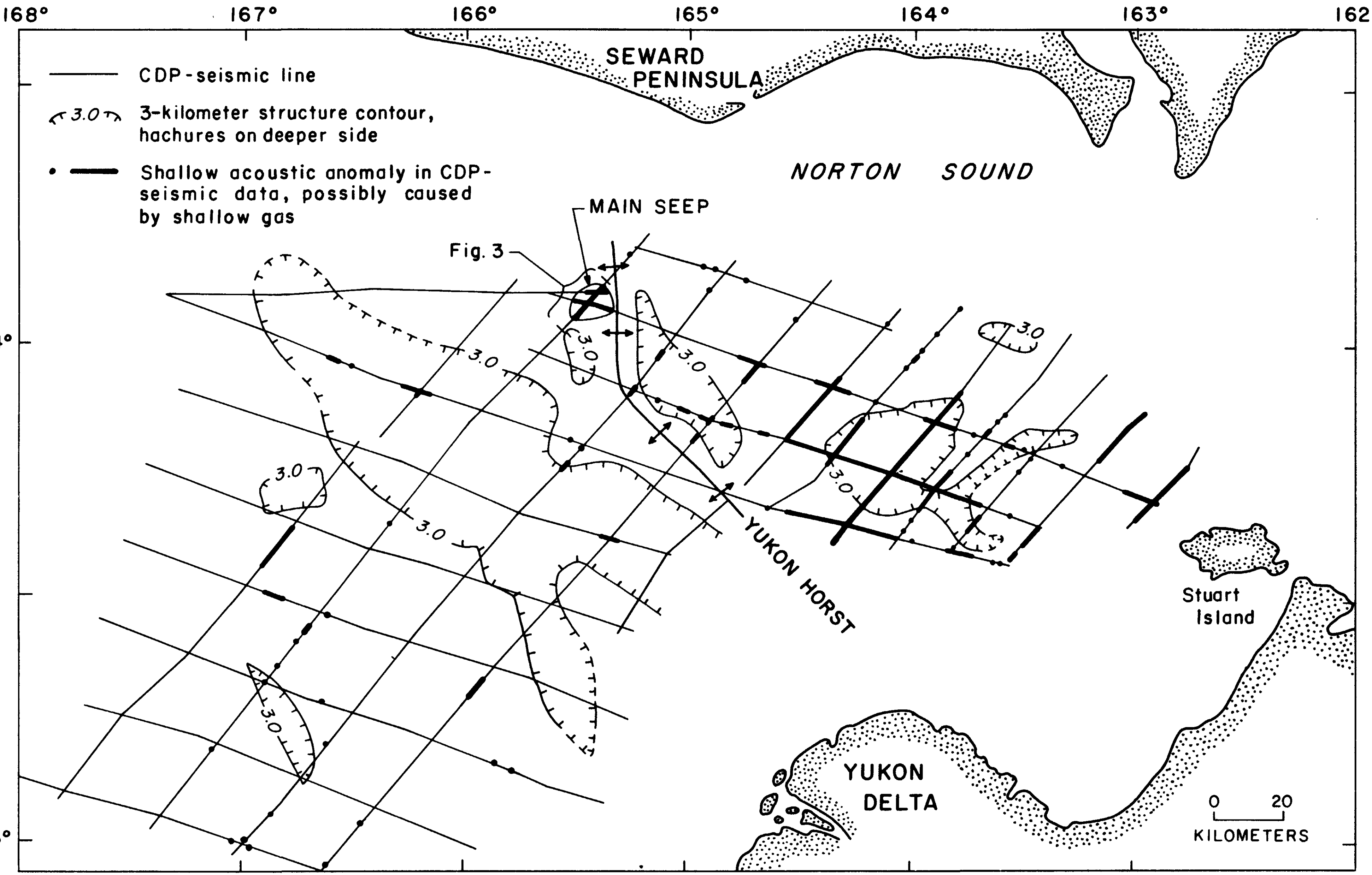
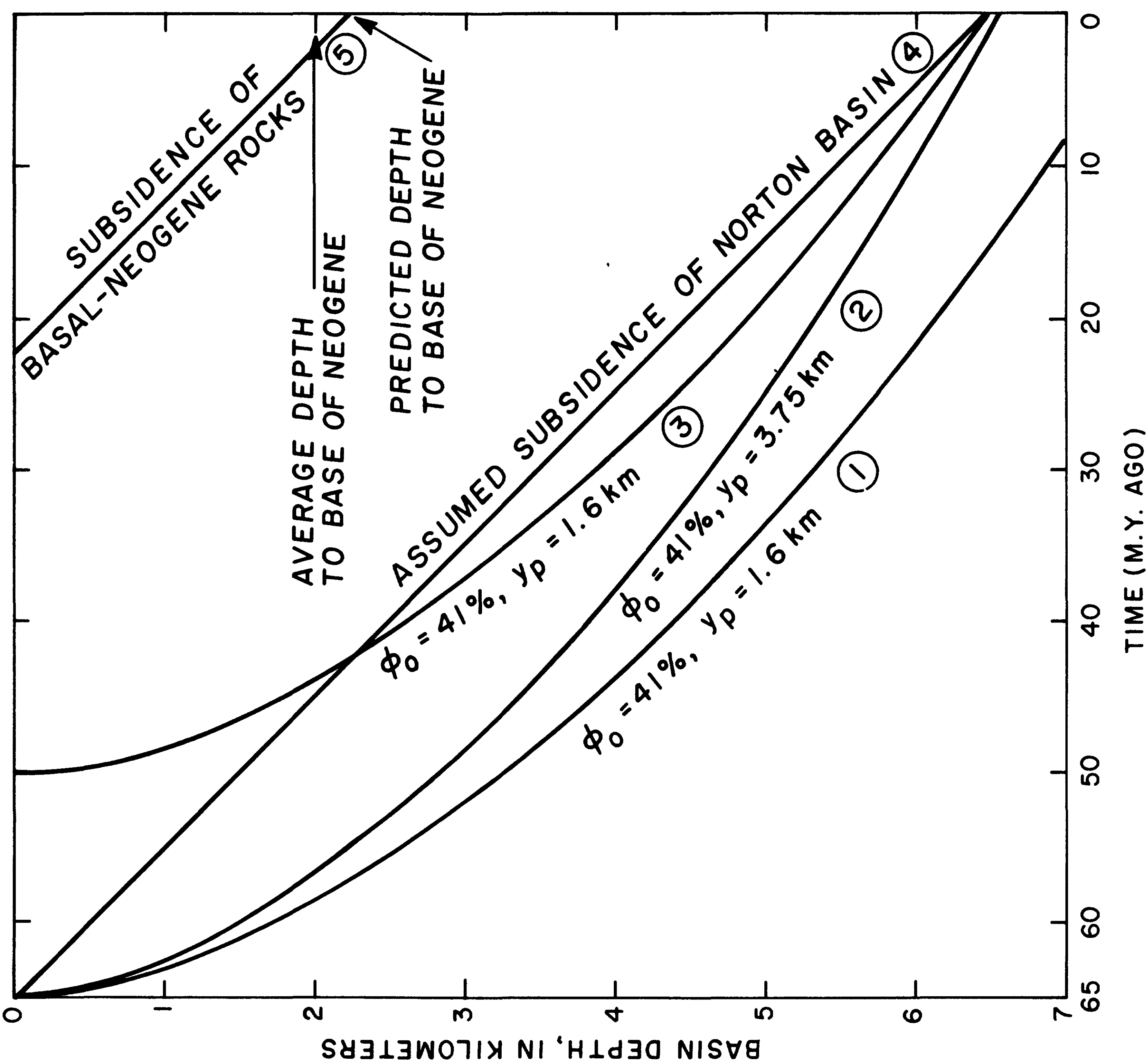

168°
167°
166°
165°
164°
163°
162°
64°
63°
CDP-seismic line
3.0
3-kilometer structure contour, hachures on deeper side
Shallow acoustic anomaly in CDP-seismic data, possibly caused by shallow gas
SEWARD PENINSULA
NORTON SOUND
MAIN SEEP
Fig. 3
3.0
YUKON HORST
Stuart Island
YUKON DELTA
0
20
KILOMETERS

FIG. 24



SUBSIDENCE OF BASAL-NEOGENE ROCKS
AVERAGE DEPTH TO BASE OF NEOGENE
PREDICTED DEPTH TO BASE OF NEOGENE
ASSUMED SUBSIDENCE OF NORTON BASIN
(1) ϕ_o = 41%, y_p = 1.6 km
(2) ϕ_o = 41%, y_p = 3.75 km
(3) ϕ_o = 41%, y_p = 1.6 km
(4)
(5)
TIME (M.Y. AGO)
0
10
20
30
40
50
60
65
BASIN DEPTH, IN KILOMETERS
0
1
2
3
4
5
6
7

FIG. 25

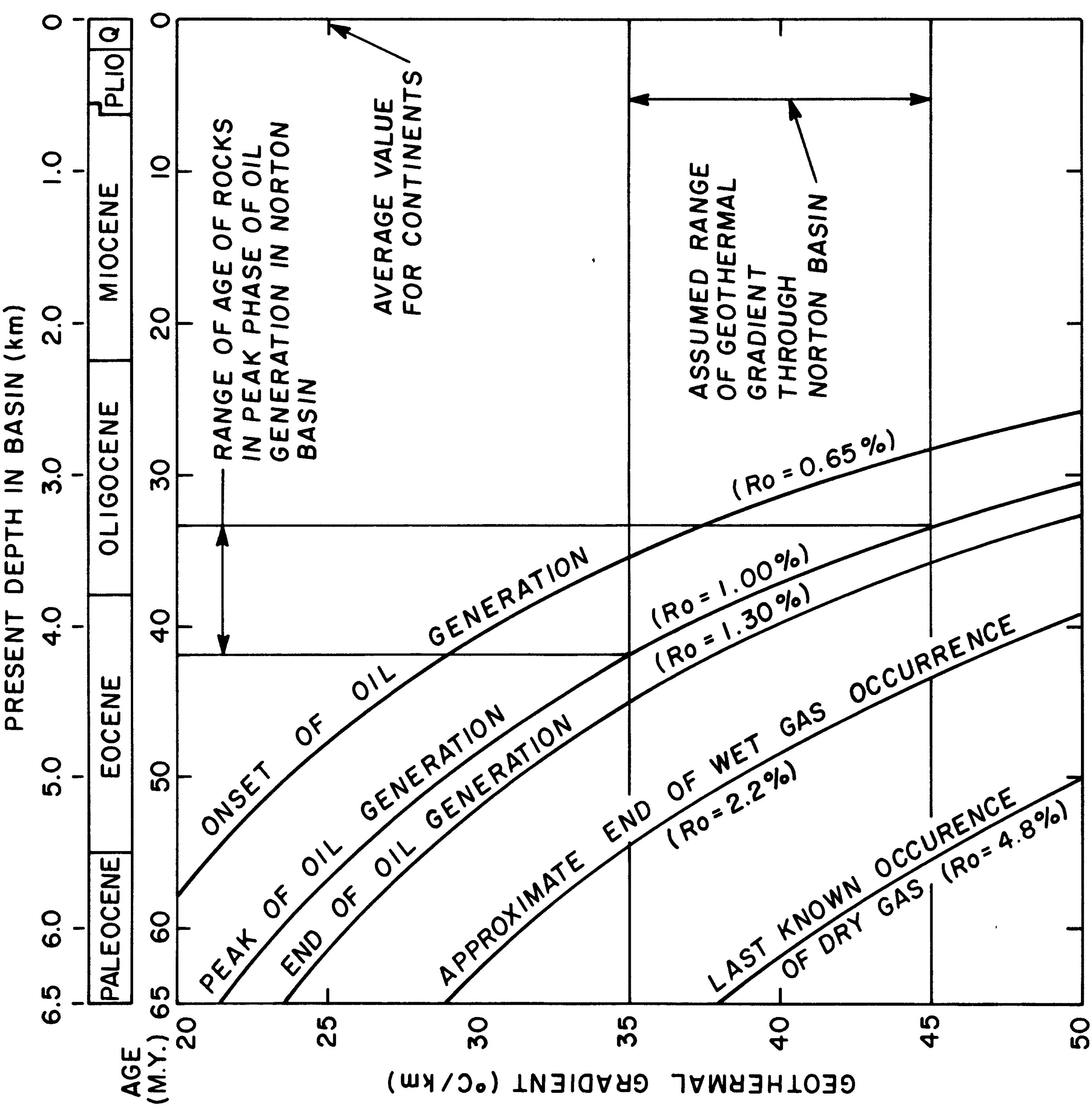

PRESENT DEPTH IN BASIN (km)
0
1.0
2.0
3.0
4.0
5.0
6.0
6.5
Q
PLIO
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
AGE (M.Y.)
0
10
20
30
40
50
60
65
20
25
30
35
40
45
50
GEOTHERMAL GRADIENT (°C/km)
RANGE OF AGE OF ROCKS IN PEAK PHASE OF OIL GENERATION IN NORTON BASIN
AVERAGE VALUE FOR CONTINENTS
ASSUMED RANGE OF GEOTHERMAL GRADIENT THROUGH NORTON BASIN
ONSET OF OIL GENERATION
(Ro = 0.65 %)
PEAK OF OIL GENERATION
(Ro = 1.00 %)
END OF OIL GENERATION
(Ro = 1.30 %)
APPROXIMATE END OF WET GAS OCCURRENCE
(Ro = 2.2 %)
LAST KNOWN OCCURENCE OF DRY GAS
(Ro = 4.8 %)

FIG. 26

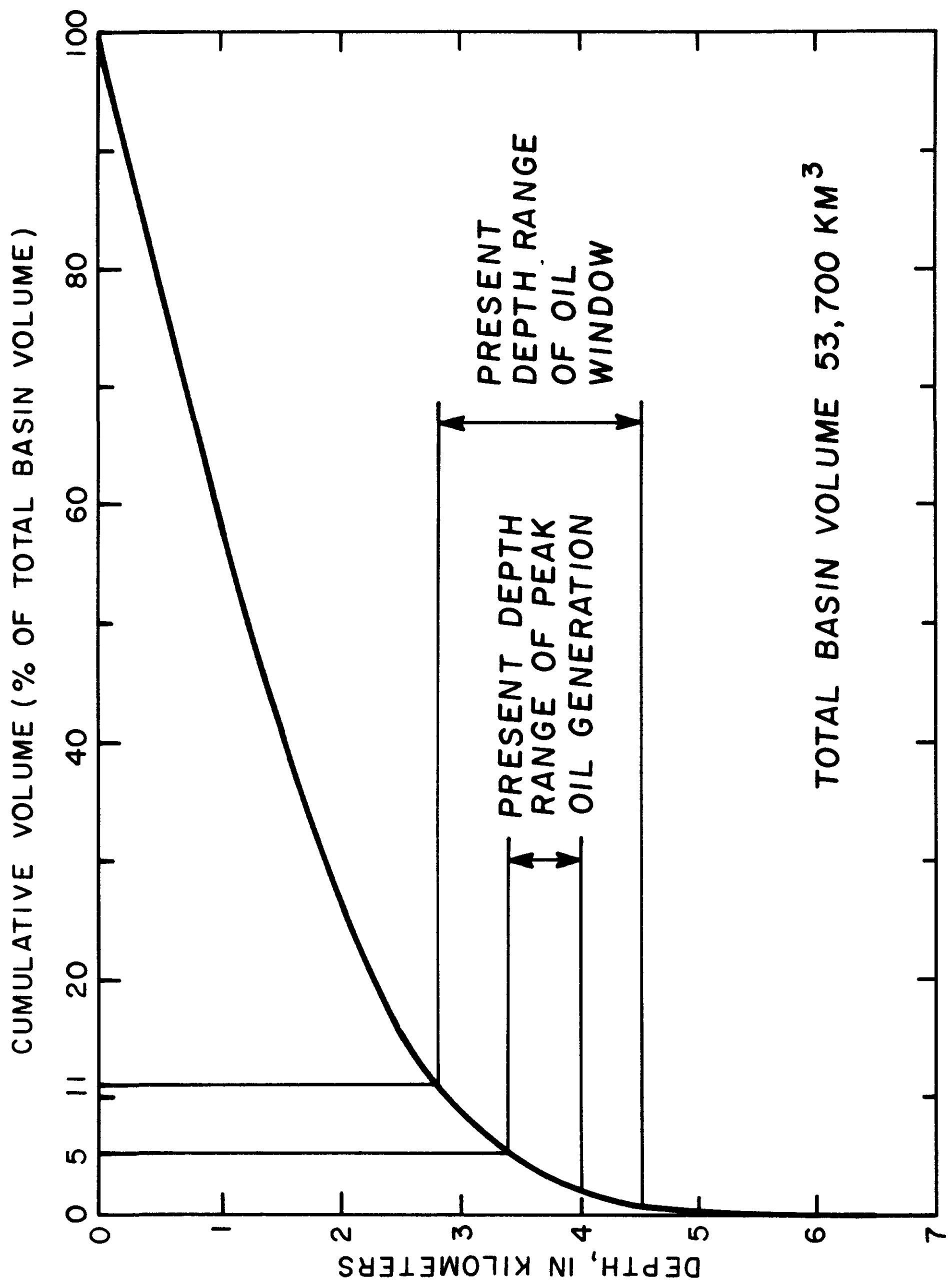

CUMULATIVE VOLUME (% OF TOTAL BASIN VOLUME)
0
5
11
20
40
60
80
100
DEPTH, IN KILOMETERS
0
1
2
3
4
5
6
7
PRESENT DEPTH RANGE OF OIL WINDOW
PRESENT DEPTH RANGE OF PEAK OIL GENERATION
TOTAL BASIN VOLUME 53,700 KM3

FIG. 27

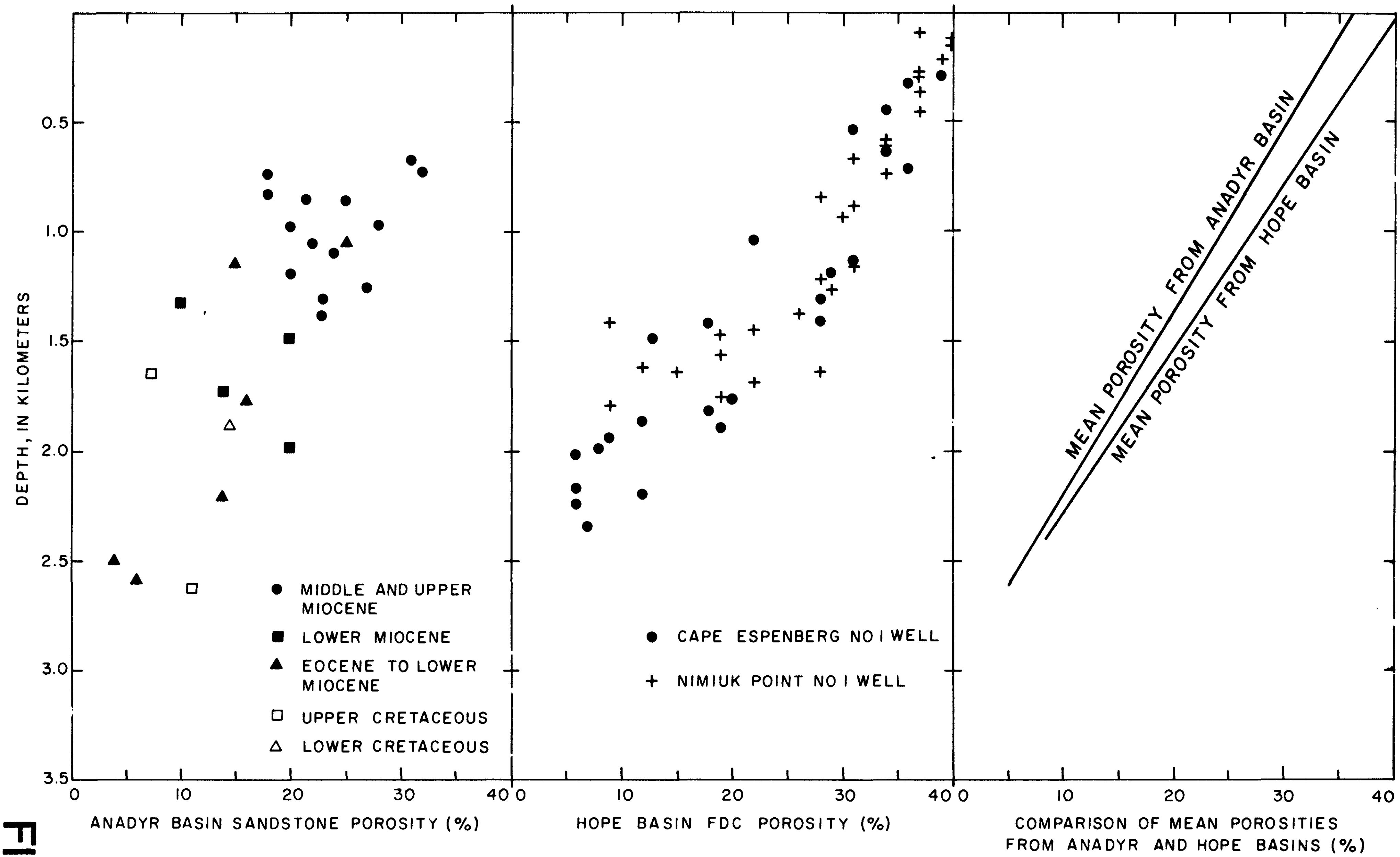

DEPTH, IN KILOMETERS
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
10
20
30
40
ANADYR BASIN SANDSTONE POROSITY (%)
MIDDLE AND UPPER MIOCENE
LOWER MIOCENE
EOCENE TO LOWER MIOCENE
UPPER CRETACEOUS
LOWER CRETACEOUS
HOPE BASIN FDC POROSITY (%)
CAPE ESPENBERG NO I WELL
NIMIUK POINT NO I WELL
MEAN POROSITY FROM ANADYR BASIN
MEAN POROSITY FROM HOPE BASIN
COMPARISON OF MEAN POROSITIES FROM ANADYR AND HOPE BASINS (%)

FIG. 28

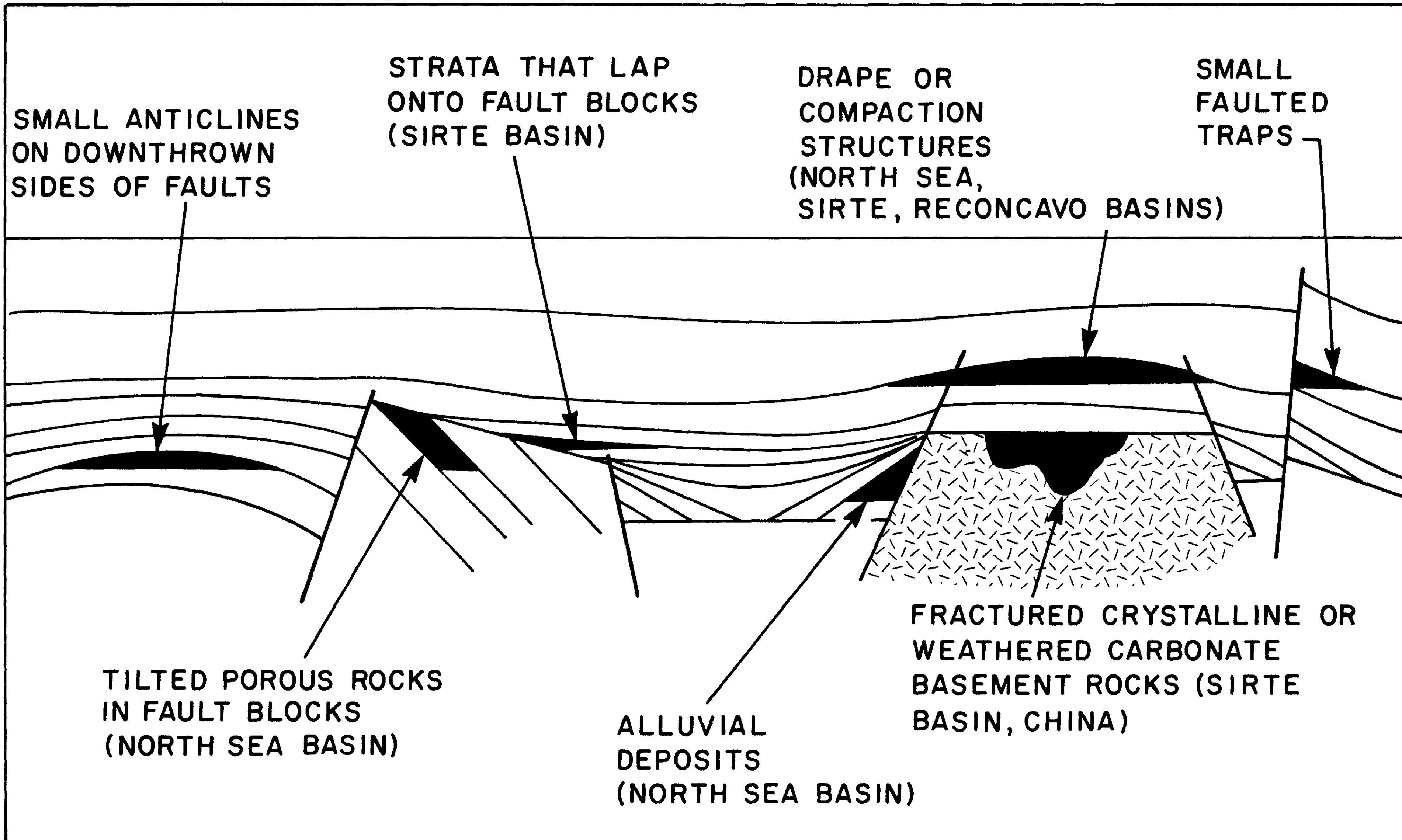

SMALL ANTICLINES
ON DOWNTHROWN
SIDES OF FAULTS
STRATA THAT LAP
ONTO FAULT BLOCKS
(SIRTE BASIN)
DRAPE OR
COMPACTION
STRUCTURES
(NORTH SEA,
SIRTE, RECONCAVO BASINS)
SMALL
FAULTED
TRAPS
TILTED POROUS ROCKS
IN FAULT BLOCKS
(NORTH SEA BASIN)
ALLUVIAL
DEPOSITS
(NORTH SEA BASIN)
FRACTURED CRYSTALLINE OR
WEATHERED CARBONATE
BASEMENT ROCKS (SIRTE
BASIN, CHINA)

FIG 29