UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

RESOURCE REPORT FOR PROPOSED OCS LEASE SALE 57:

NORTON BASIN, ALASKA

By

M. A. Fisher, W. W. Patton, Jr., D. R. Thor,
M. L. Holmes, E. W. Scott, C. H. Nelson, and C. L. Wilson

Open-File Report
79-720

This report is preliminary
and has not been edited or
reviewed for conformity
with Geological Survey
standards and nomenclature.

Menlo Park, California
April 1979

RESOURCE REPORT FOR PROPOSED OCS LEASE SALE 57:
NORTON BASIN, ALASKA

By

M. A. Fisher, W. W. Patton, Jr., D. R. Thor,
M. L. Holmes, E. W. Scott, C. H. Nelson, and C. L. Wilson

SUMMARY

(1) Rocks in the region that includes Norton Basin form three belts that are distinguished by age and lithology. First, Precambrian through lower Mesozoic strata are in a miogeoclinal belt that underlies northern Alaska and northern Siberia. Second, middle and upper Mesozoic, and locally lowermost Cenozoic, strata form a volcanic belt that adjoins the miogeoclinal belt on the south. Volcanic strata predominate in Siberia, and nonvolcanic strata predominate in Alaska. Third, a forearc belt lies south of the volcanic belt and includes Mesozoic strata. Three Cenozoic basins are superimposed across the three belts--Anadyr Basin in Siberia, Hope Basin north of the Seward Peninsula, and Norton Basin.

(2) The structure of Norton Basin is dominated by west-northwest-striking normal faults that form grabens as deep as 7 km and horsts. Basin fill may be as old as Late Cretaceous. A Paleogene age for some basin strata is indicated by refraction velocities in the strata and by volcanic flows and sills in the basin; these volcanic rocks may correlate with Paleogene volcanic rocks on St. Lawrence Island. An Oligo-Miocene(?) unconformity generally separates nonmarine-deltaic strata below from marine strata above.

(3) Norton Basin may have begun to form in the Late Cretaceous, during east-west compression between Siberia and North America. The basin formed as a pull-apart feature along the right-lateral Kaltag fault, which shows as much as 130 km of offset. A middle Cretaceous unconformity may be the

bottom of the basin. The age of rocks below the unconformity is not known in detail--the rocks could be as young as middle Cretaceous and as old as Paleozoic. Geophysical evidence, however, suggests a significant age gap exists between the Upper Cretaceous strata in the basin and the rocks underlying the unconformity at the bottom of the basin.

(4) The hydrocarbon potential of Norton Basin must be inferred from geophysical data and from the characteristics of strata, exposed around the basin, that may not be in or below the basin. Geochemical analyses of Paleozoic and lower Mesozoic rocks on St. Lawrence Island show the rocks are thermally immature (not yet capable of generating oil). If Paleozoic rocks are beneath Norton Basin and were immature when the basin began to form, deep burial beneath the basin may have brought the Paleozoic rocks to maturity during the Cenozoic. Middle Cretaceous deltaic and Tertiary nonmarine strata around the basin are generally gas prone. We infer that nonmarine and deltaic strata in the basin are also gas prone.

Traps for hydrocarbons are of two types: fault-associated and stratigraphic. The fault-associated traps are interior or exterior to the horsts. Traps could be interior to the horsts if a thick section of pre-Late Cretaceous strata overlies metamorphic basement. Traps exterior to the horsts may be in sandstone locally derived from erosion of the horsts and in strata arched by growth of horsts. Stratigraphic traps may be where basin fill pinches out against the bottom of the basin, where unconformities are overlain by bottomset or overbank deltaic deposits, and where channel sandstone is preserved in delta lobes.

Appraisal of the hydrocarbon resources show that, at 5 percent probability, 2.2 billion barrels of oil and 2.8 trillion cubic feet of gas may be in the basin; at 95 percent probability no oil or gas is present. The statistical mean of the appraisal is 0.54 billion barrels of oil and 0.85 trillion cubic feet of gas.

(5) Several types of potential environmental hazards are present in the northern Bering Sea: (a) Surface and near-surface faults are common along the northern margin of Norton Basin. (b) Gas seepage may cause unstable bottom sediment, as may liquefaction of bottom sediment during storms. (c) Ice scouring of the sea bottom is common throughout Norton Sound; scouring occurs locally in water depths as great as 30 m. Currents erode ice gouges causing large shallow depressions in Yukon-derived mud. (d) Strong bottom currents cause migrating fields of sand waves. And, (e) coastal development is threatened by storm tides caused by southerly storm winds.

INTRODUCTION

This report is a summary of information about an area of the northern Bering Sea continental shelf that is bounded by the Seward Peninsula on the north, by the line of the United States-Russia Convention of 1867 on the west, and by St. Lawrence Island and the coastline that rims Norton Sound on the south and east. Scholl and Hopkins (1969) report that a sedimentary basin underlies the offshore area. More recent data, which form the basis of part of this report, show the basin is deepest beneath Norton Sound; also, the basin has sufficent depth and areal extent that the basin may be a target for development of hydrocarbon resources after Outer Continental Shelf (OCS) Lease Sale 57. The informal, but widely used, name for the basin is Norton Basin.

The following discussion includes regional geology, geologic history, and offshore structure and stratigraphy as background data to discussion of the hydrocarbon potential and resource appraisal of the offshore area. Sections on environmental geology and on the technology and manpower needed and available for development of offshore resources are also included.

GENERAL GEOLOGY

Pre-Tertiary Rocks

The pre-Tertiary rocks of the northern Bering Sea shelf and adjoining parts of northeast Siberia and Alaska are divided into three broad geological belts herein named, miogeoclinal, volcanic, and forearc (fig. 1). Each belt has a distinctive rock assemblage and tectonic history.

Miogeoclinal belt

Included in this belt are the Brooks Range, Seward Peninsula, eastern and central parts of St. Lawrence Island, eastern and northern parts of the Chukotsk Peninsula, and Wrangel Island. The belt is composed chiefly of Precambrian, Paleozoic, and early Mesozoic nonvolcanic sedimentary rocks which accumulated on ancient continental crust. In the Brooks Range, Paleozoic and early Mesozoic carbonate and nonvolcanic sedimentary rocks are thrust to the north in imbricate slabs. The southern part of the belt is underlain by a metamorphic complex of Paleozoic and Precambrian schist and marble. The metamorphic complex extends southwestward from the Brooks Range to the eastern and central parts of the Seward Peninsula. The western part of the Seward Peninsula is underlain by a thick succession of unmetamorphosed Paleozoic carbonate rocks which rests conformably upon Precambrian slate. On St. Lawrence Island the miogeoclinal deposits are represented by unmetamorphosed Paleozoic and lower Mesozoic carbonate and nonvolcanic rocks which are nearly identical in lithology and age to the stratigraphic sequence in the northern part of the Brooks Range. On the Chukotsk Peninsula and on Wrangel Island the miogeoclinal belt is made up mostly of unmetamorphosed Paleozoic and early Mesozoic carbonate and nonvolcanic deposits. However, gneiss and schist of probable Precambrian age unconformably underlie Paleozoic strata on the eastern part of the Chukotsk Peninsula (fig. 1), and low-grade metasedimentary rocks of Paleozoic or Precambrian age occur in a small central complex on Wrangel Island.

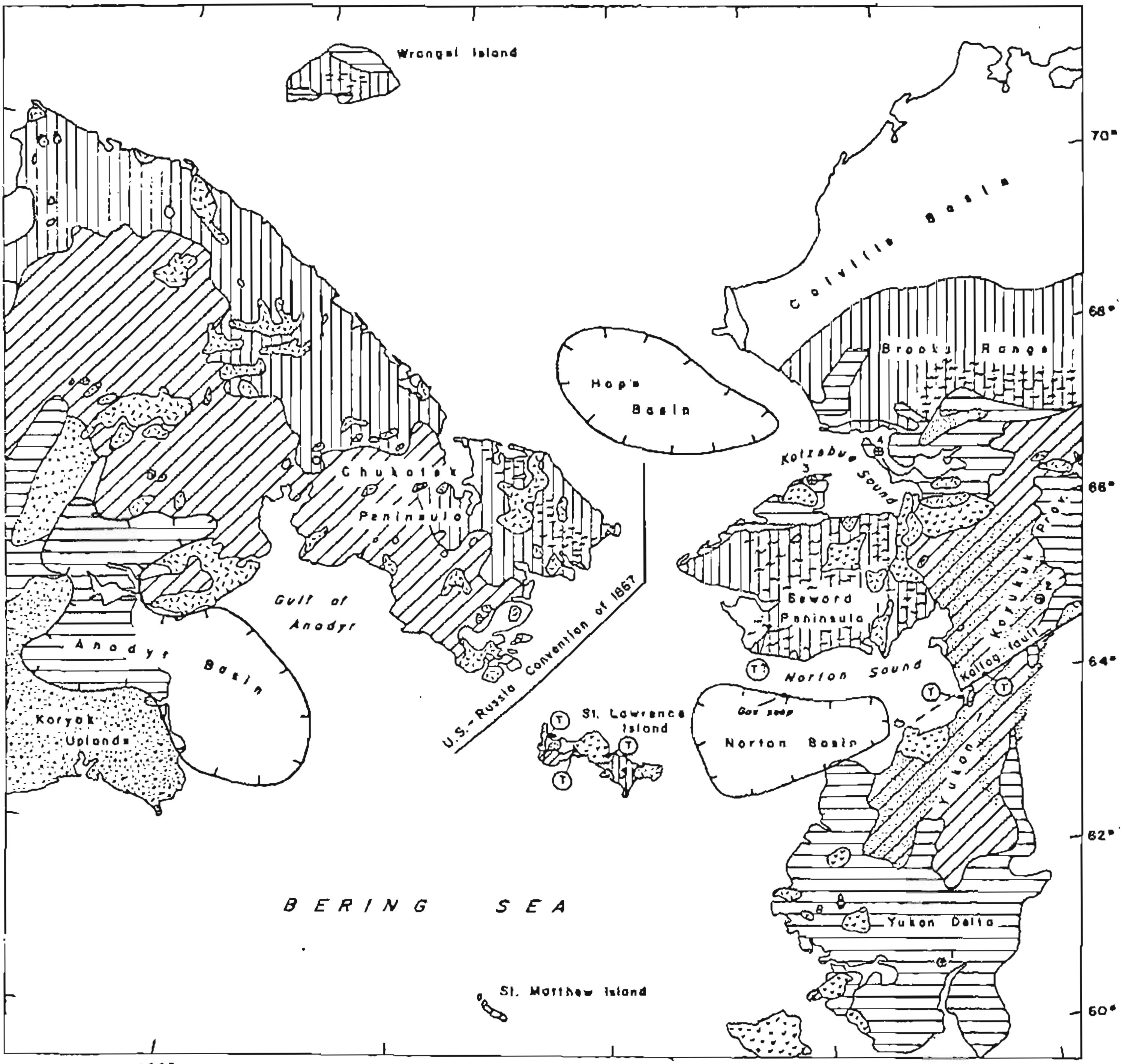

Figure 1. Geography and geology of region around Norton Basin.

EXPLANATION

Late Cenozoic

- Surficial deposits
- Subaerial volcanic rocks (chiefly basalt)

Late Mesozoic (locally includes rocks of earliest Cenozoic age)

- Fore-arc deposits (chiefly terrigenous sedimentary rocks)
- Volcanic deposits (stippled where chiefly terrigenous sedimentary rocks)

Precambrian, Paleozoic, 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

Volcanic belt

This belt includes: (1) the Yukon-Koyukuk province in western Alaska, (2) western St. Lawrence Island and St. Matthew Island in the Bering Sea, and (3) the southern Chukotsk and Anadyr River region in northeast Siberia (fig. 1). The belt is characterized chiefly by volcanic rocks and by sedimentary rocks derived from volcanic terranes. Rocks in the belt are largely of late Mesozoic age, but locally include some earliest Cenozoic strata.

Western Alaska.--In western Alaska the volcanic belt underlies the Yukon-Koyukuk province, a broad wedge of Cretaceous strata that stretches along the west coast of Alaska from the Brooks Range to the Yukon delta (fig. 2E) (Patton, 1973). The oldest strata in the province are a sequence, at least 1,500 m thick, of andesitic volcanic rocks of earliest Cretaceous (Neocomian) age (fig. 2A). These volcanic rocks are overlain by sedimentary rocks, of middle Cretaceous (Albian and Cenomanian) age, which locally may be as much as 8,000 m thick, and are made up of marine volcanic graywacke and mudstone. Some coal-bearing paralic deposits are present in the upper part of the sequence. This sequence is subdivided into four gradational lithologic units that can be mapped in a generalized way.

The bulk of the sedimentary sequence (fig. 2B) is in the first lithologic unit, and is marine volcanic graywacke, mudstone, and conglomerate of Early Cretaceous (Albian) age. These volcanic sediments may be more than 6,000 m thick along the Yukon River-Norton Sound divide. The volcanic graywacke and the mudstone are well compacted, indurated, and intensely deformed.

The second lithologic unit is nearshore and nonmarine calcareous graywacke, mudstone, and conglomerate of Early and Late Cretaceous (Albian and Cenomanian) age that overlie the volcanic sediments (fig. 2C). These calcareous strata, which may be as thick as 1,500 m, coarsen westward across the trough, and at

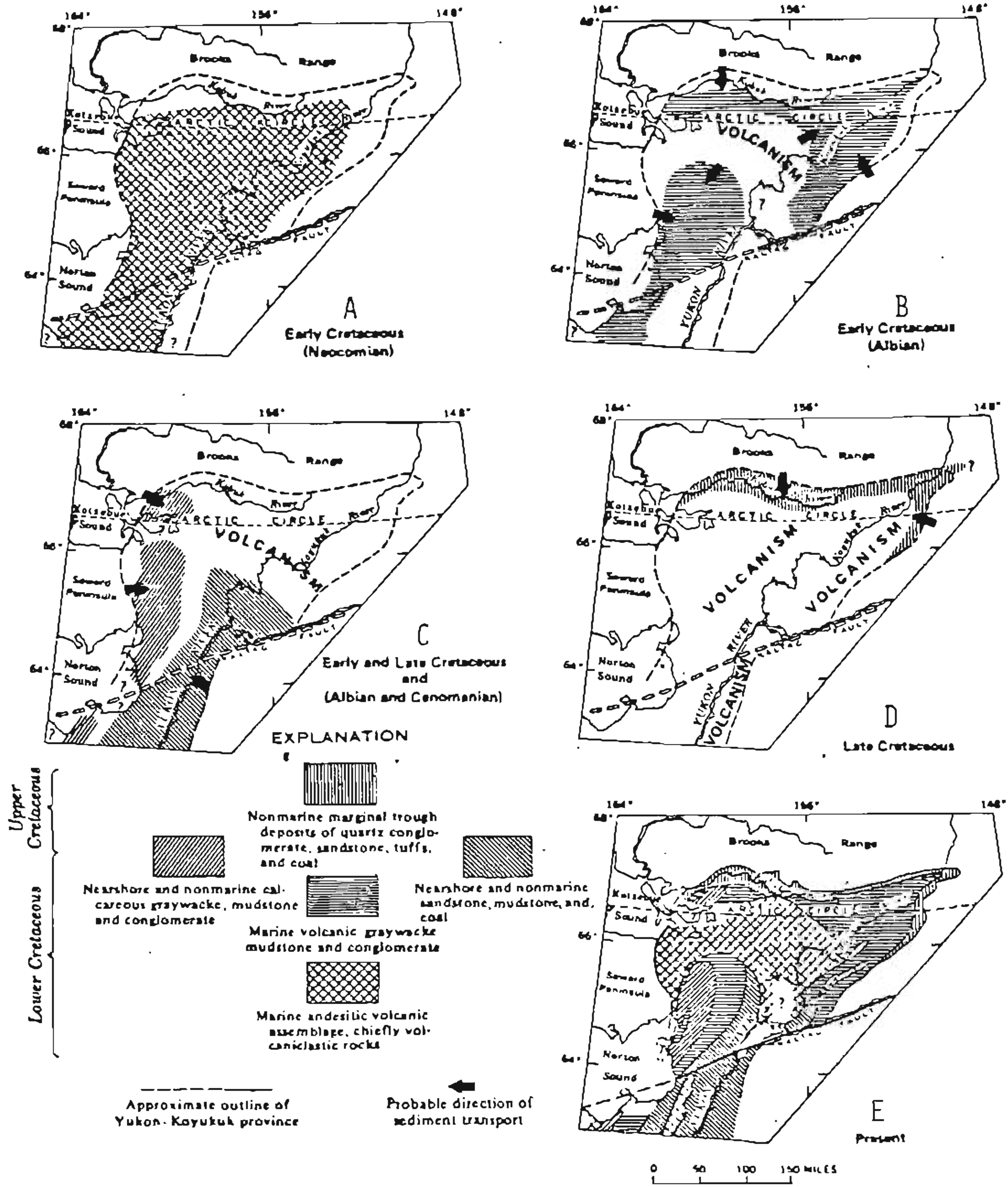

Figure 2. Cretaceous depositional basins and present-day distribution of major stratigraphic units in northern Yukon-Koyukuk province. Cretaceous depositional basins not palinspatically restored for offset along Kaltag fault.

the western edge of the province, grade into nonmarine coal-bearing deposits. Exposures of these strata along the shore of Norton Sound display the same intense deformation that characterizes the underlying volcanic sedimentary rocks.

The third lithologic unit is nearshore and nonmarine sandstone, mudstone, and coal of Early and Late Cretaceous (Albian and Cenomanian) age that overlie the volcanic sedimentary rocks in the southern and southeastern parts of the province and appear to be roughly correlative with the calcareous graywacke and mudstone unit (fig. 2C). This coal-bearing unit, which has an aggregate thickness of at least 3,000 m, consists of a regressive sequence that grades upward from marine shale and sandstone into nonmarine shale, siltstone, sandstone, and coal. Winnowed strandline sandstone and quartz conglomerate occur locally in the zone of interfingering marine and nonmarine beds. The sandstone in this unit is generally distinguished from the sandstone in the other middle Cretaceous sedimentary units by better sorting and a higher percentage of quartz and other resistant rock and mineral detritus. Structural deformation of this unit ranges from tight folding and steep dips along the Norton Sound coast to broad open folds and gentle dips along the Yukon River valley.

The fourth lithologic unit is nonmarine marginal trough deposits of quartz conglomerate, sandstone, tuff, and coal of Late Cretaceous age that form a narrow band along the northern and southeastern perimeters of the Yukon-Koyukuk province (fig. 2D). Similar assemblages have not been identified along the west border of the province.

Bering Sea shelf.--Volcanic rocks of Cretaceous age are exposed on western St. Lawrence Island and are virtually all of the exposed bedrock on St. Matthew Island. Marine magnetic data (Verba and others, 1971; Marlow and others, 1976) obtained on the Bering Sea shelf suggest that these volcanic rocks are part of a broad magmatic arc that swings across the shelf from western Alaska to the

Gulf of Anadyr. Close to the Siberian coast, the belt is about 200 km wide and is sharply defined by the magnetic data. 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 in the character of the volcanic belt between Siberia and Alaska--in Siberia the belt is narrow, and is composed almost exclusively of volcanic rocks; whereas in Alaska, the volcanic rocks are distributed over a much broader area and are intercalated and interfolded with nonmagnetic sedimentary rocks.

Northeast Siberia.--In northeast Siberia the Cretaceous volcanic rocks extend from the southern Chukotsk Peninsula northwestward nearly to Chaun Gulf, and southwestward from there to the Sea of Okhotsk. This volcanic belt separates the Mesozoic miogeoclinal belt on the north and northwest from the Cenozoic Anadyr-Koryak system on the southeast. The volcanic rocks are largely middle Cretaceous (Albian-Cenomanian) in age and range in composition from rhyolite to basalt (Belyi, 1973). In contrast to the intense deformation of middle Cretaceous rocks in Alaska, the volcanic rocks in Siberia are characterized by broad open folds and gentle dips.

Forearc belt

The Cretaceous volcanic belt is bounded on the south by late Mesozoic sedimentary rocks which appear to extend from the Koryak-Anadyr region of Siberia along the outer edge of the Bering Sea shelf to the Alaska Peninsula (fig. 1). In the Koryak-Anadyr region, Soviet geologists (Gladenkov, 1964; Avdeiko, 1971) recognize an outer band of deep-water flysch deposits with mafic volcanic rocks and an inner band of shallow-water and nonmarine sedimentary deposits. Recent dredging along the Bering Sea continental margin suggests that the shelf edge is underlain chiefly by shallow-water deposits of Late Jurassic age (Marlow and others, written commun., 1979).

Late Cretaceous and Tertiary Rocks

Anadyr Basin

The Anadyr Basin of northeast Siberia is situated on the Bering Sea coast southwest of the Chukotsk Peninsula (fig. 1). Tertiary and Upper Cretaceous deposits of the basin are superimposed on the forearc deposits of the Koryak-Anadyr region in the south and central parts of the basin and lap onto the volcanic belt around the northern and northwestern perimeter (Meyerhoff, 1972; Agapitov and others, 1973).

Upper Cretaceous and Paleogene deposits have an aggregate thickness of 1,500 to 2,000 m (fig. 3). The Upper Cretaceous strata are composed of argillite and fine-grained sandstone flysch deposits of Albian to Senonian age, and coal-bearing molasse deposits of Senonian to Danian age. These rocks are intruded and overlain by Paleocene to lower Eocene mafic and intermediate volcanic rocks. Upper Eocene to Oligocene terrigenous deposits of sandstone and argillite overlie the volcanics. The Upper Cretaceous to Paleogene section is moderately to highly folded with dips on the flanks of the folds as high as 40°.

Neogene deposits in Anadyr basin have an aggregate thickness of nearly 3,000 m and comprise the principal sedimentary fill of the basin. More than 2,000 m of this section is made up of middle and upper Miocene strata which is composed of shallow marine, littoral, and coal-bearing nonmarine deposits. Miocene strata are overlain by 400 to 500 m of Pliocene strata, and by 70 to 120 m of Quaternary unconsolidated deposits.

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) (fig. 1). The older unit is composed primarily of felsic, intermediate, and mafic flows and tuffs with thin bands of lignitic coal and tuffaceous sedi-

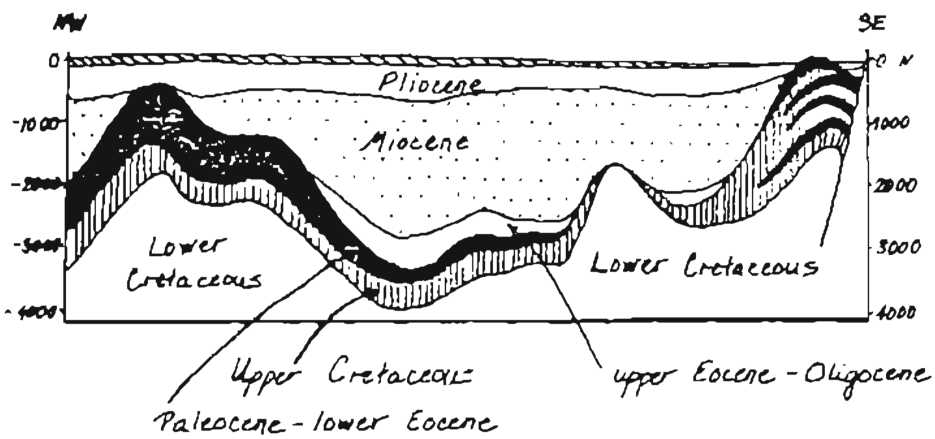

Figure 3. Schematic cross section of Anadyr basin (from Agapitov and others, 1973).

mentary rocks. The younger unit consists of poorly consolidated calcareous sandstone, grit, and 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. K/Ar determinations from the volcanic rocks give ages of 60 to 65 m.y. (Paleocene) for the older unit and 38 m.y. (early Oligocene) for the younger unit. Plant fossils from the younger unit are also Oligocene. Both of these early Tertiary units are so poorly exposed that little can be determined about their thickness and structure. The aggregate thickness of both units probably does not exceed 200 m.

Western Alaska

Hope Basin is north of Seward Peninsula and contains more than 3,000 m of Tertiary and possibly some Cretaceous strata, according to Eittreim and others (1978). They believe seismic-reflection data show the basin fill is divided by a strong reflector that may have a middle Tertiary age. Seismic velocities in rocks below the basin suggest the rocks are of middle to Lower Cretaceous age.

Two small outcrops of poorly consolidated coal-bearing beds of Tertiary age are known near Unalakleet on Norton Sound (Patton, 1973). One is located about 16 km south of Unalakleet where about 10 m of clay containing lignitic coal is exposed in low beach bluffs. The other deposit, which is of similar lithology, is exposed in a 20-m-high river bluff on the Unalakleet River, 50 km east-northeast of Unalakleet. Both deposits appear to be of limited extent and confined to small structural or topographic basins.

A small isolated patch of conglomerate of Cretaceous or Tertiary age occurs in the Sinuk River valley on the Seward Peninsula, 35 km northwest of Nome (fig. 1). The conglomerate is composed largely of poorly sorted metamorphic debris, which clearly was derived from the underlying Precambrian metamorphic complex. Sandstone, shale, and coal are present in minor amounts.

STRUCTURE AND STRATIGRAPHY OF NORTON BASIN

Sonobuoy Refraction Measurements

Thirty-four seismic-refraction profiles were obtained over Norton Basin during 1977 and 1978, aboard the R/V S. P. LEE. The interval velocities and layer thicknesses calculated from the sonobuoy profiles are shown in table A1, in the Appendix. The locations of the sonobuoys, shown in figure 4a and listed in table A1, represent the position along each sonobuoy line where the critical distance for the basement refractor was reached. The data shown in table A1 were used to compute a second-order polynomial relating two-way reflection time to one-way depth below the sea surface (fig. 4b). Although the scatter of the data points increases at reflection times exceeding 2 s, the coefficient of determination (R^2) for the fitted curve is still high (0.995).

The distribution of seismic velocities can be presented in histogram form. This presentation provides a convenient method of examining the data for groups of velocities that might be diagnostic of lithologic sequences. This technique was used successfully by Sundvor and Nysaether (1975) in a study of refraction data from the Norwegian continental shelf. Seismic velocities group into five units that are labeled Units A, B, C, D, and Basement in figure 4c.

The areal extents of velocity units B, C, and D of the basin fill are shown in figure 4d. The basal unit D is characterized by compressional velocities ranging from 4.0 to 5.0 km/s. Unit D occurs in two en echelon belts, which strike generally northwest. The axes of both belts merge, and continue as one axis southeastward beneath the Yukon River delta.

Unit C, with compressional velocities from 3.0 to 3.8 km/s underlies most of central Norton Basin. Southwest of Nome the unit narrows and changes strike slightly to the northwest, forming a long tongue-like body.

The next shallowest velocity unit, Unit B, has a distribution like the dis-

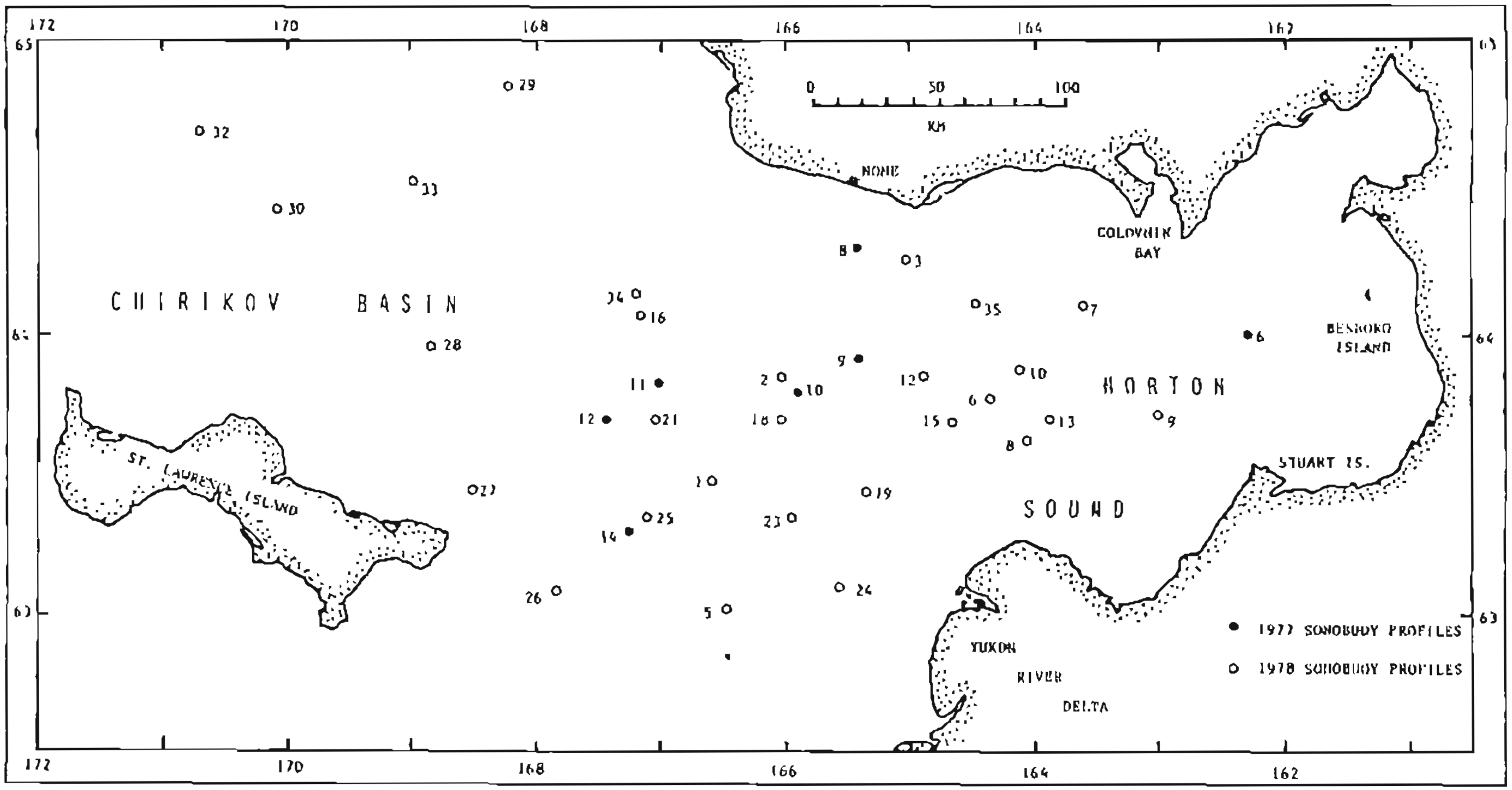

Figure 4a. Location of sonobuoy refraction stations in Norton Sound and Chirikov Basin.

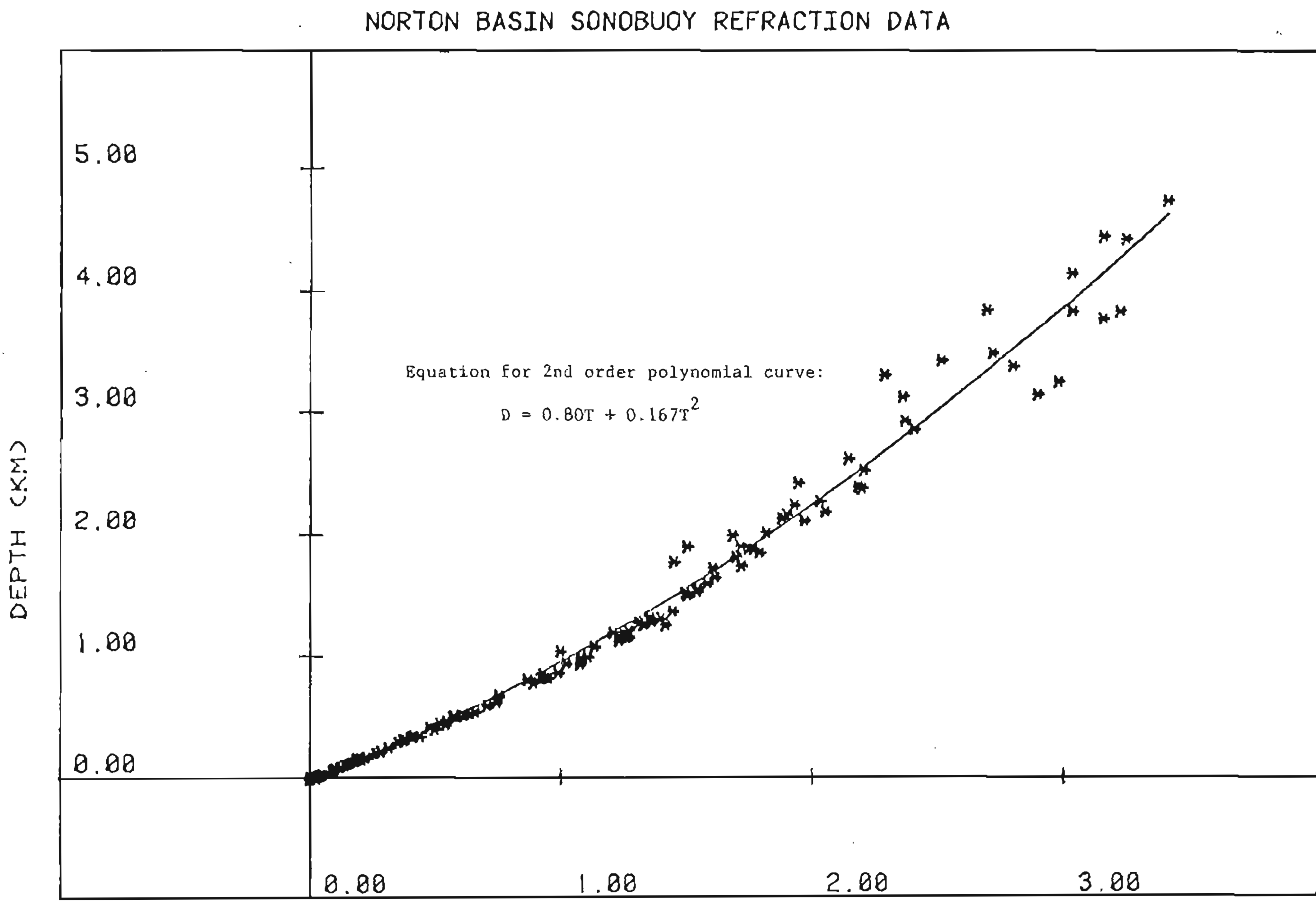

Figure 4b. Reflection time versus thickness for Norton basin refraction data.

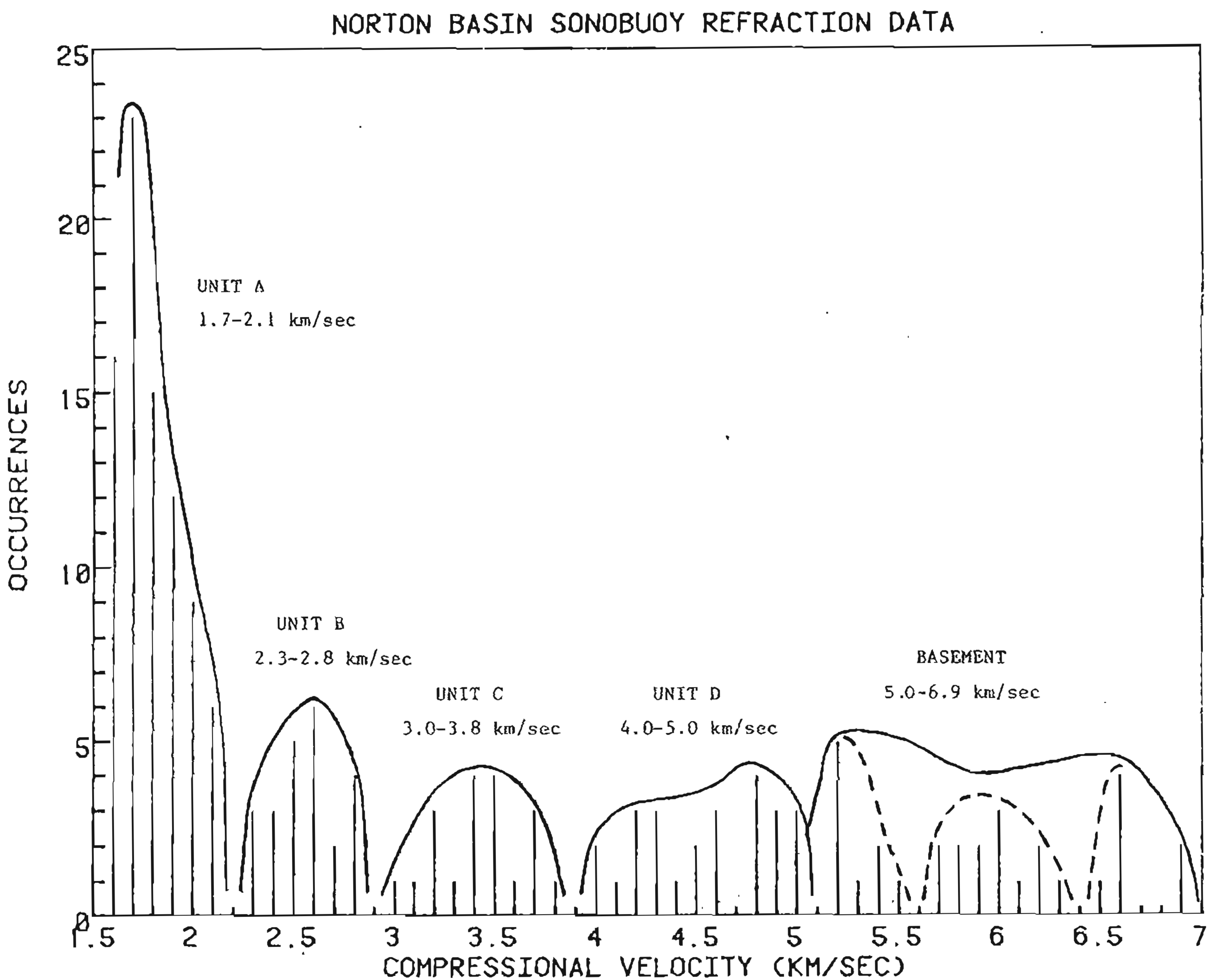

Figure 4c. Histogram of velocities from seismic refraction measurements in Norton basin showing proposed subdivision of velocity units.

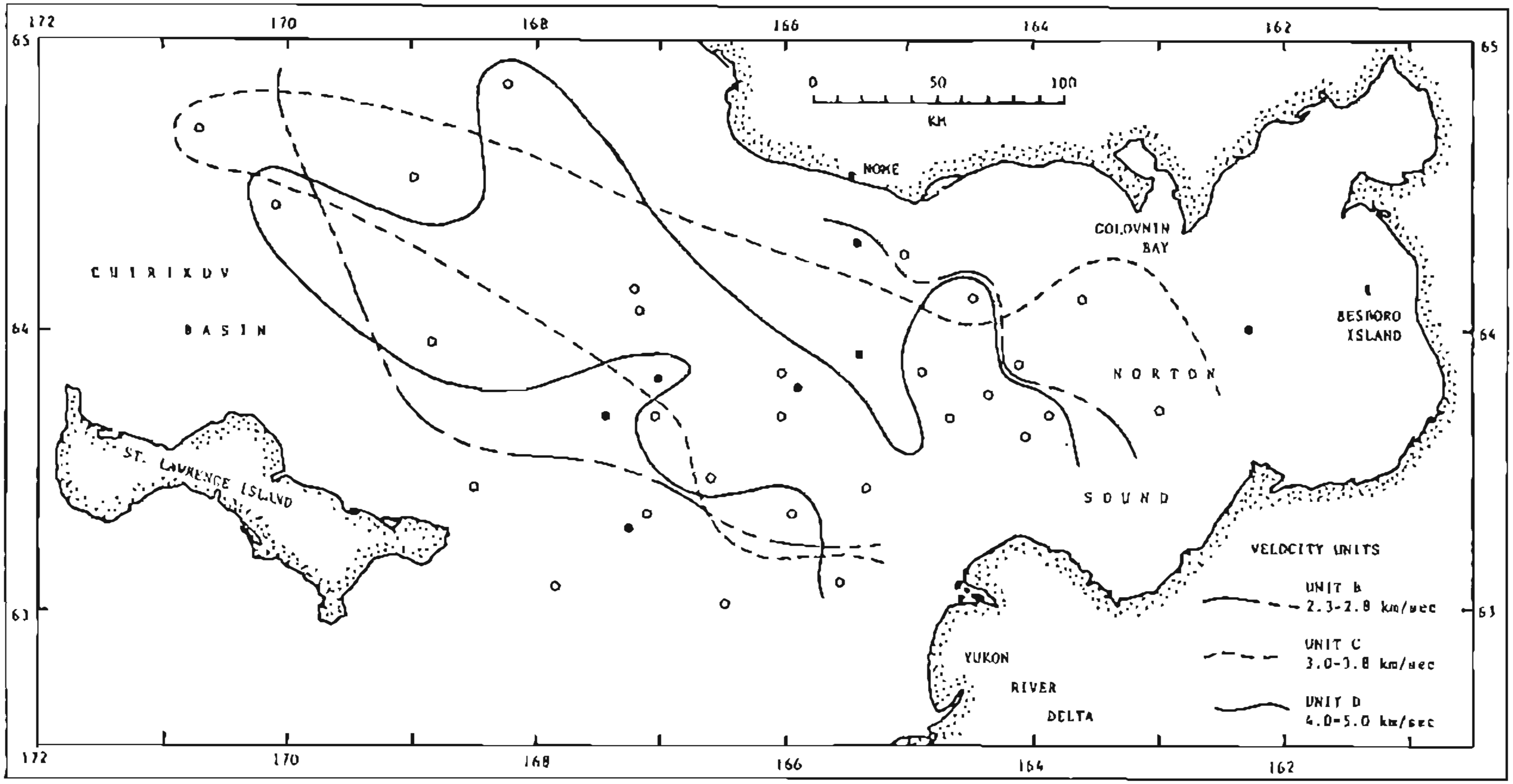

Figure 4d. Areal distribution of seismic velocity Units B,C,and D in Norton basin.

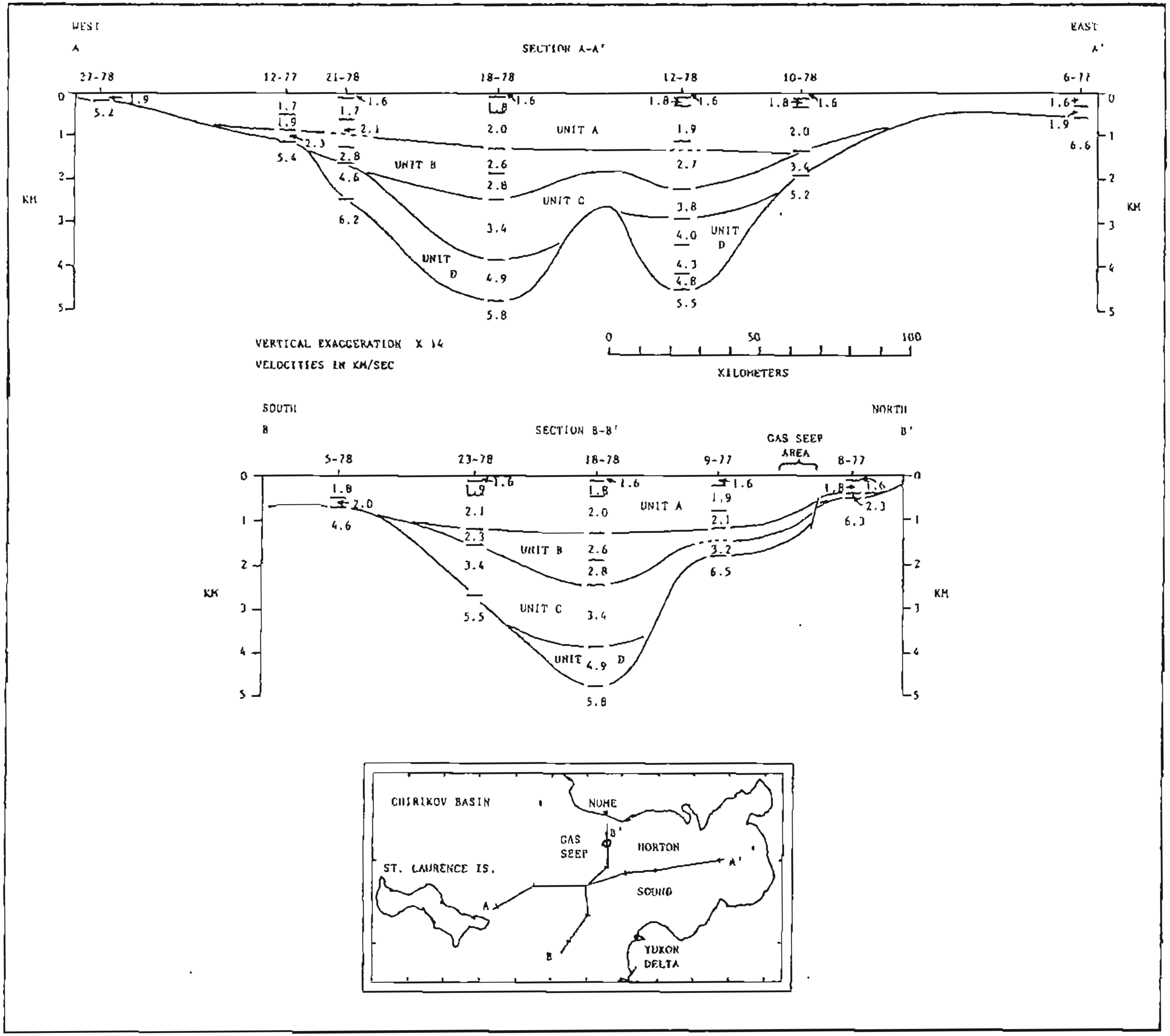

Figure 4e. Structural sections across Norton basin (Norton Sound) based on seismic refraction measurements. Velocity units are discussed in the text.

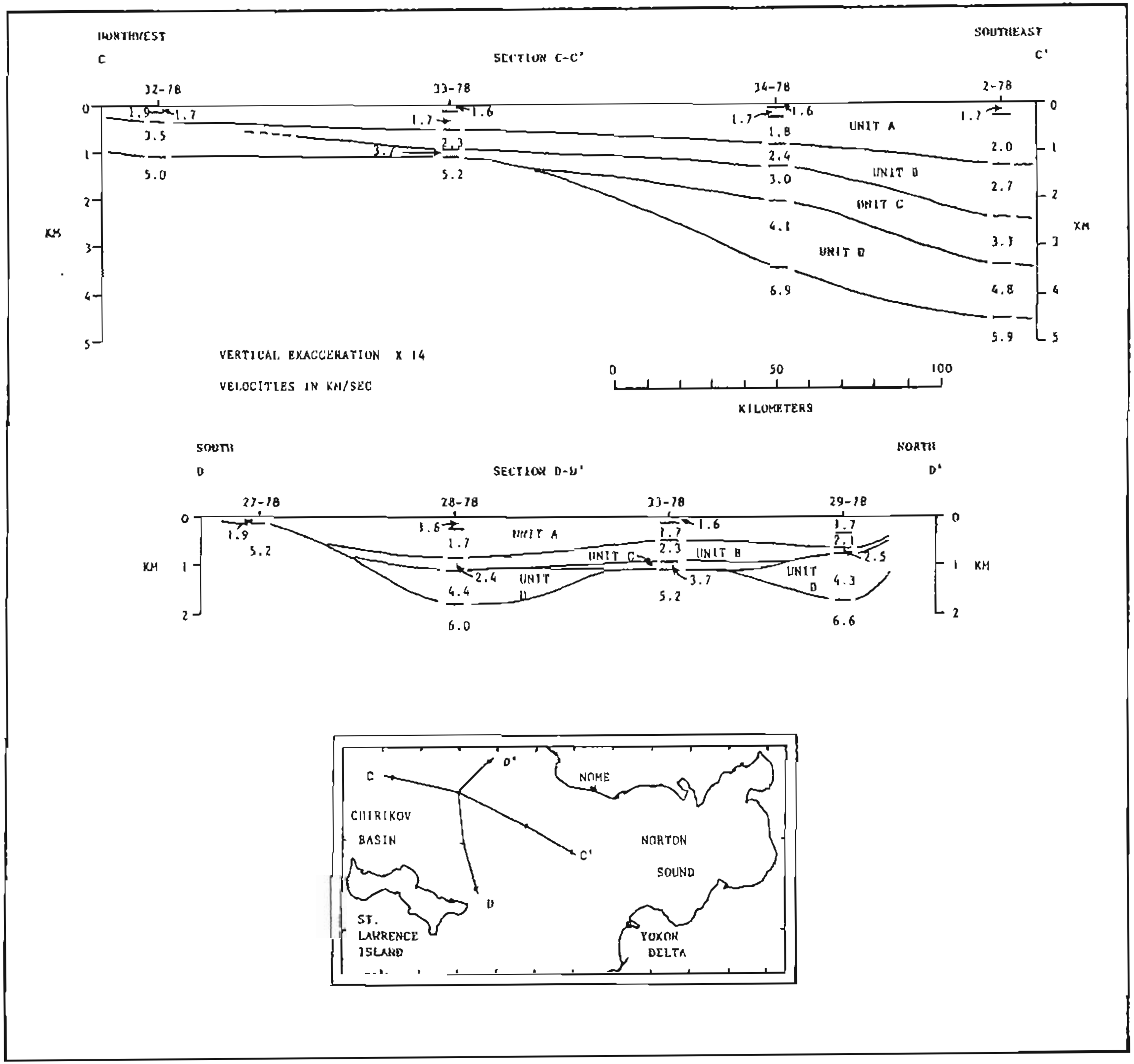

Figure 4f. Structural sections across Norton basin (Chirikov Basin) based on seismic refraction measurements. Velocity units are discussed in the text.

tribution of Unit C. In the west, however, Unit C covers a greater area than either of the other units.

The vertical distribution of the various velocity units in Norton Basin are shown in the cross section of figures 4e and 4f. Basement depth between refraction stations was obtained by converting time to depth using the curve in figure 4b. The boundary between velocity units A and B corresponds to a strong, basin-wide reflection on single channel records; the boundary in the cross sections is based on the reflection data. The other interfaces on the cross sections are drawn strictly on the basis of the velocity units derived from figure 4c.

The cross sections show that the basement surface forms a shallow (450 m) platform beneath Norton Sound between Golovin Bay and Stuart Island, and deepens toward Besboro Island (Section A-A'). Another, slightly deeper platform is between St. Lawrence Island and the Yukon delta area (Section B-B'). Most of the offshore area north of St. Lawrence Island is underlain by a fairly flat basement surface at depths of 1.0 to 1.5 km (Sections C-C' and D-D'). Basement rises northward from Norton Basin to crop out on Seward Peninsula, and rises southward to crop out on St. Lawrence Island.

Seismic-Reflection Data

Seismic-reflection data were obtained during 1978 by the R/V S. P. LEE; the data are 24-fold. This discussion is preliminary, because only limited time has been available to process and to interpret the data.

Seismic-reflection data reveal the basin is deepest north and west of the Yukon delta (fig. 5a). Traveltime to the bottom of the basin is converted to depth using the time-depth equation in figure 4b. The deepest point measured is 7 km deep. West-northwest trending normal faults form grabens, which contain the thickest basin fill; these grabens are separated by horsts over which basin fill is generally thinner than 3 km. The deep parts of the basin are formed by progressively deeper steps down fault blocks which form series of horsts, grabens and half-grabens. Deep in the basin, the faults show major displacement (measured in hundreds of meters), but above a horizon, which is generally about 2 to 3 km deep, the faults show minor displacement that is less than 100 m. This horizon may be a basinwide unconformity.

The area of horst-and-graben structure is bounded on the north by an area under which the bottom of the basin forms a platform that slopes gently basinward. The platform is shallow (less than about 1 km deep), and is relatively free of structure. A normal fault forms the southern limit of the platform in most places. A fault-bounded platform also occurs between St. Lawrence Island and the Yukon delta.

Norton Basin can be divided into two portions on the basis of the complexity of the faulting. The first portion is west of the Yukon delta where the normal faults strike west-northwest and can be connected among seismic lines without much difficulty. The second portion is north of the Yukon delta where most of the faults are difficult to connect among seismic lines; some large faults evident on one line occur on no other line. The faults are either highly discontinuous, or have variable strikes so they converge and diverge in a complex pattern. Where strikes can be determined, the faults located north of the Yukon delta strike west-northwest, like those west of the delta.

Seismic Stratigraphy

The ages of strata in the basin are not well known. The oldest strata in the basin are thought to be of Late Cretaceous age; the basis for this age is presented below in the discussion of the geologic history of the basin. Nelson Hopkins, and Scholl (1974) suggest that a regional late Miocene marine transgression occurred. They think the transgression ended pre-late Miocene deposition of nonmarine strata in Norton Basin. Most of the strata above the uncon-

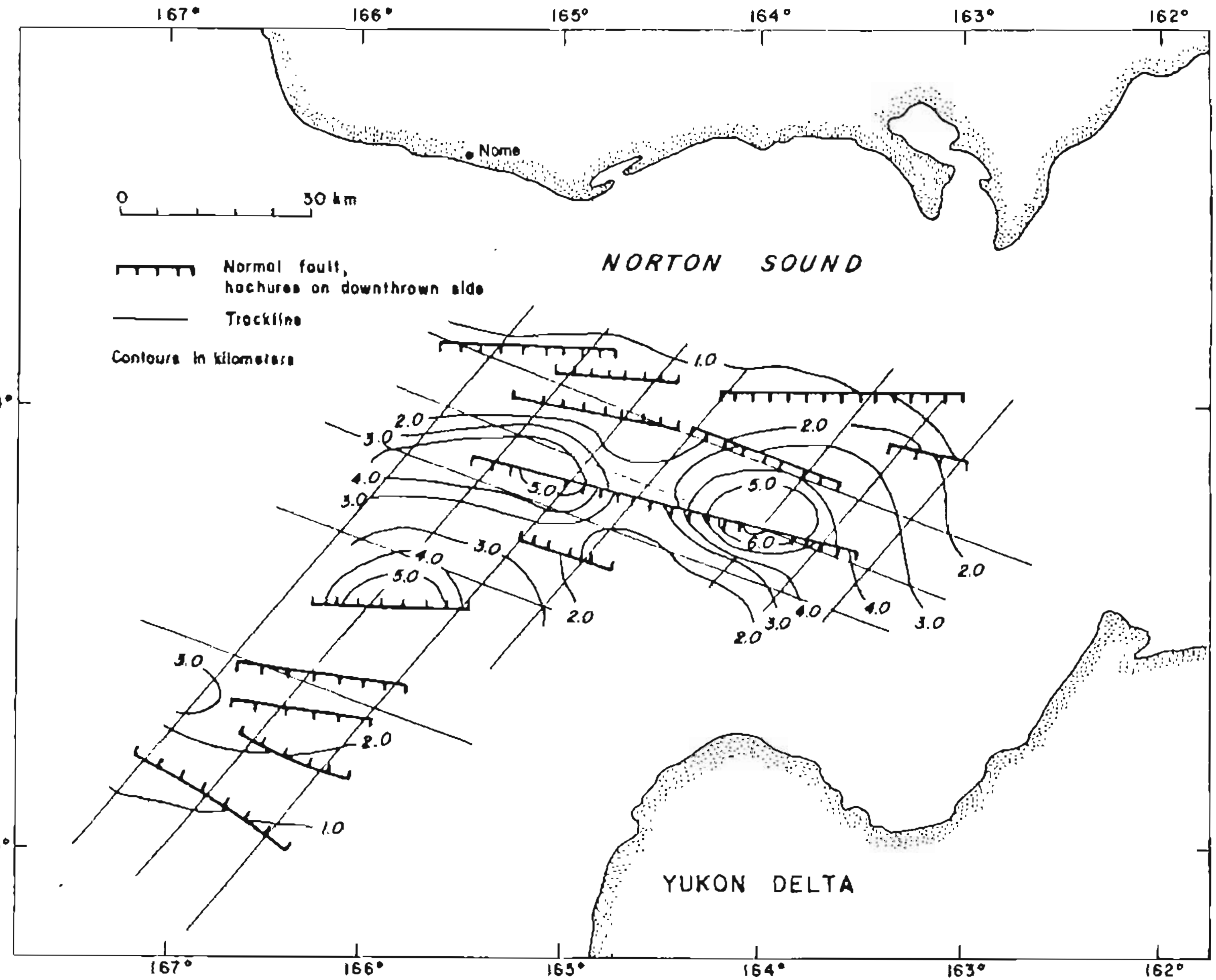

Figure 5a. Structure contours on bottom of Norton Basin. Strata in basin may be as old as Late Cretaceous; strata below basin may be as young as middle Cretaceous.

formity at which faults decrease in throw may be marine, and strata below the unconformity may be largely nonmarine or deltaic. These obeservations generally conform with the idea of Nelson, Hopkins, and Scholl (1974) of a late Miocene marine transgression.

The depositional environment of the strata near the unconformity is interpreted from the acoustic signature of the strata. Reflections just below the unconformity are mostly irregular and discontinuous, possibly indicating localized sediment bodies in fluvial or deltaic systems. The sequence of irregular reflections is widespread in the basin and appears to come from the direction of the present Yukon delta; the Yukon, therefore, may have supplied most of the strata in the sequence. Above the unconformity, reflections are extensive and parallel, suggesting deposition over wide areas by unconfined currents, like those that occur in a marine-shelf environment.

Strong, discontinuous reflections from deep within Norton Basin are interpreted to be volcanic rocks in flows or sills. The proportion of volcanic rocks in the basin is low, but the proportion is highest deep in the grabens. The presence of the volcanic rocks in the graben raises the question of whether the bottom of the basin is correctly located in the deep grabens, or whether, locally, the interpreted bottom is erroneously placed on a flow or sill. If so, the basin may be deeper than shown on figure 5a.

Volcanic rocks on St. Lawrence Island range in age from Paleocene to Oligocene, if the volcanic rocks in Norton Basin have the same age as volcanic rocks on St. Lawrence Island, basin fill that encases the volcanic rocks is at least as old as the youngest (Oligocene) volcanic rocks on the island.

Refraction-seismic data provide additional evidence for the age of strata in and beneath the basin. A simple and direct correlation of compressional velocity with age and/or rock type is often difficult to make because compressional velocities are complex functions of burial history, lithology, and age of the rocks involved. In some cases (for instance, Dolzhanskiy and others, 1966; and Sundvor and Nysaether, 1975) investigators have been able to show that certain lithologic sequences display a degree of coherence in their velocity spectra. The velocity units shown in figure 4c are distinct enough in most cases that some confidence can be placed in an interpretation that the velocity units represent age or rock-type groups.

Velocities higher than 5.0 km/s form the basement velocity unit. The velocities are characteristic of igneous, metamorphic, and indurated sedimentary rocks (Grant and West, 1965), indicating that Norton Basin is probably floored by rocks similar to the diverse Precambrian, Paleozoic, and lower Mesozoic rocks exposed on the Seward Peninsula, on St. Lawrence Island, and on the Chukotsk Peninsula. Unit D is lowermost in the basin; velocities in strata of this unit range from 4.0 to 5.0 km/s. Because these velocities are close in value to velocities measured in Mesozoic strata in Anadyr basin (Dolzhanskiy and others, 1966), strata in this velocity unit in Norton Basin also may be Mesozoic. The velocity division between Units B and C (fig. 4c) occurs at 3.0 km/s, which is close to the velocity measured at the interface between Neogene and Paleogene strata in Anadyr basin (Dolzhanskiy, 1966). Preliminary comparison of the refraction and reflection data suggests this interface is the unconformity at which faults decrease in throw. We believe the unconformity is between Oligocene and Miocene strata, and below we refer to the unconformity as the Oligo-Miocene(?) unconformity. If this age for the unconformity is correct, marine deposition in the basin began in the early Miocene, which is earlier than the late Miocene transgression proposed by Nelson, Hopkins, and Scholl (1974).

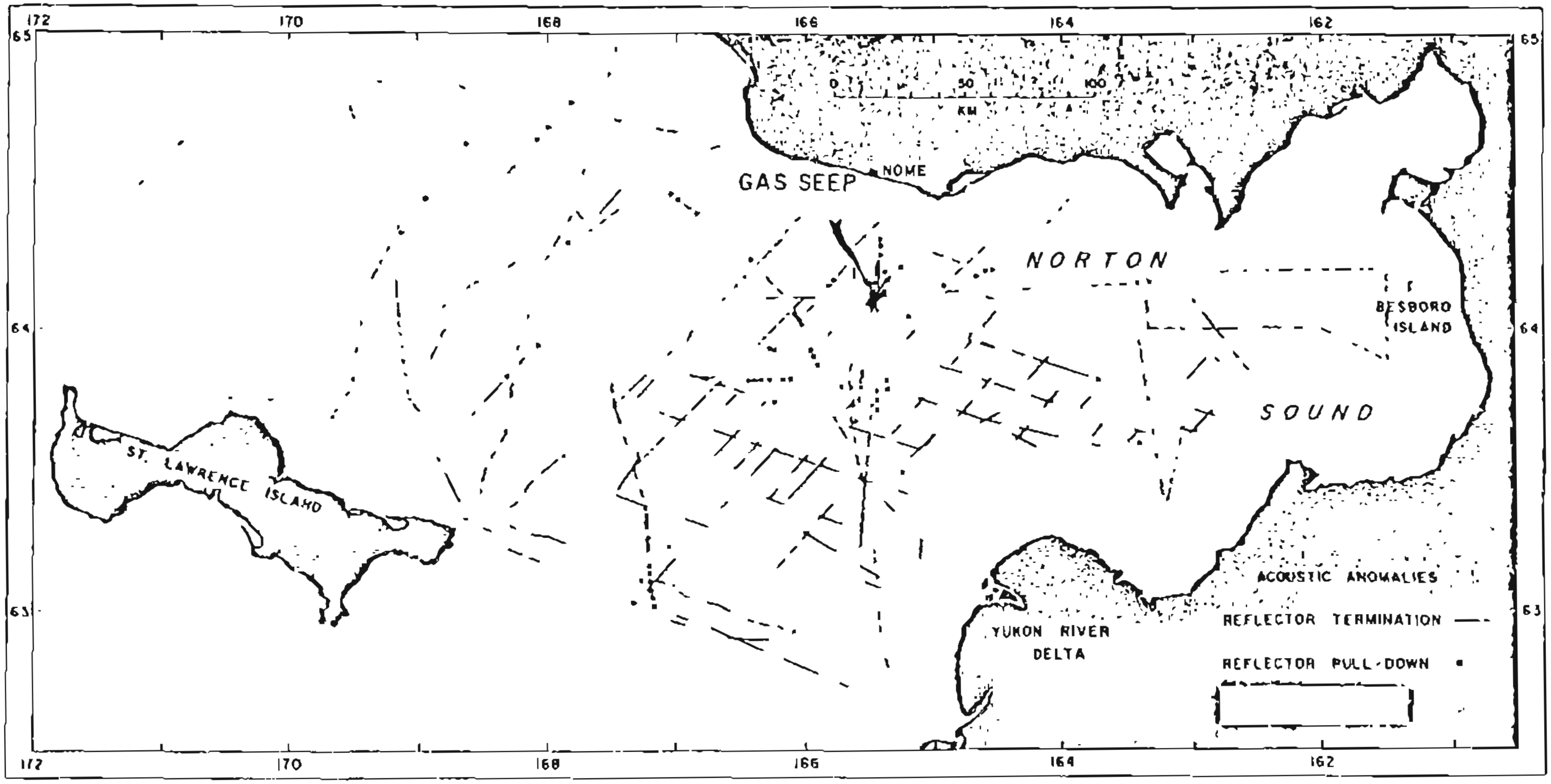

Figure 5b. Location of anomalous near-surface acoustic responses observed on single channel seismic reflection records from Norton basin. The acoustic anomalies are due to the presence of bubble phase gas in the near-surface (upper 200 m) sediment.

Acoustic Anomalies

As reported by Cline and Holmes (1977, 1978) and by Nelson and others (1977), abundant acoustic anomalies are evident in seismic data obtained over Norton Basin. Figure 5b shows the distribution of the acoustic anomalies along more than 15,000 km of seismic-reflection lines in Norton Basin. Two distinct types of acoustic anomalies are observed on the seismic reflection records: reflector "pull-downs" and reflector terminations. Both types could be caused by the presence of gas in the near-surface (upper 150 m) sediment. Reflector "pull-downs" have been observed and described by other investigators in both deep- and shallow-water areas (Lindsey and Craft, 1973; Cooper, 1978). The "pull-down" reflections are caused by a greater traveltime through the gas-charged sediment because gas causes a decrease in compressional velocity in the sediment. A decrease in compressional velocity and in density, due to the presence of gas in the sediment, results in a large negative reflection coefficient at the top of the gas-charged layer (Craft, 1973; Savit, 1974).

Extensive reflector-termination anomalies, observed throughout Norton Basin (fig. 5b), may also be caused by subsurface accumulation of gas in sufficient quantity that attenuation and scattering of the seismic signal is virtually complete. The anomaly associated with the gas seep south of Nome is characterized by a sudden termination of subbottom reflectors, and by a dramatic "pull-down" of the reflectors at the margins of the anomaly.

The distribution of acoustic anomalies, shown in figure 5b, suggests that near-surface accumulations of gas are most common in the central part of Norton Basin, northwest of the Yukon River delta. The apparent gas-free zones along the southern and eastern shores of Norton Basin are due to a lack of data from these shallow-water areas. Over western Norton Basin, however, seismic reflection coverage is good, but few acoustic anomalies are present.

GEOLOGIC HISTORY

Norton Basin is adjacent to the Kaltag fault, a major strike-slip fault showing between 60 and 130 km of right-lateral separation. The proximity of the basin to the fault and the extensional-tectonic structure of the basin suggest the basin formed as a pull-apart feature along the fault. Such an origin implies that crustal blocks on opposite sides of the fault diverged as the fault moved. The divergence could be caused by the fault curving to the northwest near the basin (fig. 6), causing an area of extensional tectonism to form between diverging blocks.

Scholl and others (1970) searched for a seaward continuation of the Kaltag fault, but could find no seismic-reflection evidence from late Cenozoic strata for this fault. They conclude the fault was active during the early and middle Tertiary. Though offset streams show that minor movement occurred along the fault in the late Cenozoic, we concur with the conclusion of Scholl and others (1970) that the fault was active during the early Tertiary. We postulate further that the fault was active during the Late Cretaceous and earliest Tertiary compression between Siberia and North America (Patton and Tailleur, 1977). The fault may have formed as a crustal break to relieve compressive stress in the region. If the extension that caused Norton Basin to form is due to movement along the Kaltag fault, the basin began to form in the Late Cretaceous with the onset of compression and consequent fault movement, or shortly thereafter.

If Norton Basin formed as a pull-apart basin, the large throw of faults below the Oligo-Miocene(?) unconformity, in comparison to the throw above the unconformity, suggests the greatest extension occurred during the Late Cretaceous and Paleogene. The basin may have filled rapidly during the time of great extension.

The basin received sediment as soon as low-lying area developed; the oldest

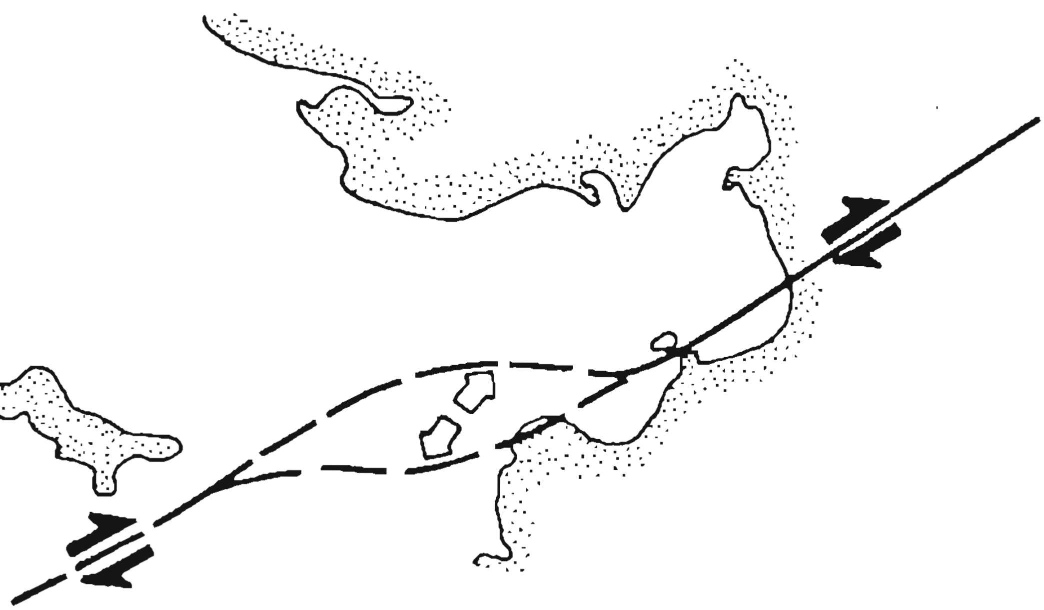

Figure 6. Formation of Norton Basin as a pull-apart basin along Kaltag fault.

strata in the basin, therefore, are probably of Late Cretaceous age. This interpretation is supported by the history of sedimentation in the Yukon-Koyukuk province where a middle Cretaceous conglomerate, lying along the entire western margin of the Yukon-Koyukuk province, contains cobbles of Paleozoic rock from the miogeoclinal belt. Middle Cretaceous deltaic strata that overlie the conglomerate are sandstone, shale, and coal; some of the sandstone is calcarenite that may have been derived from Paleozoic carbonate rocks. The source area for the deltaic strata and the conglomerate is the area now below Norton Sound; arrows in figure 2c show the direction of sediment transport. During the middle Cretaceous, therefore, the area of Norton Sound was high-standing and was eroded. Erosion exposed Paleozoic rocks over a broad area because the conglomerate extends the length of the western margin of the Yukon-Koyukuk province. The area of Norton Basin may have been eroded too, so that the middle Cretaceous unconformity forms the top of the basement beneath the Late Cretaceous and younger strata in the basin. The depth of erosion in the area of Norton Basin is not known; the age of basement strata could range from Paleozoic to middle Cretaceous. The strong reflection at the bottom of the basin suggests a large acoustic impedence contrast exists between the pre-Late Cretaceous basement rocks and the Late Cretaceous and younger basin fill; a significant age gap probably exists, therefore, between strata in the basement and the basin fill. Refraction velocities, measured in strata in and below the basin, also suggest an age gap--in the deep parts of the basin refraction velocities measured in the strata are near 5 km/s (velocity Unit D, fig. 4c); whereas velocities measured below the basin are near 6 km/s (Basement velocity unit).

Norton Basin filled in the Late Cretaceous and early Tertiary during the period of major faulting. After the early Tertiary the basin continued to subside and to receive sediment as shown by basin fill lapping away from basin center onto the basement. Late Tertiary subsidence is probably due to isostatic adjustment of the crust to the load of sediment in the extensional part of the basin. Subsidence allowed the basin to grow beyond the limits of the area affected by extensional tectonics.

The extensional tectonics that formed the basin may have caused the crust beneath Norton Basin to thin. Some normal faults could have become avenues for upward migration of magma that extruded during basin formation. Volcanism and a relatively thin crust probably increased the geothermal gradient in the basin relative to the gradient that existed away from the area of extension.

In summary, the speculative model just described suggests the area that now underlies Norton Sound was eroded in the middle Cretaceous and shed debris into the Yukon-Koyukuk province. In the Late Cretaceous, compression occurred between Siberia and North America. The compression caused the Kaltag fault to form, and while movement occurred on the fault, Norton Basin formed as a pull-apart basin. Norton Basin probably began to fill in the Late Cretaceous.

PETROLEUM GEOLOGY

Indications of Oil and Gas

The populace around Norton Sound has made numerous reports of oil seeps. Examination of some reported seeps by geologists shows, however, that what was presumed to be oil was something else; for example, some reported oil slicks turned out to be iron oxide films (Payne, 1959). Further, a "paraffin-like foam", reported to blow ashore at Nome (Cathcart, 1920), may be spume that commonly occurs on exposed beaches during times of strong onshore winds. Payne (1959) reports an oil seep may be in the Sinuk River Valley northwest of Nome; Patton and Fisher did not find a seep in the summer of 1978 while examining Tertiary(?) strata in the valley. Payne (1959) reports the existence of another seep near the mouth of the Inglutalik River, which empties into Norton Bay, and Cathcart (1920) reports the occurrence of oil in one of the two shallow (less than 100 m deep) wells drilled near Cape Nome in 1906. To date, however, we do not know of any oil occurrence that has been verified.

Gas seeps commonly occur in and around Norton Sound. Two wells at Cape Nome encountered shallow, high-pressure gas. Seeps of combustible-gas are common on the Yukon delta where gas is often trapped beneath river ice in winter; this gas may be marsh gas (methane) of biogenic origin (Payne, 1959). Offshore, craters mark large areas of the seafloor, and acoustic anomalies commonly occur in seismic data. Gas may cause both the craters and the anomalies. A gas seep, located 64 km south of Nome, contains mostly carbon-dioxide gas, but a small fraction of hydrocarbon gas is also present. The importance of the gas seep to the hydrocarbon potential of the basin is described below, in the discussion of possible sources for hydrocarbons.

The presence of oil shale on Besboro Island (Payne, 1959), northeast of Unalakleet, is unsubstantiated; presence of oil shale there, however, is unlikely.

Source, Reservoir, and Trap

Hydrocarbon-source and reservoir characteristics of strata in Norton Basin must be inferred from the characteristics of strata that rim the basin, but may not be in or beneath the basin, and from the acoustic signature of the basin fill. The discussion concerns, in turn, the topics of possible sources, reservoirs, and traps for hydrocarbons; as each topic is discussed, the characteristics of onshore strata are described first, followed by the inferred characteristics of basin strata.

Source

To determine the source potential of strata around Norton Basin, outcrop samples from St. Lawrence Island, from the Sinuk River Valley on the Seward Peninsula, and from the Yukon-Koyukuk province were analyzed for thermal maturity using vitrinite reflectance and thermal alteration index, and for source richness using solvent extraction (C_{15+}) and organic carbon percentage. Geochem Laboratories, Inc. did the analyses; the results are summarized in table 1.

Dow (1977) considers source strata to be capable of generating oil when vitrinite reflectance values from the strata are between 0.65 and 1.0 percent; this range is used in this report. Tissot and Welte (1978, p. 96) show good clastic source strata generally contain about 2 wt percent organic carbon, and 0.5 wt percent is the minimum carbon content for source rocks. Also bitumen (organic material extractable with solvents) from good source rocks contains about 50 percent hydrocarbons. Good carbonate source strata contain about 0.67 wt percent organic carbon.

Dow (1977) and Tissot and Welte (1978) show that the type of kerogen (insoluble organic matter) in strata determines the type of hydrocarbons generated from the strata. In this report, we recognize four types of kerogen: coaly, woody, herbaceous, and amorphous. Coaly kerogen is generally inert and produces little or no hydrocarbons. Woody kerogen is from the structural parts of plants and tends to produce gas. Herbaceous kerogen includes spores, pollen and plant cuticle, and may yield oil or gas or both, depending on the proportions of the constituents. Amorphous kerogen is generally from microorganisms, and yields oil. Usually, kerogen in strata is a mixture of the four types.

Nine outcrop samples from St. Lawrence Island range in age from Devonian to Tertiary. The Paleozoic and Mesozoic clastic rocks contain about 2.1 wt percent organic carbon; the carbonate rocks, however, contain only 0.4 wt percent or less. In both clastic and carbonate rocks, herbaceous and woody kerogen predominate. Thermal alteration index values show all samples are thermally immature, except for the sample of Permo-Triassic shale. The low thermal alteration of the samples of Paleozoic rocks, in comparison to the slate- and schist-

TABLE 1 ORGANIC GEOC

Sample Number	Age	Lithology	Organic Carbon (percent)	Average Vitrinite Reflectance (percent)	Indigenous Kerogen: Type[4]	Indigenous Kerogen: Thermal Alteration Index[5]	C_{15+} Extraction: Extract (ppm)	C_{15+} Extraction: Hydrocarbon in Extract (ppm)	C_{15+} Extraction: P-N[1] in Extract (percent)
St. Lawrence Island									
66A Pa 216	Tertiary	coaly siltstone	33.18	0.39	W-C;-;H	2- to 2	---	---	---
71A Pa 202	Tertiary	coal	52.6	0.39	W-C;-;Am-H	2- to 2	---	---	---
69A Pa 97	Tertiary	limey sandstone	0.44	0.24	H-W-C;-;Am	1+ to 2-	670	48	---
71A Cy 215	Tertiary	coal	81.8	0.22	W-C;H;Am	1+ to 2-	---	---	---
71A Pa 368	Triassic	limestone	0.16	---	W-C;-;H	1+ to 2-	---	---	---
69A Pa 107	Triassic	shale	2.16	---	H-W;-;-	1+ to 2-	489	31	---
71A Pa 194	Permo-Triassic	shale	2.13	---	W-C;H;-	3 to 3+	708	70	---
70A Pa 98	Devonian	limestone	0.29	---	H;W;-	1+ to 2-	---	---	---
68A Pa 562	Devonian	dolomite	0.41	---	H-W;-;-	2- to 2	439	29[2]	---
Sinuk Valley									
78A Pa 500A	Tertiary(?)	sandstone	0.37	0.86	H;W;-	1+ to 2-	469	76	1.5
78A Pa 500B	Tertiary(?)	coal	29.29	0.92	H-W;C;-	2+ to 3-	7,312	862	0.3
Unalakleet & Yukon-Koyukuk Areas									
78A Fi 010	Oligocene	coal	36.48	0.31	W;H;Am	1 to 1+	1,826	184	0.2
78A Fi 011A	Oligocene	coal	28.14	0.32	W;H;Am	1 to 1+	160	36[2]	---
78A Fi 019	Oligocene(?)	coal	21.03	0.30	H-W;-;-	1 to 1+	10,826	948	0.3
78A Fi 001	Cretaceous	siltstone	1.02	2.74	W;H;-	2 to 2+	140	24[2]	---
78A Fi 002	Cretaceous	shale	0.97	3.22	H;W;-	2 to 2+	110	28[2]	---
78A Fi 003	Cretaceous	shale	6.01	3.27	H;-;-	3- to 3	296	44[2]	---
78A Fi 006	Cretaceous	shale	1.07	3.45	H;-;W	2 to 2+	179	11	1.1
78A Fi 007	Cretaceous	shale	0.74	1.91	H;-;-	3- to 3	134	28[2]	---
78A Fi 009	Cretaceous	coal	14.06	1.93	W-C;-;H	3+ to 4-	125	34[2]	---
78A Fi 011C	Cretaceous	coal	56.42	1.88	W;-;H	2+ to 3-	3,321	413	0.2
78A Fi 011D	Cretaceous	shale	0.98	2.01	H;W;-	2+ to 3-	187	42[2]	---
78A Fi 012A	Cretaceous	shale	0.52	2.00[3]	H-W-C;-;-	3- to 3	135	42[2]	---
78A Fi 013B	Cretaceous	shale	1.33	2.24	W-C;H;-	3- to 3	157	48[2]	---
78A Fi 015A	Cretaceous	shale	0.50	1.96[3]	H-W;C;-	3- to 3	70	10[2]	---
78A Fi 015C	Cretaceous	shale	1.50	2.63	W-C;H;-	2+ to 3-	135	32[2]	---
78A Fi 015D	Cretaceous	coaly shale	6.58	2.47	H;C;W	3 to 3+	210	57	5.3
78A Fi 016A	Cretaceous	shale	0.36	2.27[3]	C;H-W;-	3 to 3+	197	38	10.1
78A Fi 016C	Cretaceous	shale	0.31	2.42	W-C;-;H	3 to 3+	138	25	---
78A Fi 018A	Cretaceous	coaly shale	7.37	2.53	H-W;C;-	3- to 3	228	75	1.8
78A Fi 018B	Cretaceous	shale	0.81	1.15	H-W;-;-	2- to 2	119	26[2]	---
78A Fi 020	Cretaceous	shale	0.52	1.29	H;-;Am-W	2- to 2	249	46	7.2
78A Fi 014	Paleozoic	carbonaceous limestone	1.36	1.86	C;-;-	5	105	18	---

Notes:

1. P-N = parafins and naphthenes
2. Estimated value
3. Scattered values in histogram
4. H = Herbaceous, spore/cuticle, C = Coaly, W = Woody, Am = Amorphous-Sapropel

   Kerogen types shown in order of abundance:

   Predominant; Secondary; Trace
   100-60% 40-20% 20-1%

5. 1 to 2- immature
   2- to 2 moderately immature
   2 to 2+ moderately mature
   2+ to 3 mature
   3 to 3+ very mature
   4- to 4 severely altered
   5 metamorphosed

grade metamorphism of Paleozoic rocks on the Seward Peninsula, implies the Paleozoic strata under the island have not been deeply buried.

The sample of Permo-Triassic shale is the one thermally mature sample from St. Lawrence Island. The maturity may be attributed to local thermal effects of Cretaceous intrusives. Despite the maturity of the sample, the predominantly woody and coaly kerogen of the sample yielded only 10 percent hydrocarbons during the solvent extraction (C_{15+}). The shale, therefore, is gas prone.

Nonmarine Tertiary strata from the younger Tertiary unit on St. Lawrence Island are mostly coaly sandstone and siltstone that have high organic-carbon contents. The predominance of woody and coaly kerogen and the low degree of thermal alteration make these strata possible sources for methane gas.

The analyses of samples from St. Lawrence Island do not indicate any oil-prone source rocks. This conclusion must be evaluated along with three reasons for caution: (1) only nine samples are analyzed and this low number is not a statistically valid estimate of the source-rock quality of the entire stratigraphic section exposed on the island; (2) the geochemical properties of the Tertiary strata are of doubtful regional significance because the outcrops are isolated and small; and (3) the samples were not collected specifically for organic geochemical analysis because access to the island is restricted by the native population, thus whatever promising samples were at hand, were analyzed.

Nonmarine strata in the Sinuk Valley are of Tertiary(?) age. The sandstone sample contains only 0.37 wt percent organic carbon, and the kerogen is mostly herbaceous and woody. A vitrinite reflectance value of 0.86 percent shows the sandstone is in the late stages of oil formation; the proportion of hydrocarbons in the solvent extract (C_{15+}), however, is low. The sample, therefore, indicates strata in the valley are gas prone.

Outcrop samples from shales in the middle Cretaceous deltaic strata exposed in sea cliffs near the town of Unalakleet generally contain about 0.5 to 1.9 wt percent organic carbon. Herbaceous and woody kerogen predominate. The strata are thermally altered--both vitrinite-reflectance and thermal alteration analyses show the strata range from mature to severely altered. The degree of thermal alteration and the type of kerogen indicate the strata are gas prone.

The predominance of woody, herbaceous, and coaly kerogen in the gas-prone Tertiary and Cretaceous strata that rim Norton Basin results from the nonmarine and deltaic environments of deposition of the strata. We infer that the same type of kerogen predominates in deltaic strata in Norton Basin, and may yield gas-prone source strata there too. The description of strata as "gas-prone" does not mean oil cannot be produced from the strata, rather the description means gas is more likely to be produced than oil. The marine (parallel bedded) strata in Norton Basin may contain more amorphous kerogen than the deltaic strata; the marine strata, therefore, may be a source for oil if the strata are thermally mature.

In the offshore area, some strata are mature enough to produce hydrocarbons as shown by gas from the seep south of Nome. Table 2 shows the composition of the gas (K. Kvenvolden, written commun., 1979). Though most of the gas is carbon dioxide, gasoline-range (C_5-C_7) hydrocarbons that are present in the gas indicate source strata of unknown quality are in the basin. The carbon isotope ratio of the methane gas is about -35 permil PDB (Peedee Belemnite standard). The ratio and the presence of hyrocarbon gases heavier than ethane (C_2) suggest the gas is not biogenic, rather the gas probably formed during thermal alteration of organic material (K. Kvenvolden, written commun., 1979; Feux, 1977). The dominant gas at the seep, carbon dioxide, has a carbon isotope ratio of about -3 permil PDB, suggesting the gas might be derived from decomposition of marine carbonates at depth (K. Kvenvolden, written commun., 1979; Feux, 1977).

Table 2.--Composition of gas from offshore seep

Component	Percent
CO_2	98.0
N_2	1.9
O_2	0.05
Ar	0.03
CH_4	0.03
hydrocarbon gasses*	0.01
H_2	0.01
He	>0.01
H_2O	trace

Hydrocarbon Gasses

Gas	ppm
methane	362
ethane	39
propane	18
n-butane	4
isobutane	20
C_{5+}	present but not quantified

*exclusive of methane (CH_4)

In addition to possible source rocks within the basin, Paleozoic and lower Mesozoic strata that may be in the basement could also be sources of hydrocarbons. Paleozoic and lower Mesozoic strata in the area of the basin may have been as thermally immature before the basin formed as strata of that age range are now under St. Lawrence Island. The accumulation of strata in the basin may have brought the Paleozoic and lower Mesozoic strata to thermal maturity during the Cenozoic.

The magnitude of the geothermal gradient in the basin is another unknown, besides the amount and type of organic matter, in the search for source rocks that have expelled hydrocarbons. The only estimates of the gradient are from uncorrected borehole temperatures from the Nulato, Napatuk, and Cape Espenberg wells (fig. 1). These wells are in different geologic provinces than Norton Basin, yet the temperatures in the wells may yield a minimum regional value for the geothermal gradient that can be applied to the basin. A minimum value for the geothermal gradient results because uncorrected borehole temperatures are usually lower than the true temperatures. Further, the extensional tectonics that formed the basin may have caused crustal attenuation beneath the basin and volcanism--the attenuation and the volcanism probably increase the geothermal gradient in the basin over the gradient that exists outside the area of extension. Rifted basins in other areas of the world generally have high geothermal gradients. The geothermal gradients calculated from uncorrected borehole temperatures in the three wells are: (1) Nulato, 17.2° C/km; (2) Napatuk, 23.8° C/km; and (3) Cape Espenberg, 28.4° C/km. These values are near the world average thermal gradient of 25° C/km, and fall within the average range of the gradients in sedimentary basins of 15 to 50° C/km (Tissot and Welte, 1978). The gradient in the basin is probably average (25° C/km), or higher. Tissot and Welte (1978, p. 282) state that, source rocks must be heated to at least 50 to 70° C before hydrocarbons are produced in quantity. Also, most hydrocarbons are found at subsurface temperatures in the range of 60 to 150° C (Louis and Tissot, 1967; Evans and Staplin, 1971; Philippi, 1975). Assuming a temperature of 0° C at the sea bottom and using the world average gradient (25° C/km) shows a temperature of 70° C could be present at a depth of about 3 km in the basin. Paleogene and older strata, therefore, could be at high enough temperatures, and could be old enough, to be sources for petroleum.

Reservoir

Table 3 shows values of porosity and permeability of outcrop samples from St. Lawrence Island and from the area around Unalakleet. Core Laboratories, Inc. measured the values. Tissot and Welte (1978, p. 317) show that fair reservoir rocks have porosities of 10 to 15 percent and permeabilities of 1 to 10 md. Using these porosity and permeability ranges to grade the reservoir quality of sandstone samples from around Norton Sound shows the rocks sampled would make poor reservoirs.

In Norton Basin the quality of reservoir strata older than late Miocene may be dependent on the provenance of the reservoir strata--the provenance may determine the percentage of quartz in the reservoirs. Since the late Miocene the Yukon River has had an enormous drainage area (Nelson, Hopkins, and Scholl, 1974) that has supplied quartz to Norton Basin, as shown by modern Yukon sediment that contains an average of 25 percent quartz (VenkataRathnam, 1970). Before the late Miocene, however, the proto-Yukon had a more restricted drainage area (Nelson, Hopkins, and Scholl, 1974), and may have received a large proportion of sediment from Cretaceous strata in the Yukon-Koyukuk province. Strata in the province typically contain only 8 percent quartz. Hence the reservoir potential of middle Miocene and older strata in the basin may be limited.

Seismic data show a delta of large areal extent in Norton Basin that appears unsuccessful. Though drilling results have been disappointing in both areas, drilling has been too sparse to state conclusively that no commercial hydrocarbons occur in either area.

Two exploratory wells were drilled in Hope Basin at Cape Espenberg on the Seward Peninsula and at Nimiuk near the northeast coast of Kotzebue Sound (fig. 1). Neither produced hydrocarbons in commercial quantities.

Exploratory drilling for hydrocarbons in Anadyr Basin began in 1966; the results of the drilling are summarized by Meyerhoff (1972) and by Agapitov and others (1973). Gas commonly occurs in Neogene and older strata; but after a brief initial gush, the production of gas invariably reduces to zero. Though oil shows are common, the search for economic quantities of oil continues. The oil shows occur in Neogene and older strata; Agapitov and others (1973), however, consider strata of Paleogene and Cretaceous age as the most likely host strata for petroleum deposits because oil flowed from a fractured Paleogene siltstone, and oil shows occur in Lower Cretaceous tuffs.

The source for oil may be strata of Albian through Maestrichtian and Eocene through Oligocene age. High volcaniclastic content of Paleocene strata reduces the source potential of the strata.

HYDROCARBON RESOURCE ASSESSMENT

The area considered for this assessment is bounded by latitudes 63°00' and 64°45' N, and longitudes 162°00' and 170°00' W. The assessed area is larger than 40,000 km^2, and includes the prospective portions of Norton Basin. The basin in the assessment area has a sediment volume estimated at about 60,000 km^3.

The assessed area coincides with the area used in a prior assessment by the Resource Appraisal Group (RAG), Branch of Oil and Gas Resources, U.S. Geological Survey. A review of geological and geophysical data acquired after the prior RAG assessment indicated that the prior assessment was reasonable, and the figures are retained for this report.

to head at or near the present Yukon delta, suggesting a large portion of the pre-late Miocene basin fill came from the Yukon. Sediment may also have been introduced from quartzose sources on the Seward Peninsula. Accordingly, reservoir quality may improve northward from the Yukon delta in strata older than late Miocene. The deepest part of the basin, however, is adjacent to the mouth of the Yukon. Reservoir quality may locally improve because of sorting of the quartz-poor sediment by the proto-Yukon River.

Local sources for basin fill include erosion of high-standing fault blocks and volcanic activity associated with the rifting that formed Norton Basin. If the fault blocks exposed metamorphic rocks like those of the Seward Peninsula, local quartz-rich sandstones could occur along the margins of the fault blocks. Another local source for basin fill is Paleogene volcanic activity that may have reduced the reservoir quality of Paleogene strata by introducing into the basin fill chemically reactive material, like volcanic ash and tuff, that later turn to clay and to low-grade metamorphic minerals, like zeolites, impairing both porosity and permeability. Migration of petroleum from Cretaceous or lower Paleogene strata into stratigraphic or structural traps in the grabens may be adversely affected if Paleogene strata contain a large volcaniclastic component.

Trap

Traps for petroleum in Norton Basin may be fault-associated or stratigraphic. The fault-associated traps may be the most economically important traps in the basin, especially those traps developed in and on the margins of horsts. If the horsts contain source and reservoir strata and are enclosed in impermeable strata petroleum may be contained within the horsts. Such traps are important to the hydrocarbon resources of the North Sea Basin (Williams, Conner, and Peterson, 1973; Watson and Swanson, 1975) and of other rifted basins. Determining the age and characteristics of rocks within the horsts is, thus, a crucial problem--

TABLE 3 POROSITY AND PERMEABILITY DATA

Sample Number	Age	Porosity (percent)	Permeability (Md)
St. Lawrence Island			
69A Pa 097	Tertiary	8.1	0.12
71A Pa 202	Tertiary	11.3	2.6
66A Pa 216	Tertiary	7.8	0.67
71A Pa 190	Permo-Triassic	2.3	0.28
Unalakleet and Yukon-Koyukuk Areas			
78A Fi 004	Cretaceous	7.6	<0.01
78A Fi 005	Cretaceous	6.6	<0.01
78A Fi 008	Cretaceous	6.4	<0.01
78A Fi 011B	Cretaceous	2.9	<0.01
78A Fi 011E	Cretaceous	2.6	<0.01
78A Fi 012B	Cretaceous	2.2	<0.01
78A Fi 012C	Cretaceous	7.0	.033
78A Fi 013A	Cretaceous	2.8	<0.01
78A Fi 015B	Cretaceous	1.1	<0.01
78A Fi 015E	Cretaceous	1.7	<0.01
78A Fi 016B	Cretaceous	0.6	<0.01
78A Fi 017	Cretaceous	1.3	<0.01
78A Fi 020B	Cretaceous	4.0	<0.01
78A Fi 020C	Cretaceous	10.2	1.42
GP-2-78	Cretaceous	0.8	0.04
GP-6-78	Cretaceous	4.6	2.79
GP-10-78	Cretaceous	1.1	0.04
GP-14-78	Cretaceous	1.2	0.26
GP-16-78	Cretaceous	4.5	0.19
GP-18-78	Cretaceous	4.8	0.20
GP-24-78	Cretaceous	0.6	0.04
GP-27-78	Cretaceous	1.7	0.05
GP-29-78	Cretaceous	2.8	0.17
GP-30-78	Cretaceous	3.9	0.07
GP-31-78	Cretaceous	2.4	1.06
GP-32-78	Cretaceous	2.0	0.06

if the rocks are equivalent to the metamorphic rocks of the Seward Peninsula, hydrocarbons cannot be contained within the horsts; alternatively, if a thick section of pre-Late Cretaceous strata overlies the metamorphic basement in the horsts, hydrocarbons could be trapped within the horsts.

Another type of trap that may be associated with horsts forms where reservoir beds in a graben terminate at, or lap onto, one of the fault planes that bounds a horst. This type of trap contains most of the reserves in the Sirte Basin of Libya, where beach sand laps onto the flanks of horsts and form reservoirs (Roberts, 1970; Sanford, 1970). The potential for similar traps in Norton Basin depends on the presence of well-sorted sandstones derived from the fault blocks as described in the previous section. Growth of normal faults may impose structural closure on these traps, and may result in arching of strata that overlie horsts, forming anticlinal traps.

Stratigraphic traps may form where strata in the basin pinch out against the basement. Additional stratigraphic traps may be at unconformities, especially at the base of the deltaic strata where the unconformity could be overlain by fine-grained bottomset beds or overbank deposits. Channel sandstone in abandoned delta lobes may also form stratigraphic traps.

The basin appears to have potential for numerous unconnected hydrocarbon accumulations because migration paths are broken by faults and by horsts. The potential for numerous accumulations does not mean the accumulations need be small, they could be of economic importance, but exploitation of the resources is likely to be more expensive and more difficult than if all hydrocarbons were concentrated in a few areas.

Results of Exploratory Drilling in Neighboring Basins

Onshore exploratory wells in two basins near Norton Basin--in the Hope Basin north of the Seward Peninsula, and in Anadyr Basin in Siberia--were

The hydrocarbon-resource appraisal involved use of a series of geologic and volumetric-yield analogical procedures that provide a suite of oil- and gas-yield values. The Cook Inlet and Uinta basins were used as geologic analogs to Norton Basin in the appraisal procedure.

A comprehensive review was made of geologic data for the Norton Basin by RAG, which then made a resource appraisal by a subjective probability technique as follows:

1. A low estimate was made, corresponding to a 95 percent probability that there is at least that amount of contained oil and gas.
2. A high estimate was made, corresponding to a 5 percent probability that there is at least that amount of contained oil and gas.
3. A modal estimate was made, which is associated with the highest probability that there will be that amount.
4. A statistical mean was calculated by adding the low, high, and modal values and dividing the sum by three.

The subjective judgments of RAG are assessments of the quantities of hydrocarbons likely at the 5 and 95 percent probability levels. These assessments were made to account for at least 90 percent of the probable undiscovered, recoverable oil and gas resources in the province.

A computer was employed to fit a lognormal distribution to the low, high, and modal values of the RAG assessments to compute the probability distribution for presence of oil and gas in Norton Basin.

Norton Basin is a frontier area in regard to petroleum exploration; the RAG, therefore, assigned marginal probabilities to the event that commercial oil or gas might be found. The marginal probabilities were applied to the sub-

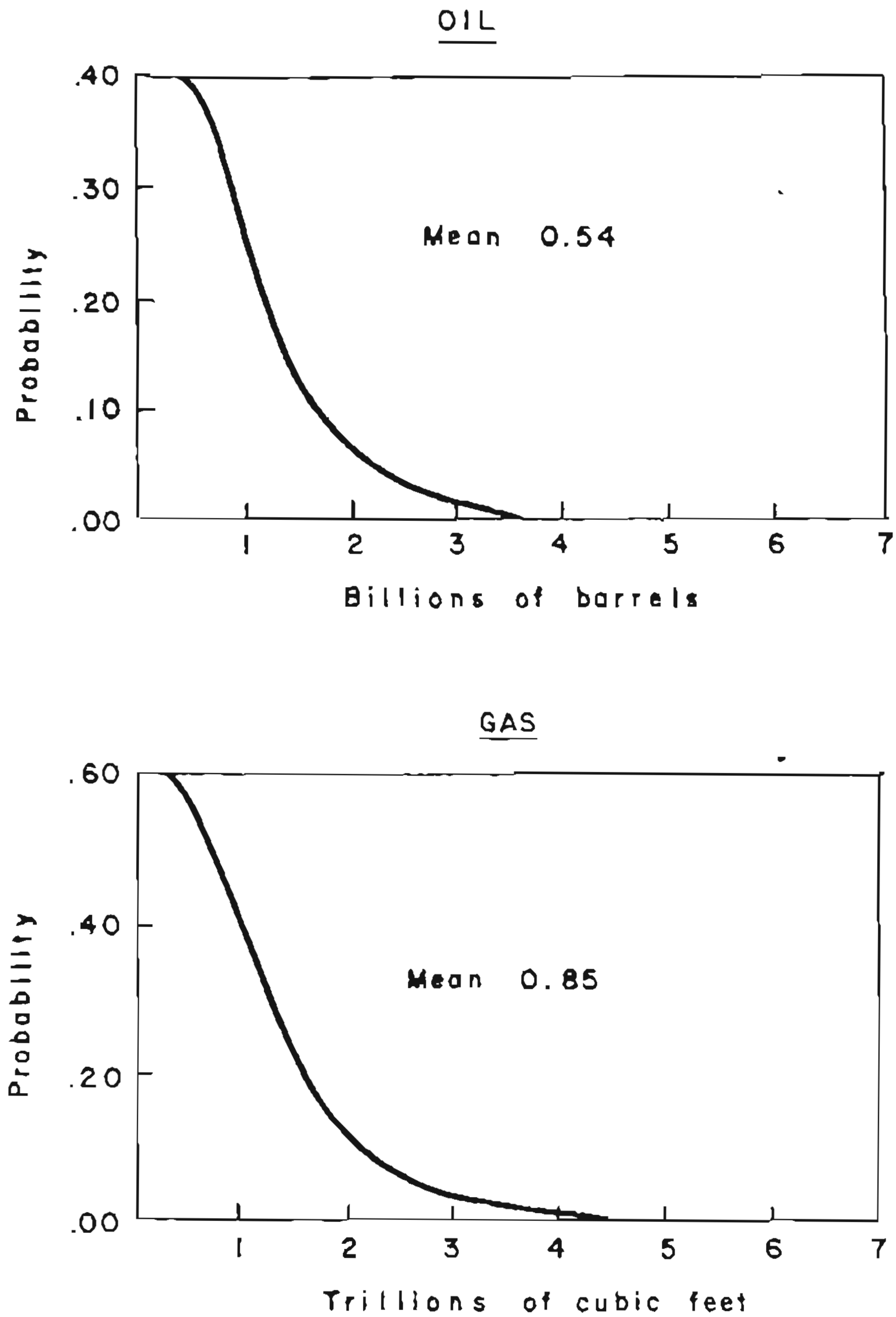

Figure 7. Lognormal distribution curves showing probability values for recoverable oil and natural gas in Norton Basin.

jective judgments of the resources to determine the final probability distribution of hydrocarbon resources. The marginal probability applied to oil was 40 percent and that applied to gas was 60 percent.

The lognormal-distribution curves, with marginal probabilities applied (fig. 7), show estimates of undiscovered recoverable oil and gas. The estimates are:

	95% Probability	5% Probability	Statistical Mean
OIL (Billion of barrels)	0	2.2	0.54
GAS (Trillion of cubic feet)	0	2.8	0.85

Organic geochemical data from strata exposed around Norton Basin became available after the resource assessment was made. Taken together, geochemical and geophysical data suggest strata in the basin may be gas-prone; hence, the basin may produce more gas than oil. Accordingly, some of the assessed oil quantities might better be considered as gas-equivalents.

ENVIRONMENTAL GEOLOGY

The data base for this evaluation of possible geoenvironmental hazards present in the northern Bering Sea includes (1) three cruises sponsored by OCSEAP (Outer Continental Shelf Environmental Assessment Project) covering 9,000 km of trackline (Nelson and others, 1978b; Thor and Nelson, 1978, in press); (2) 1977 and 1978 OCSEAP Annual Reports of the Norton Basin geoenvironmental hazards project (Nelson, 1977, 1978) and (3) OCSEAP Annual Reports from investigators studying associated environmental problems (Biswas and others, 1977; Cacchione and Drake, 1977, 1978; Cline and Holmes, 1977; Dupré, 1977, 1978; Sallenger and others, 1978). A summary bibliography of Norton Basin environmental geologic research is given in Nelson (1978). Figure 8 shows a summary of cruise tracklines run for environmental geologic research by the USGS in northern Bering Sea. The data base for this environmental assessment includes geophysical data collected along the tracklines shown in figure 8 as well as over 1,000 grab samples, 400 box cores, and 60 vibracores, collected for sediment analysis by the USGS; and hundreds of camera, hydrographic, and current meter stations occupied over the past decade by USGS and NOAA vessels. The data show a number of geologic hazards that may pose problems in the development of hydrocarbon resources. Bathymetry and geographic setting of the northern Bering Sea are shown in figure 9.

Tectonic Instability

Surface and near-surface faults are prominent along the entire northern margin of Norton Basin, but Holocene fault activity is difficult to determine because strong current scour may be preserving or exhuming old scarps (Johnson and Holmes, 1978). Surface and near-surface faults are rare in west-central Norton Basin and become more common along the southwest margin, particularly in the strait east of St. Lawrence Island. Determination of recent earthquake activity depends mainly on completion of seismicity studies; Norton Basin, however, is seismically more active than previously thought (Biswas and others, 1977, p. 304). Faults and sea floor scarp relief in Norton Basin are shown in figure 10.

Sediment Instability

Potentially unstable near-bottom sediment results from gas seepage in a local area 40 km south of Nome and from a wide region of biogenic gas charging in north-central Norton Sound. The presence of the gas seep south of Nome suggests a possible hazard for drilling activity in this area. Any man-made structures that penetrate the gas accumulation may provide direct avenues for uncontrolled gas migration to the sea floor. Such structures also may encounter reduced bearing capacity in the gas-charged substrate. Figure 11 shows the location of the thermogenic gas-charged sediment and seep.

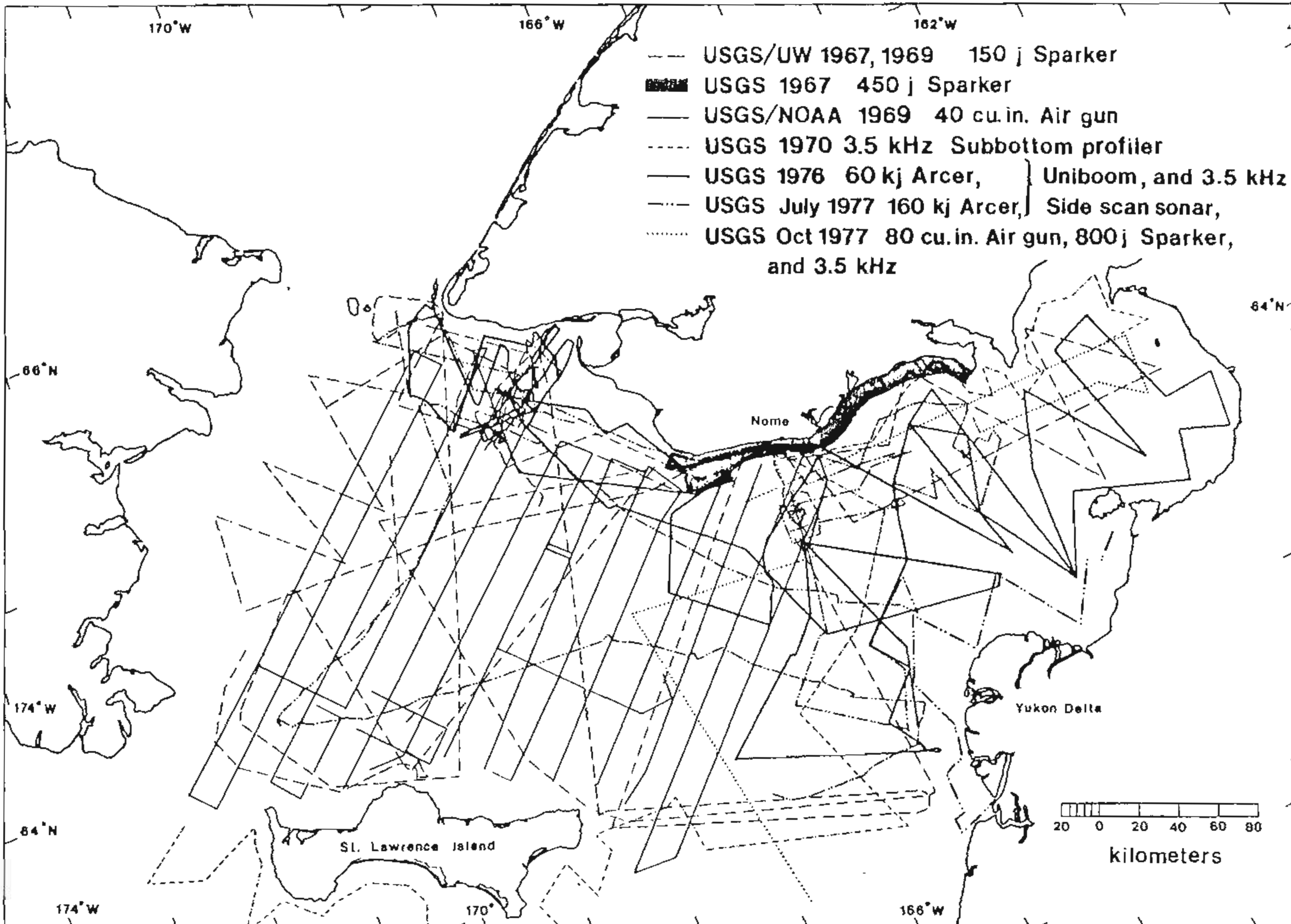

Figure 8. Coverage of geophysical studies conducted in northern Bering Sea (modified from Johnson and Holmes, 1978).

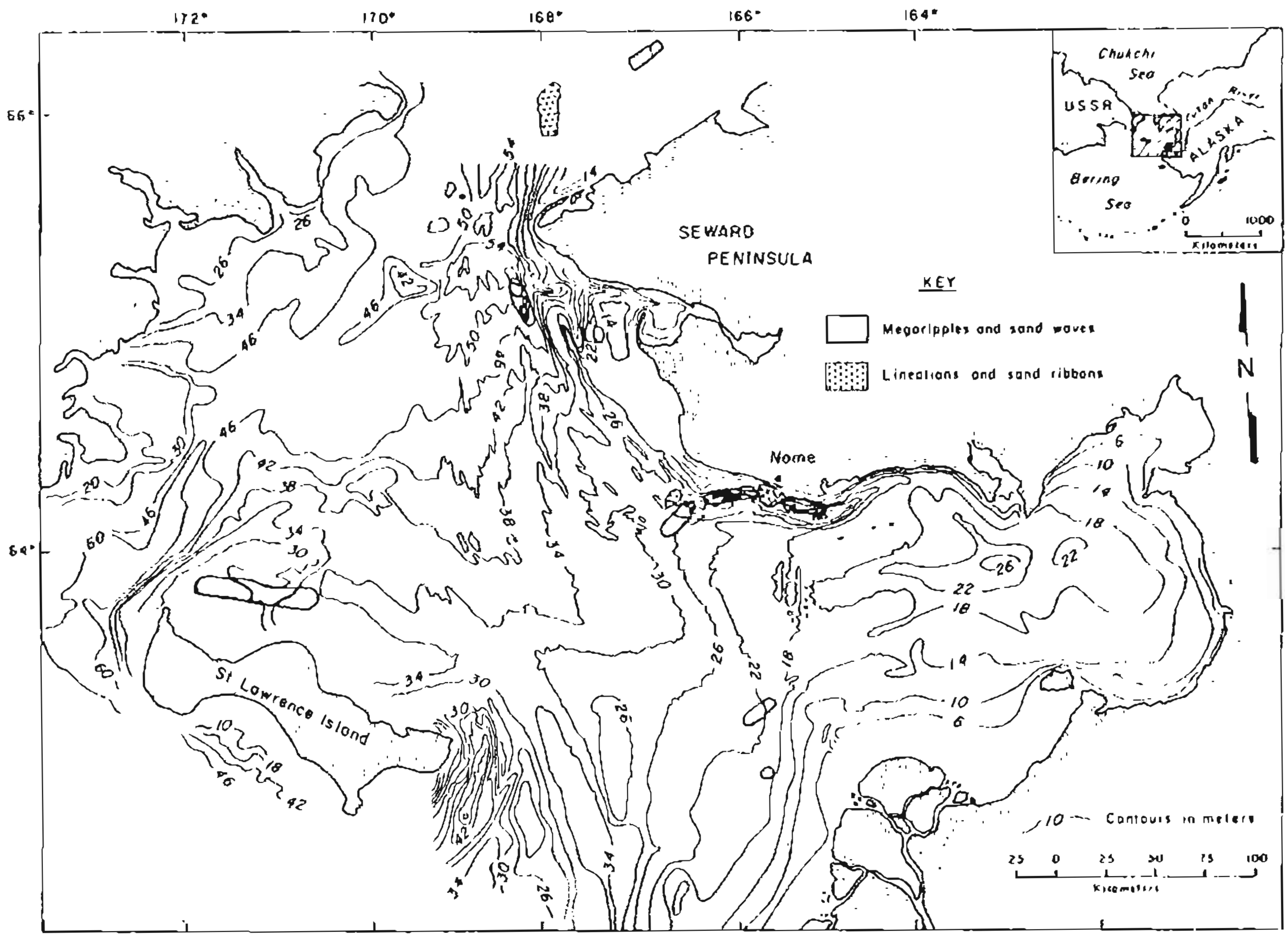

Figure 9. Bathymetry of northern Bering Sea. Also indicated is distribution of major areas of mobile bedforms (from Nelson and others, 1978e).

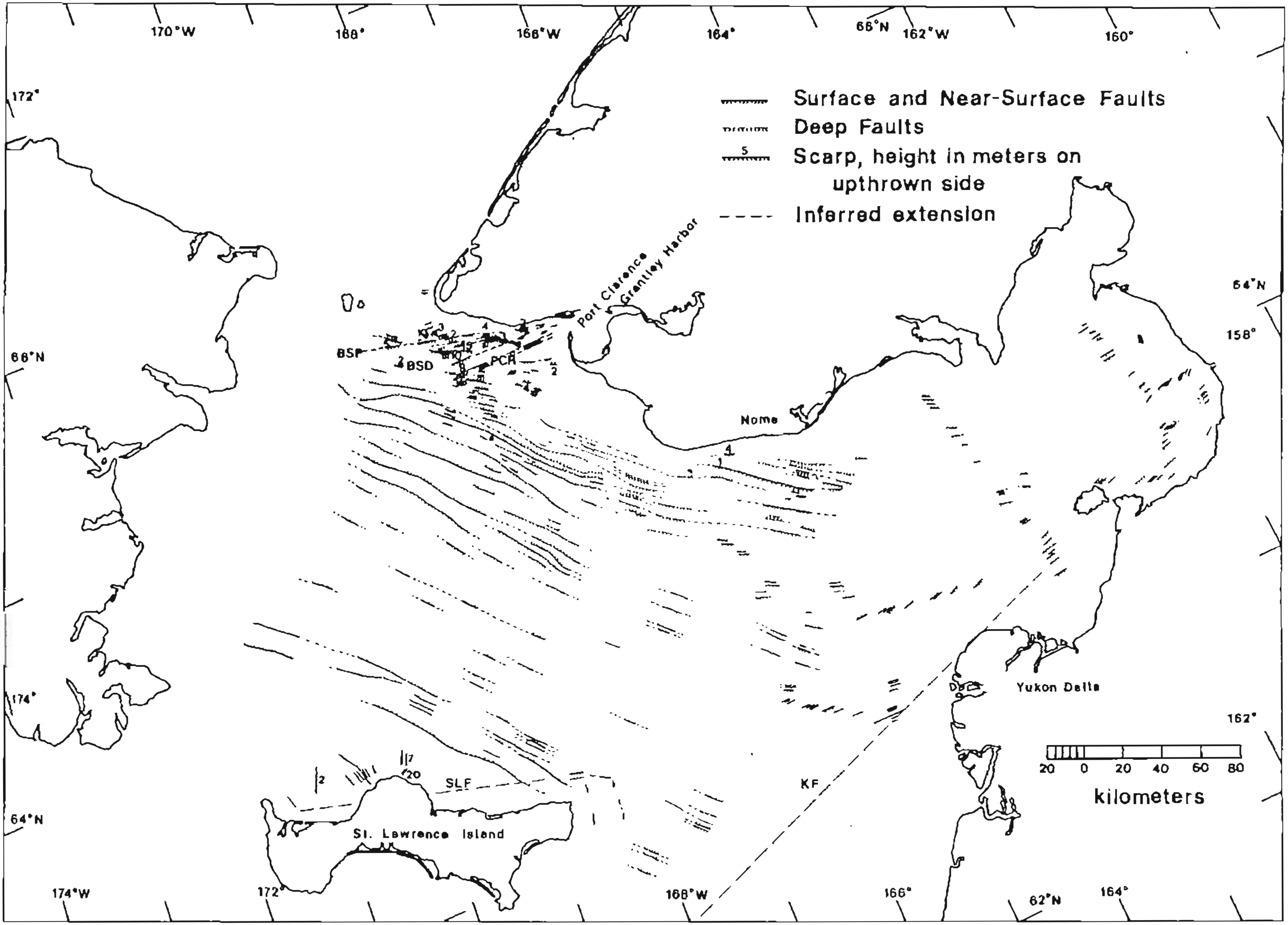

Figure 10. Faults in Norton Basin (from Johnson and Holmes, 1978).

Small (3 to 8 m in diameter), shallow (less than 0.5 m deep), circular craters observed on sonographs over a large area of north-central Norton Sound appear to be caused by active gas venting (Nelson and others, 1978e, in press). The craters are associated with near-surface peat layers, gas-rich sediment, and acoustic anomalies observed in high-resolution seismic-reflection profiles. Near-surface peaty-mud layers from 1 to 2 m below the sea floor have been vibracored throughout the northern Bering Sea. These peaty muds are nonmarine, pre-Holocene deposits with high amounts (3 to 7 wt percent) of organic carbon. Biogenic methane gas forms from the buried organic debris. Both acoustic anomalies and gas craters occur only where freshwater mud is now covered by a relatively thin (1 to 2 m) layer of Holocene mud. Craters are lacking where Holocene mud is thick near the Yukon delta or where the mud grades into sand north of St. Lawrence Island. The areal extent of the gas crater field and isopachs of Holocene mud are shown on figure 11.

In calm weather conditions, the near-surface gas may be trapped by thin modern muds. Apparently the gas escapes and forms craters during periodic storms that cause rapid changes in pore water pressures because of sea level rise, seiches, storm waves, and unloading of sediment. The unloading is due to sediment resuspension and erosion of covering muds. Gas venting and sediment depressions, often formed during peak storm periods, may have been associated with pipeline breaks in the oil-producing regions of the North Sea and the Gulf of Mexico. The near-surface gas-charged sediment and peaty mud also may possess reduced bearing strength for some offshore platforms.

The fine-grained sand and coarse-grained silt which form the substrate of Norton Sound are highly susceptible to liquefaction due to wave or seismically-induced cyclic loading (Clukey and others, written commun., 1978). Normal yearly storm waves propagating through the full fetch of Bering Sea intersect the shallow Yukon prodelta area and appear to be capable of inducing sufficient loading to liquefy Norton Sound sediment to a depth of 1 to 2 m. Liquefaction of sediment to this depth may contribute to formation of small local slumps and gas craters. The stability of underwater pipelines and the bearing capacity for man-made structures on the bottom could be seriously impaired if the top few meters of the substrate were to liquefy during major storms.

Erosion and Deposition Hazards

Ice scouring of bottom sediment is present throughout the northeastern Bering Sea beyond the shorefast ice zone where water depths are less than 20 m; scouring, however, also has been noted in water depths up to 30 m at scattered locations (Thor and others, 1978, in press). Ice-gouge furrows cut into bottom sediment to a maximum depth of 1 m and occur in most areas as solitary gouges. Pressure-ridge raking of the sea bottom is most common around the shoals of the Yukon delta because a well-developed ice-shear zone is present there. Most of Norton Sound is affected to some degree by ice gouging as are the margins and the areas of shoal sand ridges in the northwestern Bering Sea. Gouge distribution and density and shorefast ice limits are shown in figure 12.

Much of the gouging in Norton Sound is probably caused by pressure ridges formed along shear zones as pack ice moves past the stationary shorefast ice. The combination of Yukon prodelta shoals and ice convergence offshore from the delta accounts for the high density of gouging in this area. Because ice gouging is a pervasive scouring agent, any bottom facilities, such as cables or pipelines, should be buried below the depth of potential gouge penetrations. The base of any man-made structures on the sea floor should be protected from ice keels.

In certain areas of intense ice gouging and strong bottom currents, large scour depressions are associated with the gouge furrows. A series of large

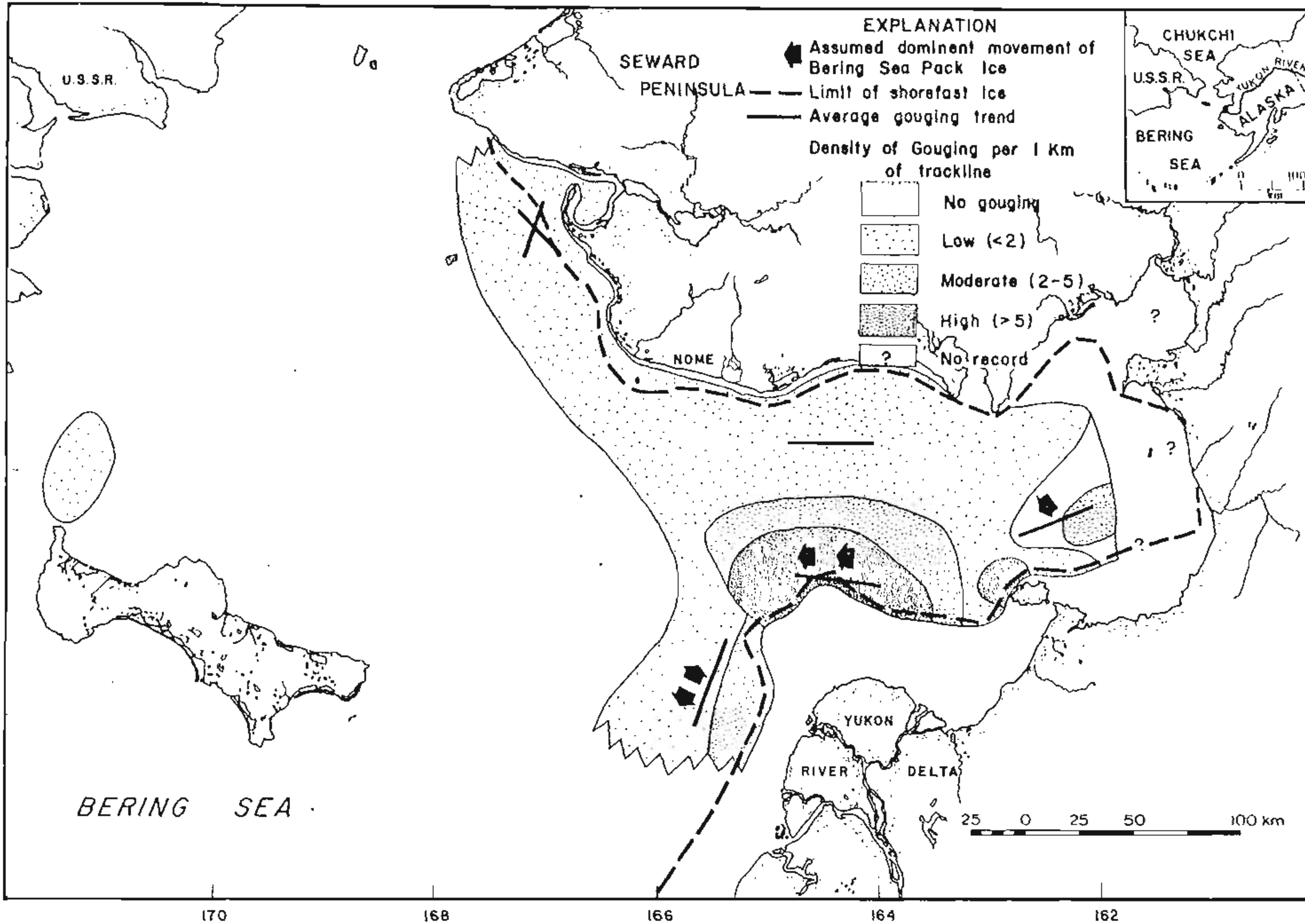

Figure 12. Distribution and density of ice gouging, movement directions of pack ice, and limits of shorefast ice in northern Bering Sea (modified from Nelson and Creager, 1977).

(25 to 150 m in diameter), irregularly shaped, shallow (less than 1 m deep) depressions in Yukon-derived silty mud occurs along the southwestern margin of the Yukon prodelta area and on the flanks of an extensive, shallow trough in north-central Norton Sound (Larsen and others, 1978, in press). The depressions usually are associated with increased bottom steepness and regions of high bottom-current speeds. Some of the northern depressions are near seafloor scarps of unknown origin; those west of the prodelta front are definitely associated with ice-gouge furrows. In regions where current speed is increased because of constriction of water flow along flanks of troughs, shoals, or prodelta fronts, any further local topographic disruption of current flow by slump scarps or ice-gouge furrows appears to initiate scour of the Yukon River-derived sediment to form large, shallow depressions. The distribution of scour depressions, shown in figure 13, shows where artificial structures that disrupt current flow may cause extensive erosion of Yukon mud and potentially hazardous undercutting of the structure.

Buried structures may be subject to scour because naturally occurring ice gouges may be greatly broadened and deepened by currents sufficiently strong to expose the buried structures. Full assessment of this geologic hazard requires long-term current monitoring in specific scour regions to predict current intensity and periodicity, especially during major storms when combined storm tide and wave currents may be several times greater than normal currents. Short-term current monitoring has shown fair-weather currents up to 30 cm/s and storm-related currents up to 70 cm/s (Cacchione and Drake, 1978).

Strong storm-wave-induced currents transport extensive sand sheets out onto the Yukon prodelta. Fine-grained sand, apparently originating from sand bars off the Yukon River delta, is deposited in well-sorted, clean sand beds up to 75 km from the shoreline of the delta. Beds are 5 cm to 20 cm thick

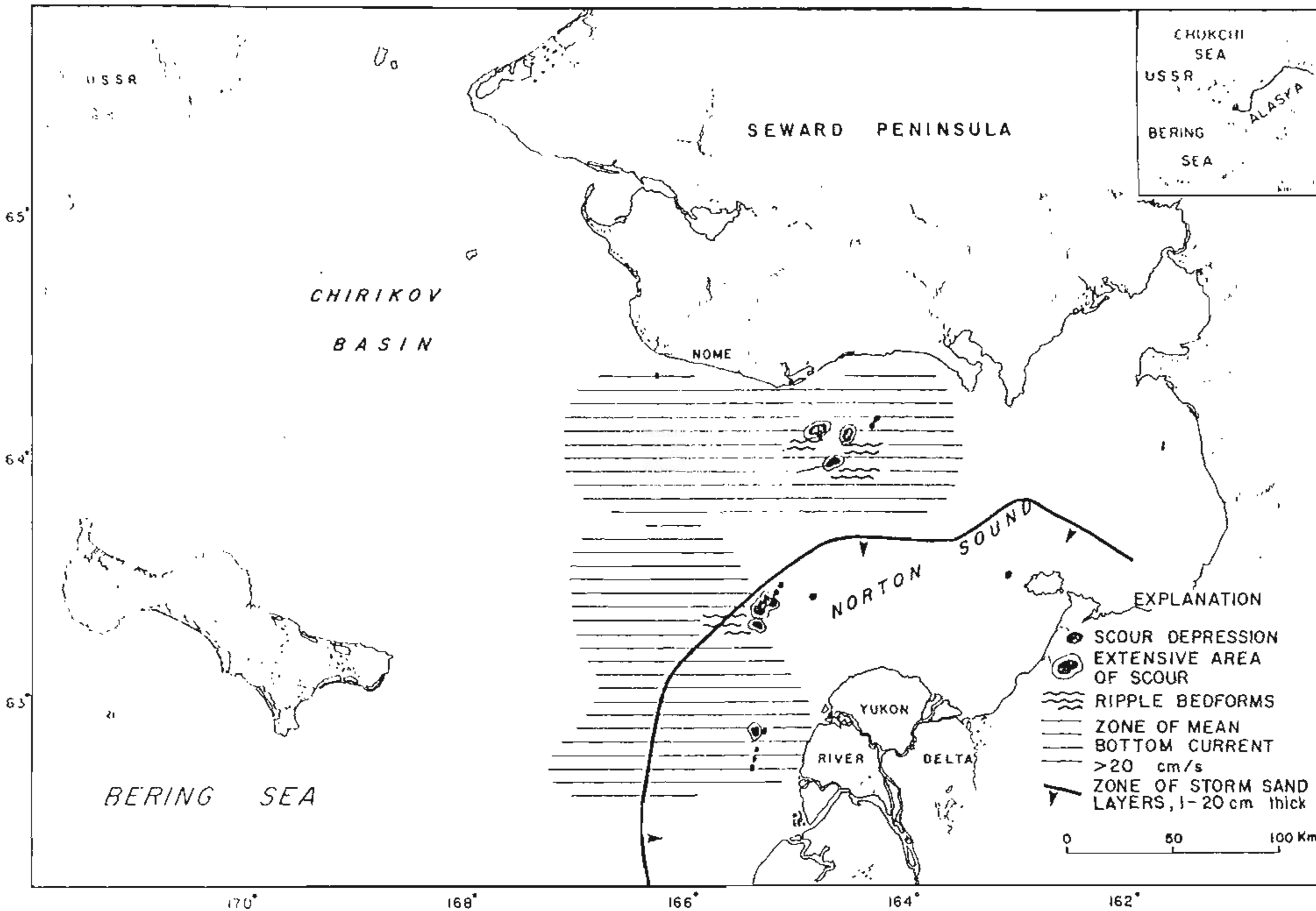

Figure 13. Location of scour depressions, extensive scour and ripple zones, and strong bottom currents in Norton Sound. Also shown is the area of storm sand deposition (modified from Larsen and others, 1978).

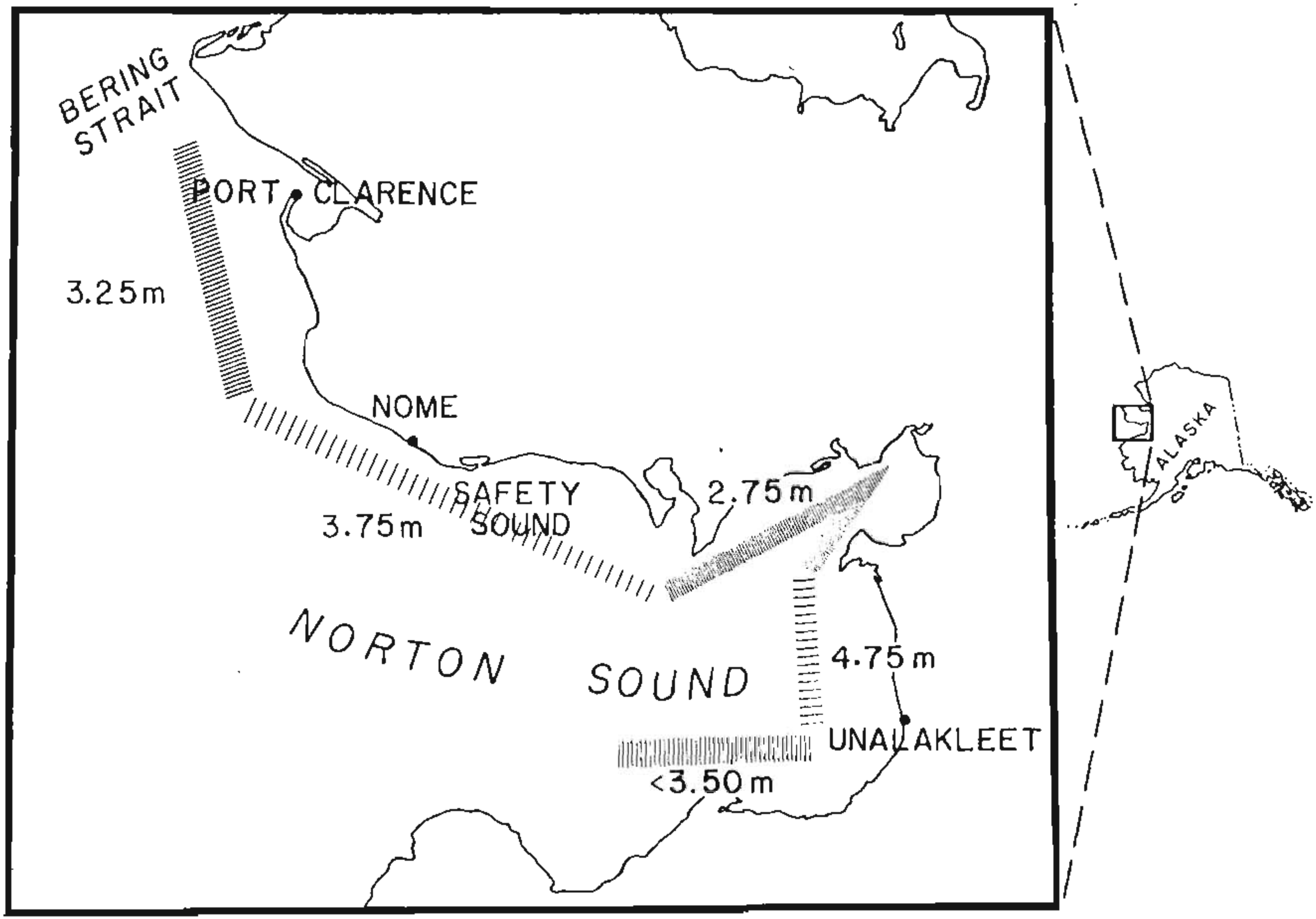

Figure 14. Summary of measurements of average debris line elevations from the November, 1974, storm surge (from Sallenager and others, 1978).

within 30 km of the shoreline and vary from 1 to 5 cm thick and 30 to 75 km from the shoreline. The widespread distribution of these storm sand layers (fig. 13) shows that significant quantities of sand are transported across the Yukon prodelta during storms; some man-made structures, therefore, could act as a dam and inhibit sediment movement.

Where the sea bottom is sandy, strong bottom currents result in migrating fields of mobile bedforms. Sand waves, 1 to 2 m high with wavelengths of 10 to 20 m or 150 to 200 m, and ripples 4 cm high with 20 cm wavelengths, occupy the crests and some flanks of a series of large, linear sand ridges lying west of the Port Clarence area (Cacchione and others, 1977; Field and others, 1977; Nelson and others 1977). Ice gouges are found in varying states of preservation on several ridges, which indicates active sand-wave modification and recent bedform movement. Survey tracklines of 1976 were replicated in 1977; local changes in bedform type and trend substantiate the occurrence of recent bedform activity. Movement of small-scale sand waves and bedload transport occur during calm weather, but maximum change of large-scale sand waves may take place when northerly current flow is enhanced by sea level rise caused by major southerly or southwesterly storms. Strong north winds from the Arctic, however, reduce the strength of the continuous northerly currents near Bering Strait, reducing the amount of bedload transport and activity of mobile bedforms.

Low pressure storm winds from the south to southwest pose a major hazard to coastal development along the Bering Sea shoreline. Beach debris lines nearly 5 m above mean sea level, and recession of tundra bluffs by as much as 45 m inland occurred during the November, 1974 storm surge (Sallenger and others, 1978). Coastal development should be set back away from the shoreline to avoid flooding by storm surges and undermining by coastal erosion. Figure 14 shows debris-line elevations (above sea level) around Norton Sound due to the November, 1974 storm surge.

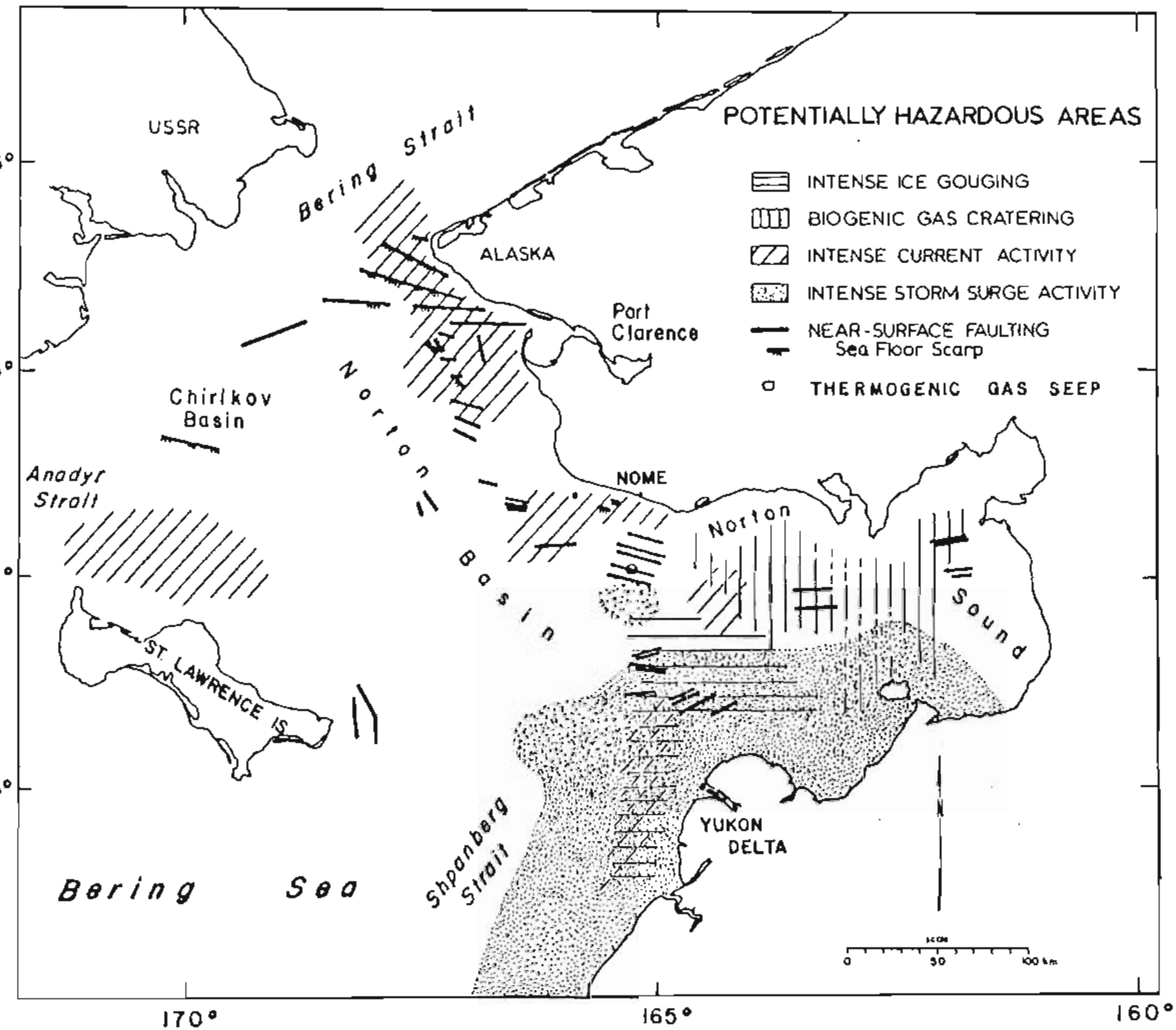

Figure 15. Summary of potentially hazardous regions in northern Bering Sea.

Port Clarence is the only natural harbor north of the Bristol Bay area, and its use as a future port is possible if resource development takes place in the northeastern Bering Sea. The long-term dynamics of the largest mobile bedform areas surrounding the entrance to Port Clarence must be defined so that realistic recommendations can be made for location and for depth of burial of pipelines and seafloor structures. Distribution of bedform fields throughout Norton Basin is shown on figure 9; details of the Port Clarence sand wave field are given in Nelson and others (1978a).

In summary, the offshore area near the Yukon delta and the area southeast of the Bering Straits have the most potentially severe combination of geological hazards. Ice gouging, bottom-current scour, and storm-surge activity are all intense over a wide region around the shallow Yukon prodelta. Gas-charged sediment and cratering in surficial sediment is present in north-central Norton Sound. Faulting and current activity are most intense southeast of the Bering Straits. Figure 15 summarizes the distribution of potentially, geologically hazardous regions.

TECHNOLOGY AND MANPOWER

The type of drilling equipment that may be used in the sale area varies according to water depth. In shallow (0 to 15 m) water, gravel or sandbag islands may be constructed with or without cassions. In very shallow water, however, use of sunken drilling barges is also possible. In areas beneath water of medium (15 to 30 m) depth, exploratory jack-up rigs will probably be used. And in water of moderate (30 to 50 m) depth, semisubmersible platforms or drillships may be used. The water-depth limits placed on the use of various types of equipment are only approximate. Production facilities may be built on artificial islands in shallow-water areas, and on steel-tower platforms in medium- and moderate-depth areas. Shallow water is present in 19 percent of the sale area; medium water-depth is in 52 percent; moderate water-depth is in 29 percent.

If commercial quantities of oil or gas are discovered in the sale area, the hydrocarbons will most likely be transported to a terminal and dock at Nome by undersea pipelines. Due to the presence of winter ice throughout the northern Bering Sea, tankers that transport the hydrocarbon to southern market areas must be strengthened against damage by ice, and the tankers may need the assistance of ice breakers. If commercial quantities of gas are discovered, the gas may be delivered to market areas either by tanker or by a gas pipeline that follows the Yukon River valley to Fairbanks; there to connect with the planned Northwest Gas pipeline.

As an aid to planning the socio-economic impact caused by the extraction of hydrocarbon resources, three statistical analyses were made of the possible intensity of oil-field development. The three analyses are based on different assumed quantities of producible hydrocarbons. The quantities are as follows:

	Minimum	Mean	Maximum
OIL (millions of barrels)	380	1400	2600
GAS (trillions of cubic feet)	1200	2300	3200

These quantities are derived from the resource estimates, shown in figure 7 and in the table on page 29, by removing the marginal probabilities that were applied because Norton Basin is a frontier area. Tables 4 through 6 show the statistically-probable development of oil fields that could occur for each of the three assumed quantities of producible hydrocarbons.

The current population of towns and villages within 80 km of the coastline around the sale area is about 7,000. The population is concentrated in Nome (2,500), in Unalakleet (400 to 500), and in Gambel and Savoonga on St. Lawrence Island (each have 300 to 400). Each of the other villages has 250 persons or less.

TABLE 4

SALE 57
MINIMUM CASE
380 Mil. Bbl. Oil
1200 Mil. MCF Gas

Sale Scheduled for
December 1981

Preliminary
Norton-Bering

Sale Year	Calendar Year	Exploratory Drilling Wells	Number of Platforms	Development Drilling Wells**	Production Oil Mil. Bbls.	Production Gas Mil. MCF	Pipeline Construction Miles	Oil Pipeline Terminals	Gas Prep. Plants
0	1980								
0	1981								
1	1982								
2	1983	2							
3	1984	2*							
4	1985	8*							
5	1986	5	1	8					
6	1987	2		16					
7	1988	1		16			75 X 2	1	1
8	1989			8	19	24			
9	1990				36	82			
10	1991				38	84			
11	1992				38	84			
12	1993				38	84			
13	1994				38	84			
14	1995				36	82			
15	1996				30	74			
16	1997				23	65			
17	1998				19	60			
18	1999				13	53			
19	2000				12	50			
20	2001				10	48			
21	2002				8	46			
22	2003				6	43			
23	2004				4	41			
24	2005				4	41			
25	2006				3	41			
26	2007				3	39			
27	2008				2	39			
28	2009					35			
29	2010								

* Three exploratory, three expend. wells, on successful prospect.
** Includes one service well for each four production wells.
Two rigs working per platform.
Gas main trunkline excluded.

1/18/79

TABLE 5

SALE 57
"MEAN" CASE
1400 Mil. Bbl. Oil
2300 Mil. MCF Gas

Sale Scheduled for
December 1981

Preliminary
Norton-Bering

Sale Year	Calendar Year	Exploratory Drilling Wells	Number of Platforms	Development Drilling Wells**	Production Oil Mil. Bbls.	Production Gas Mil. MCF	Pipeline Construction Miles	Oil Pipeline Terminals	Gas Prep. Plants
0	1980								
0	1981								
1	1982	2							
2	1983	4							
3	1984	9*							
4	1985	10*							
5	1986	10*	1						
6	1987	5	3	39			75 X 2		
7	1988	2	1	100			75 X 4	1	1
8	1989			55	69	46			
9	1990				133	156			
10	1991				140	161			
11	1992				140	161			
12	1993				140	161			
13	1994				140	161			
14	1995				133	156			
15	1996				112	143			
16	1997				84	124			
17	1998				70	115			
18	1999				49	101			
19	2000				41	97			
20	2001				35	92			
21	2002				28	88			
22	2003				21	83			
23	2004				15	78			
24	2005				14	78			
25	2006				13	78			
26	2007				12	76			
27	2008				11	76			
28	2009					69			
29	2010								

* Nine Exploratory wells, nine expend. wells, on successful prospects.
** Includes one service well for each four producing wells.
Two rigs working per platform.
Gas main trunkline omitted.

1/18/79

Sale Scheduled for
December 1981

SALE 57
MAXIMUM CASE
2600 Mil. Bbl. Oil
3200 Mil. MCF Gas

TABLE 6

Preliminary
Norton-Bering

Sale Year	Calendar Year	Exploratory Drilling Wells	Number of Platforms	Development Drilling Wells**	Production Oil Mil. Bbls.	Production Gas Mil. MCF	Pipeline Construction Miles	Oil Pipeline Terminals	Gas Prep. Plants
0	1980								
0	1981								
1	1982	2							
2	1983	8*							
3	1984	19*							
4	1985	19*	2	48					
5	1986	16	3	104					
6	1987	10	3	138			75 X 4		
7	1988	5		71			75 X 6	1	1
8	1989				130	64			
9	1990				247	218			
10	1991				260	224			
11	1992				260	224			
12	1993				260	224			
13	1994				260	224			
14	1995				247	217			
15	1996				208	198			
16	1997				156	173			
17	1998				130	160			
18	1999				91	141			
19	2000				78	135			
20	2001				65	128			
21	2002				52	122			
22	2003				39	115			
23	2004				26	109			
24	2005				26	109			
25	2006				26	108			
26	2007				21	106			
27	2008				18	105			
28	2009					96			
29	2010								

* Fifteen exploratory wells, sixteen expend. wells, on successful prospects.
** Includes one service well for each four production wells.
Two rigs working per platform.
Gas main trunkline omitted.

1/18/79

OUTLINE OF THE SALE AREA

The proposed outline of the sale area follows the United States-Russia Convention Line south from the latitude of Little Diomede Island in Bering Strait to the 63° N parallel of latitude. The outline extends eastward along that parallel to the Yukon delta, and then along the coastline that rims Norton Sound and northern Bering Sea to Cape Prince of Wales in the Bering Strait; thence to Little Diomede Island. Areas east of 162° W longitude, north of 65° N latitude and west of 170° W longitude have low hydrocarbon potential because of the shallow (generally less than 1 km) depth of burial of rocks in which we have measured high refraction-velocities (between 5.0 and 6.5 km/s). These area should be deleted from the sale area. Figure 16 shows the proposed and recommended sale area outlines.

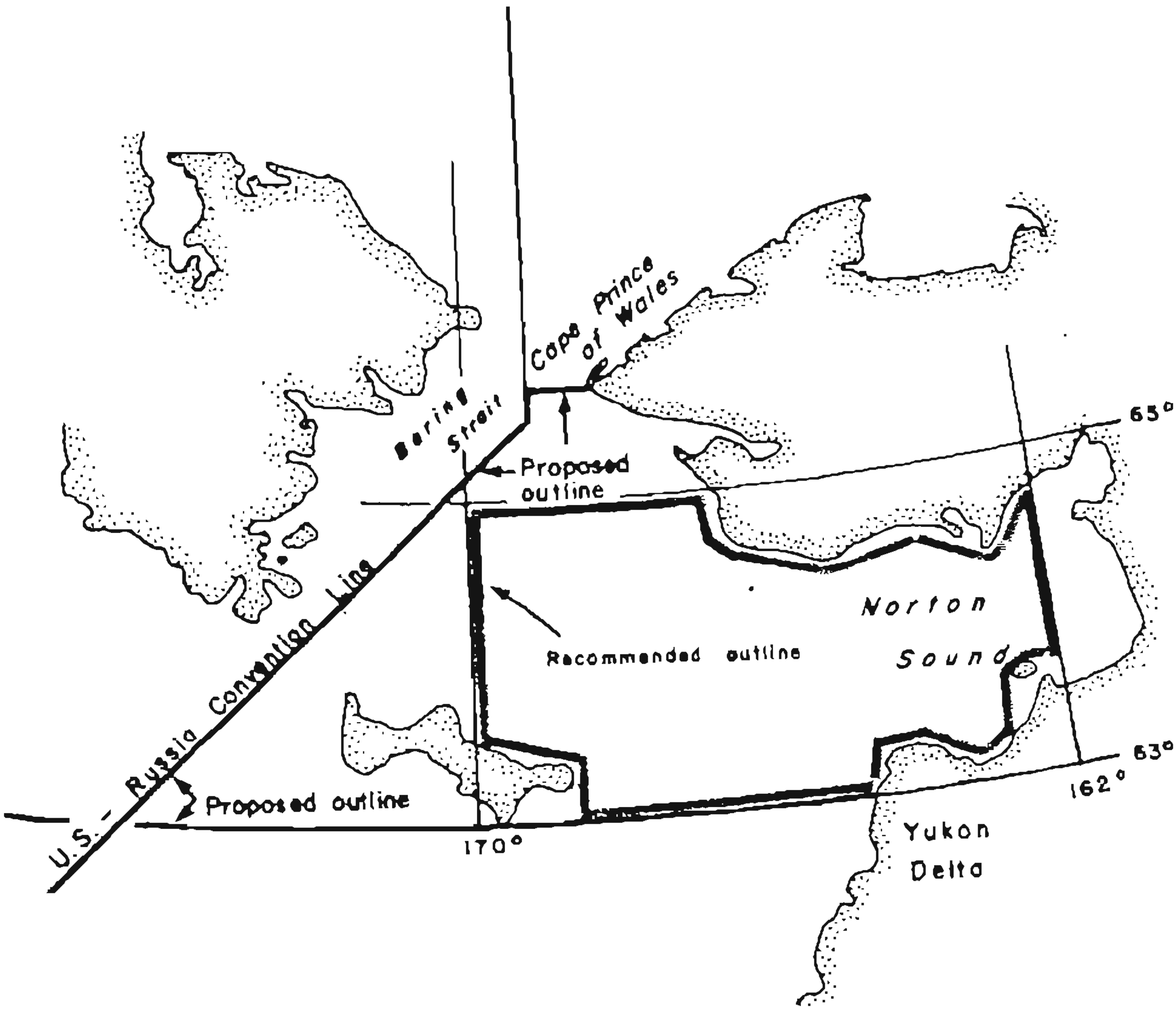

Figure 16. Proposed and recommended sale outlines.

REFERENCES CITED

Agapitov, D. I., Ivanov, V. V., and Krainov, V. G., 1973, Novye dannye po geologii i perspectivam neftegazonosnocti anadyrckoi vpadiny (New data on the oil and gas prospects of the Anadyr basin): Trudy, Akademiia Nauk SSSR, Sibirskoe otdelenie severo-vostochnyi kompleksnyi nauchno-issledovatelskii institut, vyp 49, Magadan, p. 23-39.

Avdeiko, G. P., 1971, Evolution of geosyncline on Kamchatka: Pacific Geology, v. 3, p. 1-14.

Belyi, V. F., 1973, Okhotsk-Chukotsk fold belt and the problem of volcanic arcs in northeast Asia: American Association of Petroleum Geologists Memoir 19, p. 252-258.

Biswas, N. N., Gedney, L., and Huang, P., 1977, Seismicity studies: (A) northeast Alaska and (B) Norton and Kotzebue Sounds, in Environmental assessment of the Alaskan continental shelf, Annual report of principal investigators for the year ending March, 1977: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 18, p. 169-315.

Cacchione, D. A., and Drake, D. E., 1977, Sediment transport in Norton Sound-northern Bering Sea, Alaska, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1977: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Deparment of Commerce, v. 18, p. 130-158.

______, 1978, Sediment transport in Norton Sound, northern Bering Sea, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 12, p. 308-450.

Cacchione, D. A., Drake, D. E., and Nelson, Hans, 1977, Sediment transport in Norton Sound, Alaska (abs.): Transactions of the American Geophysical Union, EOS, v. 58, no. 6, p. 408.

Cathcart, S. H., 1920, Mining in northwestern Alaska: U.S. Geological Survey Bulletin 712, p. 185-198.

Cline, J. D., and Holmes, M. L., 1977, Submarine seepage of natural gas in Norton Sound, Alaska, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1977: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 13, p. 269-289.

______ 1978, Anomalous gaseous hydrocarbons in Norton Sound: Biogenic or thermogenic?: Proceedings, Offshore Technology Conference, Houston, Texas, p. 81-86.

Coachman, L. K., Aagaard, K., and Tripp, R. B., 1976, Bering Strait: The regional physical oceanography: Seattle, Washington University Press, 186 p.

Cooper, A. K., 1978, Hydrocarbon prospects for the frontier abyssal areas of the Bering Sea: The Oil and Gas Journal, Oct. 23, p. 196-201.

Craft, C. I., 1973, Detecting hydrocarbons--for years the goal of exploration geophysicists: The Oil and Gas Journal, February 19, p. 122-125.

Dolzhanskiy, B. G., Ivanov, V. V., Dontsov, V. V., Burlin, Yu. K., and Roshchin, 1966, New data on the subsurface structure of the central part of the Anadyr Basin: Geologiya Nefti i Gaza 10: 15-20.

Dow, W. G., 1977, Kerogen studies and geological interpretations: Journal of Geochemical Exploration, v. 7, p. 79-99.

Dupré, W. R., 1977, Yukon delta coastal process study, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1977: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Deparment of Commerce, v. 14, p. 508-553.

______ 1978, Yukon delta coastal process study, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 11, p. 384-446.

Eittreim, S., Grantz, A., and Whitney, O. T., 1978, Isopach maps of Tertiary sediments, Hope Basin, southern Chukchi Sea, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-906, 1 sheet, scale 1:1,000,000.

Evans, C. R., and Staplin, F. L., 1971, Regional facies of organic metamorphism, in Geochemical exploration: Canadian Institute of Mining and Metallurgy, Special volume II.

Fathauer, T. F., 1975, The great Bering Sea storms of 9-19 November, 1974: Weatherwise Magazine., American Meteorological Society, v. 28, p. 76-83.

Feux, A. N., 1977, The use of stable carbon isotopes in hydrocarbon exploration: Journal of Geochemical Exploration, v. 7, p. 155-188.

Field, M. E., Nelson, Hans, Cacchione, D. A., and Drake, D. E., 1977, Dynamics of bedforms of an epicontinental shelf: northern Bering Sea (abs.): Transactions of the American Geophysical Union, EOS, v. 58, no. 12, p. 1162.

Gladenkov, Iu. B., 1964, O tektonike vostochnoi chasti Koryakskogo Nagor'ya (Tectonics in the eastern part of the Koryak Uplands): Trudy, Geologicheskii Institut, Akademiia Nauk SSSR, v. 113, p. 7-23.

Grant, F. S., and West, G. F., 1965, Interpretation theory in applied geophysics: McGraw-Hill, New York, p. 8.

Holmes, M. L., and Cline, J. D., 1978, Geological setting of the Norton basin gas seep: Proceedings Offshore Technology Conference, Houston, Texas, p. 73-80.

Johnson, J. L., and Holmes, M. L., 1978, Report on surface and subsurface faulting in Norton Sound and northeastern Chirikov basin, Alaska, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 12 (in press).

Larsen, M. C., Nelson, Hans, Thor, D. R., 1978, Scour depressions and zones in Norton Sound, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 12 (in press).

______ Scour depressions and zones in Norton Sound: Environmental Geology, in press.

Lindsey, J. P., and Craft, C. I., 1973, How hydrocarbon reserves are estimated from seismic data: World Oil, August 1, p. 23-25.

Louis, M. C., and Tissot, B. P., 1967, Influence de la temperature et de la pression sur la formation des hydrocarbures dans les argiles a kerogene: Proceedings, 7th World Petroleum Congress, Mexico City, 2:47-60.

Marlow, M. S., Scholl, D. W., Cooper, A. K., Buffington, E. C., 1976, Structure and evolution of Bering Sea shelf south of St. Lawrence Island: American Association of Petroleum Geologists Bulletin, v. 60, no. 2, p. 161-183.

Meyerhoff, A. A., 1972, Russians look hard at the Anadyr basin: Oil and Gas Journal, v. 70, no. 43, pt. I, p. 124-129; no. 44, pt. II, p. 84-89.

Nelson, Hans, 1977, Summary of faulting, sediment instability and deposition hazards of the Norton basin sea floor, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1977: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 18, p. 1-13.

______ 1978, Faulting, sediment instability, and erosion and deposition hazards of Norton basin sea floor, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the yar ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 12, 187-307.

Nelson, Hans, Cacchione, D. A., and Field, M. E., 1977, Complex ridge and trough topography on a shallow current-dominated shelf, northwest Alaska (abs.): American Association of Petroleum Geologists Bulletin, v. 61, p. 817.

Nelson, Hans, Creager, J. S., 1977, Sediment budgets and displacement of Yukon River sediments from Bering Sea in the late Holocene: Geology, v. 5, p. 141-146.

Nelson, Hans, Field, M. E., Cacchione, D. A., and Drake, D. E., 1978a, Areas of active, large-scale sand waves and ripple fields with scour potential, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 12 (in press).

Nelson, Hans, Holmes, M. L., Thor, D. R., and Johnson, J. L., 1978b, Continuous seismic-reflection data, Sea 5-76-BS cruise, northern Bering Sea: U.S. Geological Survey Open-file Report 78-609, 6 p.

Nelson, Hans, and Hopkins, D. M., 1972, Sedimentary processes and distribution of particular gold in northern Bering Sea: U.S. Geological Survey Professional Paper 689, 27 p.

Nelson, Hans, Hopkins, D. M., and Scholl, D. W., 1974, Cenozoic sedimentary and tectonic history of the Bering Sea, in Hood, D. W., and Kelley, E. J., eds., Oceanography of the Bering Sea: University of Alaska Institute of Marine Sciences, Occasional Publication No. 2, p. 485-516.

Nelson, Hans, Kvenvolden, K. E., and Clukey, E. C., 1978c, Thermogenic gas in sediment of Norton Sound, Alaska: Proceedings, Offshore Technology Conference, Houston, Texas, OTC 3354, p. 1612-1633.

______ 1978d, Identification of thermogenic gas-charged sediment in Norton Basin and potential hazards, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 12 (in press).

Nelson, Hans, Thor, D. R., and Sandstrom, M. W., 1978e, Modern biogenic gas craters (sea floor "pockmarks") on the Bering shelf, Alaska, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 12 (in press).

Patton, W. W., Jr., 1973, Reconnaissance geology of the northern Yukon-Koyukuk province, Alaska: U.S. Geological Survey Professional Paper 774-A, p. A1-A17.

Patton, W. W., Jr., and Csejtey, Béla, Jr., 1971, Preliminary geologic investigations of western St. Lawrence Island, Alaska: U.S. Geological Survey Professional Paper 684-C, p. C1-C15.

Patton, W. W., Jr., and Tailleur, I. L., 1977, Evidence in the Bering Strait region for differential movement between North America and Eurasia: Geological Society of America Bulletin, v. 88, p. 1298-1304.

Payne, T. G., 1959, Central Alaska, in Miller, D. J., Payne, T. G., and Gryc, George, eds., Geology of possible petroleum provinces in Alaska: U.S. Geological Survey Bulletin 1094, p. 53-88.

Philippi, G. T., 1975, The deep subsurface temperature controlled origin of the gaseous and gasoline-range hydrocarbons of petroleum: Geochimica et Cosmochimica Acta 39:1353-1374.

Roberts, J. M., 1970, Amal field, Libya, in Halbouty, M. T., ed., Geology of giant petroleum fields: American Association of Petroleum Geologists Memoir 14, p. 438-448.

Sallenger, A. H., Jr., Dingler, J. R., and Hunter, R. E., 1978, Coastal processes and morphology of the Bering Sea coast of Alaska, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Department of Commerce, v. 12 (in press).

Sanford, R. M., 1970, Sarir oil field, Libya--desert surprise, in Halbouty, M. T., ed., Geology of giant petroleum fields: American Association of Petroleum Geologists Memoir 14, p. 449-476.

Savit, C. H., 1974, Bright spot in the energy picture: Ocean Industry, February p. 60-65.

Scholl, D. W., and Hopkins, D. M., 1969, Newly discovered Cenozoic basins, Bering Sea shelf, Alaska: American Association of Petroleum Geologists Bulltein, v. 53, p. 2067-2078.

Scholl, D. W., Marlow, M. S., Creager, J. S., Holmes, M. L., Wolf, S. C., and Cooper, A. K., 1970, A search for the seaward extension of the Kaltag fault beneath the Bering Sea: Geological Society of America, Abstracts with Programs, v. 2, p. 141-142.

Sundvor, E., and Nysaether, E., 1975, Geological outline of the Norwegian continental margin between 60° and 68° North, in Yorath, C. J., Parker, E. R., and Glass, D. J., eds., Canada's continental margins and offshore petroleum Exploration: Canadian Society of Petroleum Geologists Memoir 5, Calgary, p. 267-281.

Thor, D. R., and Nelson, Hans, 1978, Continuous seismic-reflection data, Sea 5-77-BS cruise, northern Bering Sea: U.S. Geological Survey Open-File Report 78-608, 8 p.

______ Continuous seismic reflection data, Sea 9-78-BS cruise, northern Bering Sea: U.S. Geological Survey Open-File Report, in press.

Thor, D. R., and Nelson, Hans, and Williams, R. O., 1978, Potential hazards of ice gouging over the Norton Basin sea floor, in Environmental assessment of the Alaskan continental shelf, Annual Report of Principal Investigators for the year ending March, 1978: Environmental Research Laboratory, Boulder, Colorado, NOAA, U.S. Deparment of Commerce, v. 12, in press.

Tissot, B. P., and Welte, D. H., 1978, Petroleum formation and occurrence: New York, Springer-Verlag, 538 p.

VenkataRathnam, Kolla, 1970, Sediments on the continental shelf in the northern Bering Sea: Final Report, U.S. Geological Survey Contract No. 14-08-0001-11995, Department of Oceanography, University of Washington, Seattle, Washington, p. 2-93.

Verba, M. L., Gaponenko, G. I., Ivanov, S. S., Orlov, A. N., Timofeev, V. I., and Cherenkov, Iu. F., 1971, Glubinnoe stroesue i perspektivy neftigazonosnosti severo-zapadnoi chasti beringova moria-V sb (Deep structure of northwestern part of the Bering Sea and the prospects of finding oil and gas): Geofizicheskie metody razvedki v Arktike L, Niiga, vyp 6, p. 70-74.

Watson, J. M., and Swanson, C. A., 1975, North Sea--Major petroleum province: American Association of Petroleum Geologists Bulletin, v. 59, no. 7, p. 1098-1112.

Williams, J. J., Conner, D. C., and Peterson, K. E., 1975, Piper oil field, North Sea: Fault-block structure with Upper Jurassic Beach/Bar reservoir sands: American Association of Petroleum Geologists Bulletin, v. 59, no. 9, p. 1585-1601.

APPENDIX

Table A1. Norton Basin Sonobuoy Refraction Results

Sonobuoy Profile	Velocity (km/sec)									Water Depth (m)	Thickness (km)								Lat N	Long W
	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}		h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9		
6-77	1.6	1.9	6.6							18	.33	.26							64-00.0	162-15.7
8-77	1.6	1.8	2.3	6.3						32	.13	.24	.11						64-18.5	165-25.3
9-77	1.6	1.9	2.1	3.2	6.6					19	.21	.57	.39	.65					63-55.0	165-23.5
10-77	1.6	1.8	1.9	2.6	4.9	6.0				22	.18	.72	.32	1.90	.63				63-48.0	165-54.5
11-77	1.8	2.0	2.6	3.7	5.8					33	.29	.90	.44	.49					63-50.5	167-00.0
12-77	1.7	1.9	2.3	5.4						32	.51	.30	.33						63-43.0	167-26.2
14-77	1.7	2.0	6.2							29	.52	.61							63-17.8	167-16.0
1-78	1.7	1.8	2.6	3.6	4.2	6.6				28	.05	.93	.57	.69	1.61				63-28.5	166-40.0
2-78	1.7	2.0	2.7	3.3	4.8	5.9				28	.29	.97	1.11	1.00	1.06				63-50.2	166-02.0
3-78	1.6	1.7	5.2							17	.09	.33							64-15.0	165-02.5
5-78	1.8	2.0	4.6							24	.49	.17							63-01.0	166-31.0
6-78	1.7	1.9	2.4	3.4	4.0					17	.23	.74	.76	.54					63-45.7	164-23.0
7-78	1.7	2.0	3.5	5.9						21	.13	.66	.23						64-06.2	163-37.0
8-78	1.7	1.9	2.6	3.2	4.8					16	.29	.82	.40	.35					63-37.6	164-03.0
9-78	1.6	1.7	2.1	3.7	5.2					17	.11	.27	.45	1.05					63-42.6	162-36.0
10-78	1.7	1.8	2.0	3.4	5.2					18	.08	.26	1.02	.52					63-53.1	164-06.0
12-78	1.7	1.8	1.9	2.7	3.8	4.0	4.3	4.8	5.5	18	.07	.21	.87	1.04	.67	.63	.67	.30	63-51.1	164-34.0
13-78	1.6	1.8	2.6	4.2	6.5					15	.15	.70	.42	2.04					63-42.9	163-52.6
15-78	1.7	1.8	2.5	4.3	6.1					18	.14	.80	.35	.70					63-41.2	164-41.2
16-78	1.7	1.8	1.9	2.5	3.3	3.5	4.1	6.9		34	.16	.34	.46	.52	.32	.35	.97		64-04.2	167-09.5
18-78	1.6	1.8	2.0	2.6	2.8	3.4	4.9	5.8		28	.06	.38	.80	.60	.55	1.45	.90		63-42.4	166-01.5
19-78	1.6	1.8	2.0	2.8	3.5	5.0	5.4			23	.09	.23	.98	.81	.42	.41			63-26.1	165-18.0
21-78	1.6	1.7	2.1	2.8	4.6	6.2				31	.09	.57	.64	.34	.84				63-42.0	167-04.2
23-78	1.7	1.9	2.1	2.3	3.4	5.5				25	.13	.27	.78	.33	1.11				63-22.0	165-38.6
24-78	1.8	2.0	4.6	5.7						22	.44	.21	.86						63-05.8	165-31.5
25-78	1.7	2.1	4.9							31	.49	.43							63-21.3	167-08.0
26-78	1.6	1.7	5.0							27	.18	.24							63-06.0	167-30.0
27-78	1.9	5.2								28	.15								63-24.0	168-30.0
28-78	1.6	1.7	2.4	4.4	6.0					38	.19	.63	.26	.66					63-57.0	168-49.5
29-78	1.7	2.1	2.5	4.3	6.6					44	.35	.28	.10	1.01					64-30.6	168-12.0
30-78	1.6	4.2	4.8	6.0						45	.24	.39	.38						64-25.3	170-05.5
32-78	1.7	1.9	3.5	5.0						48	.09	.21	.83						64-40.0	170-42.2
33-78	1.6	1.7	2.3	3.7	5.2					44	.10	.41	.39	.11					64-30.8	168-58.0
34-78	1.6	1.7	1.8	2.4	3.0	4.1	6.9			32	.04	.10	.67	.49	.70	1.62			64-08.3	167-11.5
35-78	1.6	1.9	2.4	4.5	5.7					21	.12	.70	.26	.70					64-05.5	164-28.5