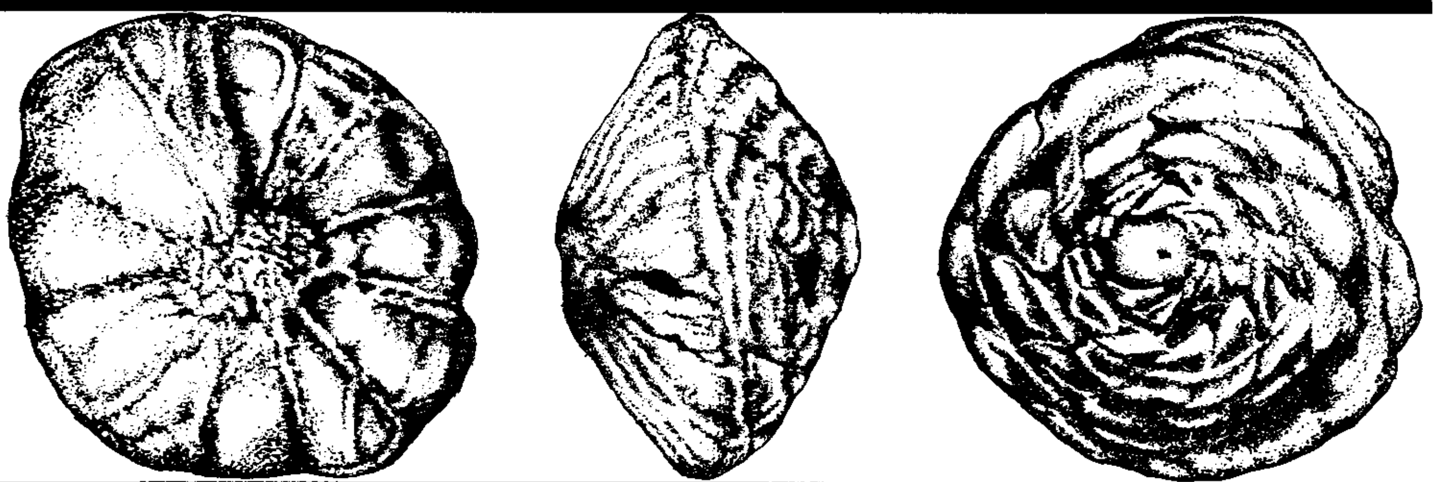
OCS Report
MMS 86-0033

Geologic Report for the NORTON BASIN Planning Area, Bering Sea, Alaska



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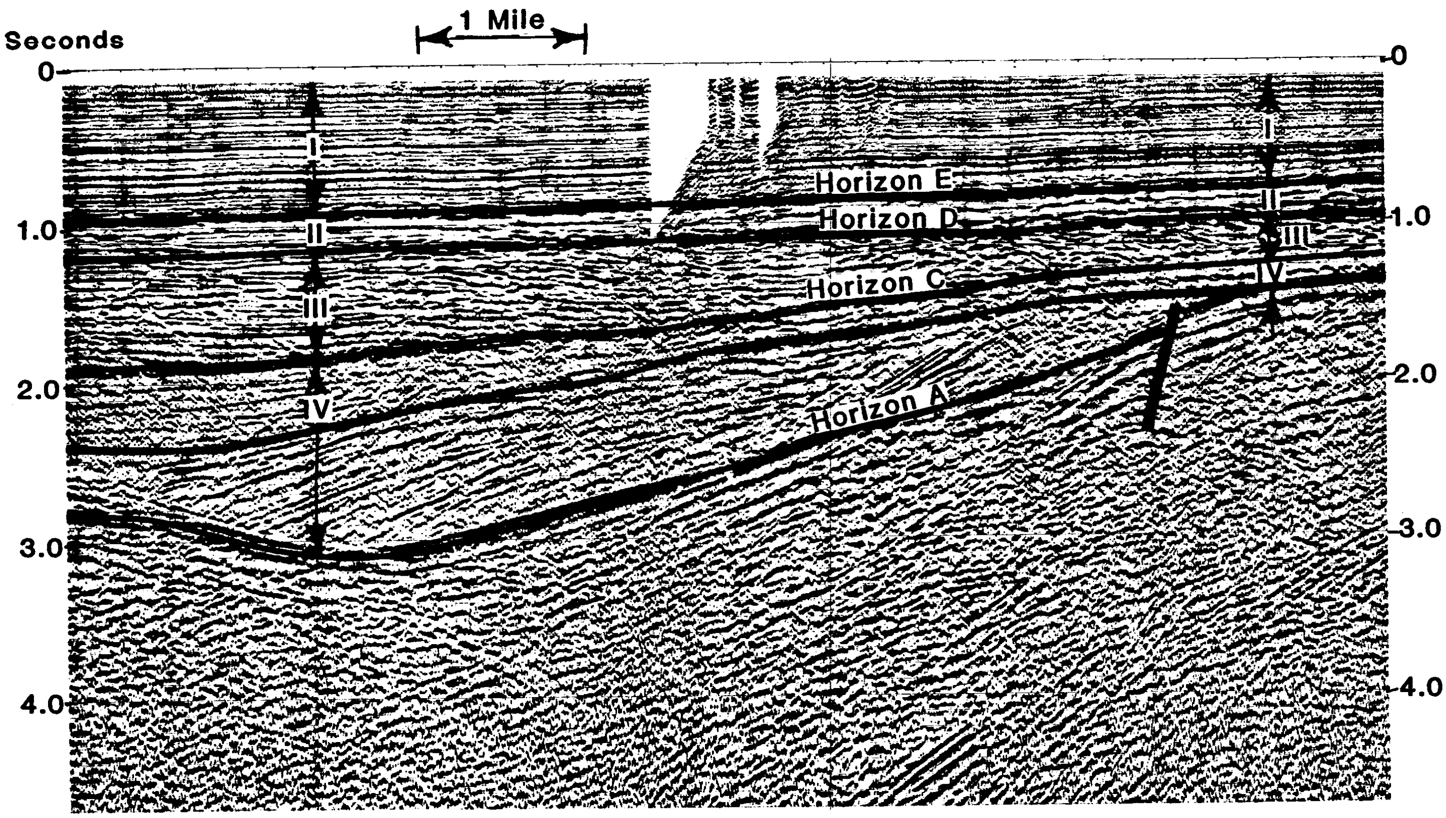

Seismic horizons and sequences on the western flank of the Yukon horst, St. Lawrence subbasin.
Uninterpreted seismic profile courtesy of Western Geophysical Company of America.

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Geologic Report for the Norton Basin Planning Area, Bering Sea, Alaska

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Introduction

This report is a summary of the regional geology, petroleum geology, and environmental characteristics of the Norton Basin Planning Area. To some extent, the interpretations herein are based on previous detailed studies by the Minerals Management Service (MMS) of two deep stratigraphic test wells, the Norton Basin COST No. 1 and No. 2 wells (Turner and others, 1983a,b). However, since the release of these reports, a great deal of these data have been reprocessed and reinterpreted. In addition, new data have been collected or become publically available. In particular, the common-depth-point (CDP) seismic reflection data base has been improved and expanded by the inclusion of lines generously released to MMS by Western Geophysical Company.

The Norton Basin Planning Area (fig. 1) is roughly bounded by the Norton Sound coastline on the east and southeast, the Seward Peninsula on the north, the 63 degree line of north latitude on the south, and the disputed US-USSR 1867 convention line on the west. The most prospective part of the planning area underlies Norton Sound.

The volume, quality, and distribution of reservoir rocks, the presence of potential seals, and a diversity of trapping configurations should combine to ensure further exploration in the Norton Basin. The timing of source rock maturation in relation to trap development also appears favorable for hydrocarbon entrapment. The volume, quality, and distribution of source rocks appear to represent the most serious constraints on the potential for commercial hydrocarbon accumulations in the basin.

Lease Sale 57, held March 19, 1983, generated $325 million in high bids. Ninety-eight bids were received on 64 tracts; 59 bids were accepted, 5 rejected. Lease Sale 100 is scheduled for March 1986.

Six exploratory wells have been drilled in the Norton Basin since 1984. All of these wells have been plugged and abandoned. No commercial hydrocarbon discoveries have been announced.

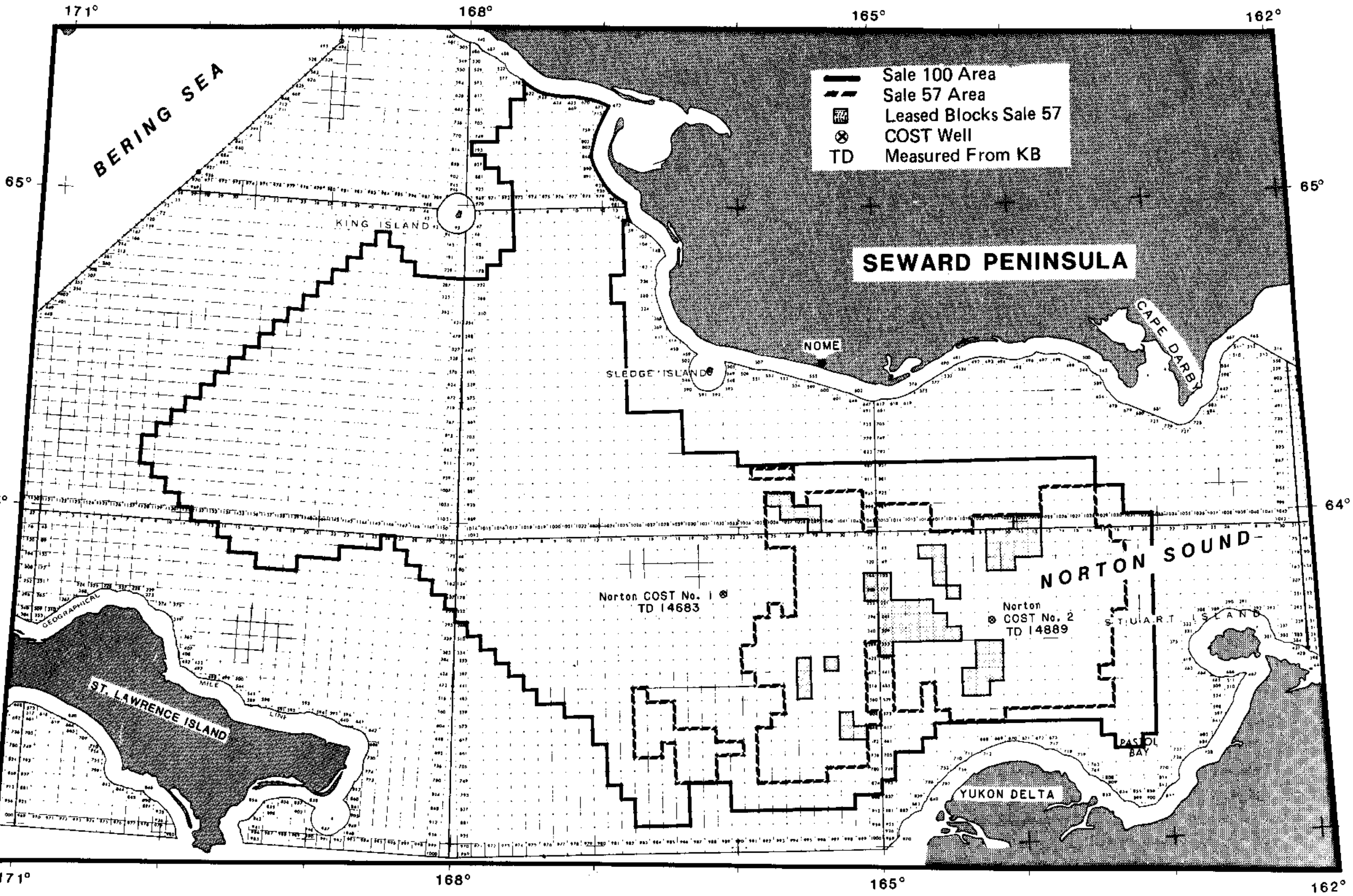


FIGURE 1. **Location of Norton Basin Planning Area, including Sale 57 and Sale 100 areas.**

Part 1
Regional Geology

1

Geologic Framework

The Norton Basin is located off the coast of west-central Alaska, approximately coincident with Norton Sound (fig. 1). It is one of several major Tertiary basins on the Bering Sea continental shelf (fig. 2). The basin is approximately 125 miles long and ranges from 30 to 60 miles in width. It is bounded by the Seward Peninsula on the north, the Yukon-Koyukuk geologic province on the east, the Chukotsk Peninsula on the west, and the Yukon Delta and St. Lawrence Island on the south.

The presence of a sedimentary basin beneath Norton Sound was first suggested by Payne (1955) from onshore regional trends. Subsequent seismic mapping in the area (Scholl and Hopkins, 1969) indicated the presence of significant accumulations of relatively young, undeformed sedimentary strata beneath the sound. More detailed seismic mapping subsequently revealed that the Norton Basin consists of two distinct subbasins, each with a somewhat different geological history. The subbasins contain up to 24,000 feet of marine and nonmarine Tertiary strata.

The pre-Tertiary basement complex of the Bering Sea shelf, parts of northeastern Siberia, and western Alaska has been subdivided into three broad tectonostratigraphic provinces (Fisher and others, 1979). These provinces, from north to south, are termed the miogeoclinal belt, the Okhotsk-Chukotsk volcanic belt, and the forearc basin belt. The Tertiary basins of the Bering Sea shelf are superimposed on these three provinces (fig. 2). The stratigraphic and lithologic characteristics of the sediments contained within these basins have been greatly influenced by the source terrane and tectonic style of the pre-Tertiary tectonostratigraphic province or belt within which they were formed. The Norton Basin lies within the miogeoclinal belt, near its border with the Okhotsk-Chukotsk volcanic belt, and the strata of the Norton subbasins consequently reflect provenances within both of these tectonostratigraphic provinces.

MIOGEOCLINAL BELT

The miogeoclinal belt of Fisher and others (1979) extends from the northern Chukotsk Peninsula and Wrangel Island to the Seward

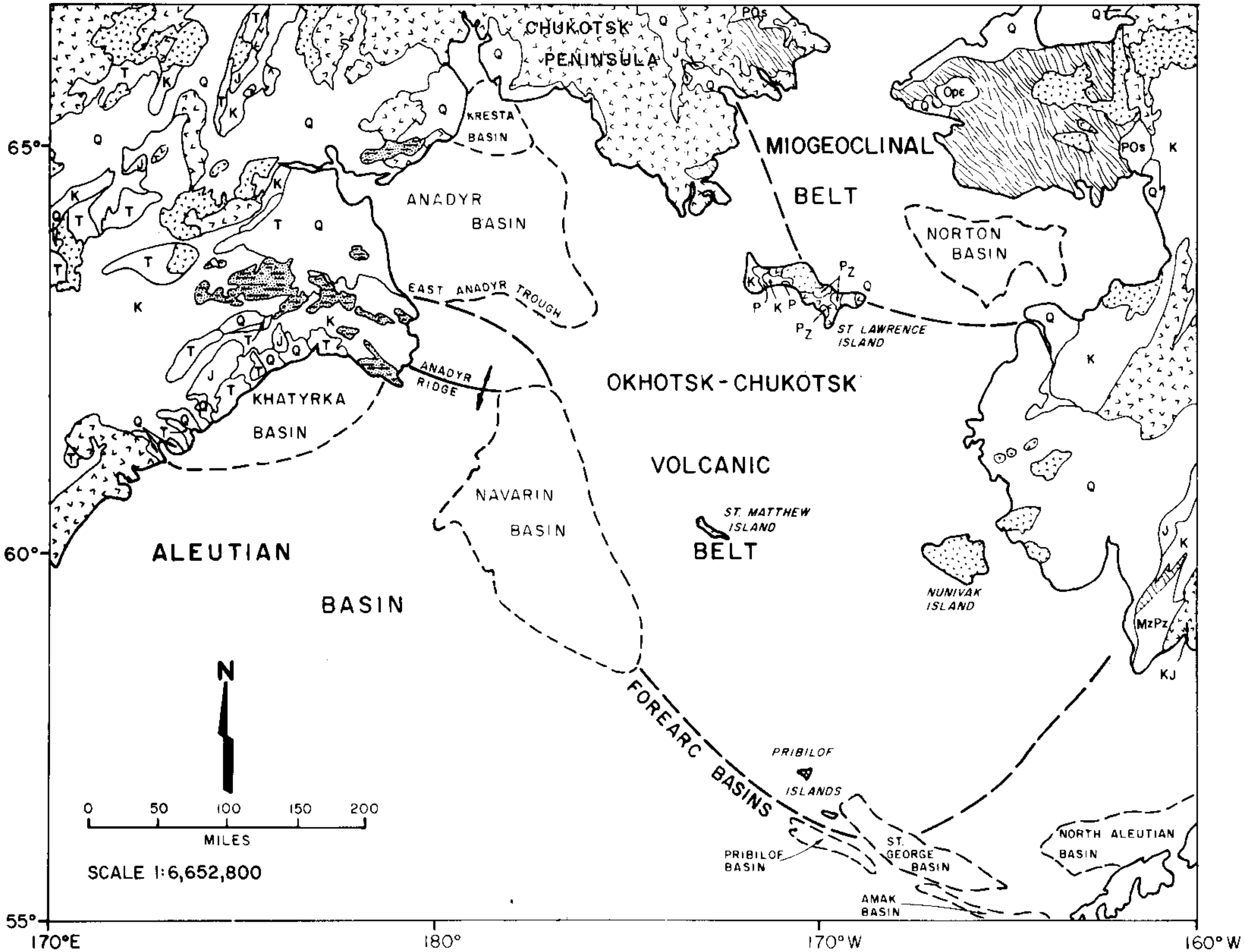
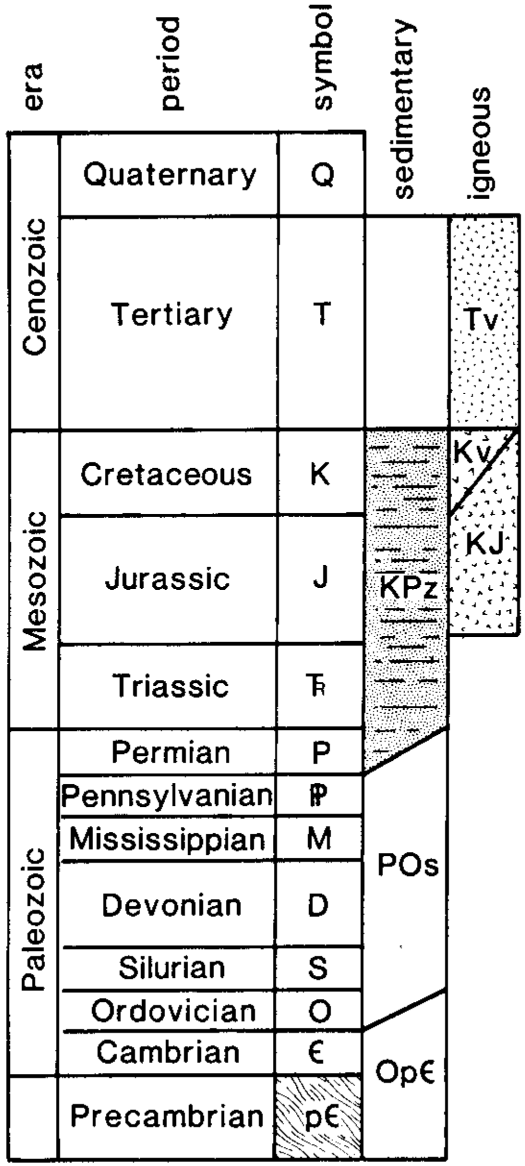


FIGURE 2. **General geologic map of eastern Siberia, Bering Sea, and western Alaska. Major Tertiary basins and pre-Tertiary geologic provinces of Fisher and others (1979) are indicated. Adapted from Link and others (1960), Beikman (1980), and Marlow and others (Tectonic Evolution, 1983).**

EXPLANATION FOR FIGURE 2.



Tv: undifferentiated volcanic rocks.

Kv: undifferentiated volcanic rocks.

KJ: lava, tuff, agglomerate, argillite, shale, graywacke, quartzite, and conglomerate. Slightly metamorphosed in places.

KPz: south of 64° N latitude sandstone, siltstone, limestone, chert, and volcaniclastic rocks of Permian through Late Cretaceous age. Locally includes melange and olistostrome sequences. North of 64° N latitude are sandstone, siltstone, argillite, conglomerate, coal, spilite, and basalt.

POs: sedimentary rocks of Permian and Mississippian age. Includes some Ordovician, Silurian, and Mississippian limestone.

OpЄ: phyllite, sandstone, siltstone, limestone, chert, and quartzite.

pЄ: undifferentiated metasedimentary and metamorphic rocks.

Peninsula and into the Brooks Range (fig. 2). This belt is composed of Precambrian through lower Mesozoic metamorphic and sedimentary rocks overlying continental crust.

In the northern Chukotsk Peninsula, surface exposures consist mostly of unmetamorphosed lower Mesozoic carbonates and clastics. In the eastern part of the Chukotsk Peninsula, gneiss and schist of probable Precambrian age unconformably underlie Paleozoic strata. Miogeoclinal belt strata in the Brooks Range consist of imbricate slabs of Paleozoic carbonates and early Mesozoic sedimentary rocks. In the western parts of the Seward Peninsula, unmetamorphosed Paleozoic carbonates conformably overlie a thick succession of Precambrian slate (Sainsbury and others, 1970). On St. Lawrence Island, near the southern border of the miogeoclinal belt, these rocks are represented by unmetamorphosed Paleozoic and lower Mesozoic carbonates and fine-grained clastics (Dutro, 1981).

Miogeoclinal belt rocks in the basement complex penetrated by the two Norton Basin COST wells consist of quartzite, marble, phyllite, and slate which are thought to be of Precambrian to Paleozoic age (Turner and others, 1983a, 1983b). These rocks are similar to the metamorphic complex of Precambrian and Paleozoic schists and marbles that are exposed in the central and eastern parts of the Seward Peninsula and the western Brooks Range. These rocks are inferred to constitute basement over most of the Norton Basin.

OKHOTSK-CHUKOTSK VOLCANIC BELT

The Okhotsk-Chukotsk volcanic belt (fig. 2) is a continuous band of mostly upper Mesozoic volcaniclastic and volcanic rocks that borders the miogeoclinal belt to the south. It can be traced from the region of the southern Chukotsk Peninsula to western St. Lawrence Island, and is exposed at isolated locations on St. Matthew, Nunivak, and the Pribilof Islands in the Bering Sea. It continues into the Yukon-Koyukuk province of west-central Alaska (fig. 2).

In western Alaska, the Okhotsk-Chukotsk belt consists of marine andesitic volcanic rocks of Early Cretaceous age overlain by as much as 26,000 feet of middle Cretaceous volcaniclastic graywacke, mudstone, and coal-bearing strata (Patton, 1973). In eastern Siberia, the belt is composed almost exclusively of volcanic rocks. Rocks of this tectonostratigraphic province may compose the basement of the Norton Basin near the Yukon Delta.

Paleozoic and early Mesozoic oceanic crust is thought to underlie the Okhotsk-Chukotsk volcanic belt (Patton and Tailleur, 1977). This is in contrast to the Precambrian crystalline rocks composing the continental crust underlying the miogeoclinal belt.

Marlow and others (1976) speculated that the volcanic belt represents a magmatic arc associated with the Late Cretaceous to early Tertiary oblique subduction of the Kula plate at the Beringian margin. Exposures of granitic plutons of Cretaceous age on onshore areas of the northern Bering Sea region are clustered along the boundary between the volcanic and miogeoclinal belts. These granitic plutons may be genetically related to magmatic arc processes associated with the subduction of the Kula plate.

Cretaceous granodiorite is exposed on King Island near the northwest edge of the Norton Basin (Hudson, 1977). Magnetic anomalies around the island and along the west edge of the basin (Department of Commerce, 1969) suggest that significant nearby areas are underlain by subcropping granodiorite. These plutons, if exhumed, may have contributed quartz-rich sand to adjacent areas of the basin. Quartz monzonite of Cretaceous age is exposed near the eastern edge of the Norton Basin on the Darby Peninsula along the southeastern margin of the Seward Peninsula (Miller and Bunker, 1976). There, a magnetic anomaly extends offshore into the east side of the Norton Basin and is inferred to delineate a subcrop of similar quartz monzonite (Fisher and others, 1982). Although the amount of sediment shed into Norton Basin from these granite sources is probably minor relative to that shed from the miogeoclinal and volcanic belt terranes, it may locally constitute a significant percentage of quartz-rich detritus in the basin fill.

FOREARC BASIN BELT

The Okhotsk-Chukotsk volcanic belt is bounded on the south by the forearc belt. The forearc belt consists of Paleozoic and Mesozoic deepwater melange and olistostromes, mafic volcanics, and nonmarine and marine sediments. Rocks from this belt probably form the basement along the outer Beringian shelf. Because of their remoteness, forearc belt rocks probably contributed very little sediment to the Norton Basin.

2

Regional Geologic History

The present geologic configuration of the Norton Basin area is the result of a series of complex Mesozoic and early Tertiary tectonic events. During the Late Jurassic and Early Cretaceous, rocks of the Brooks Range and Seward Peninsula formed a continental block that was partially subducted to the south beneath an oceanic plate that supported a magmatic arc complex (Fisher and others, 1982). Northward-directed overthrusting, or obduction, of the oceanic crust resulted in the emplacement of stacked ophiolite bodies in the central Brooks Range (Roeder and Mull, 1978). Evidence for this obduction is provided by the presence of klippen of ophiolitic rocks overlying Precambrian and Paleozoic metamorphic rocks in the Brooks Range. At the time the Brooks Range and Seward Peninsula continental crust was subducted beneath the oceanic crust, the continental rocks were metamorphosed to blueschist facies and strongly deformed (Fisher and others, 1982). The Brooks Range and Seward Peninsula continental block continued to be subducted until the subduction zone ceased to function, possibly during the Early Cretaceous (Fisher and others, 1982). Subsequent isostatic rebound of the subducted continental crust resulted in extensive erosion of the uplifted ophiolite and underlying crust in the Brooks Range, Seward Peninsula, and Norton Sound areas.

Albian and Cenomanian conglomerates are widespread in the northern Yukon-Koyukuk province. These conglomerates contain abundant ophiolite debris and are overlain in part by strata composed of sediment sourced from a Precambrian and Paleozoic metamorphic terrane (Patton, 1973). This depositional relationship suggests that the overthrust Brooks Range ophiolites were the first to be exposed and that the detritus was transported southward into a depocenter in the northern Yukon-Koyukuk province. This was followed by subsequent erosion, transport, and deposition of detritus derived from the older Precambrian and Paleozoic metamorphic rocks initially emplaced beneath the ophiolite klippen.

The Yukon-Koyukuk province was a depocenter for much of the eroded sediments as well as for volcanogenic debris generated by concurrent volcanism throughout west-central Alaska and eastern Siberia (Patton, 1973). A wide, arcuate band of granitic plutons was intruded into rocks of the Yukon-Koyukuk province, the eastern Seward Peninsula, St. Lawrence Island, and the Chukotsk Peninsula of Siberia during the middle Cretaceous (Fisher and others, 1981).

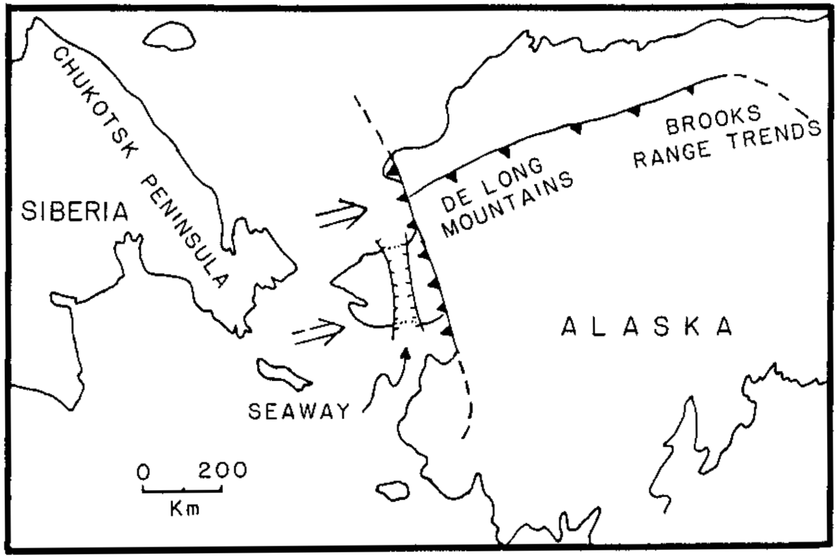


FIGURE 3A. Middle Late Cretaceous tectonic framework of the Bering Strait region. Diagram modified from Holmes and Creager, 1981.

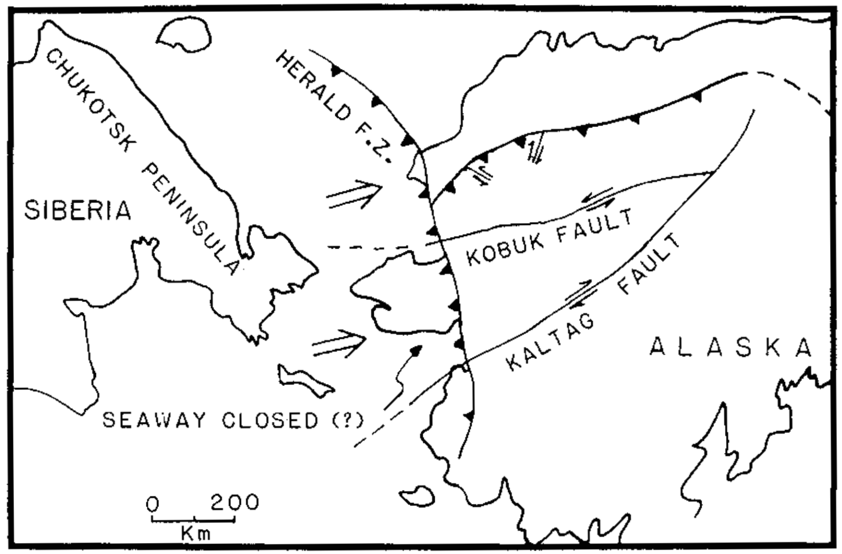


FIGURE 3B. Late Late Cretaceous tectonic framework of the Bering Strait region. Diagram modified from Holmes and Creager, 1981.

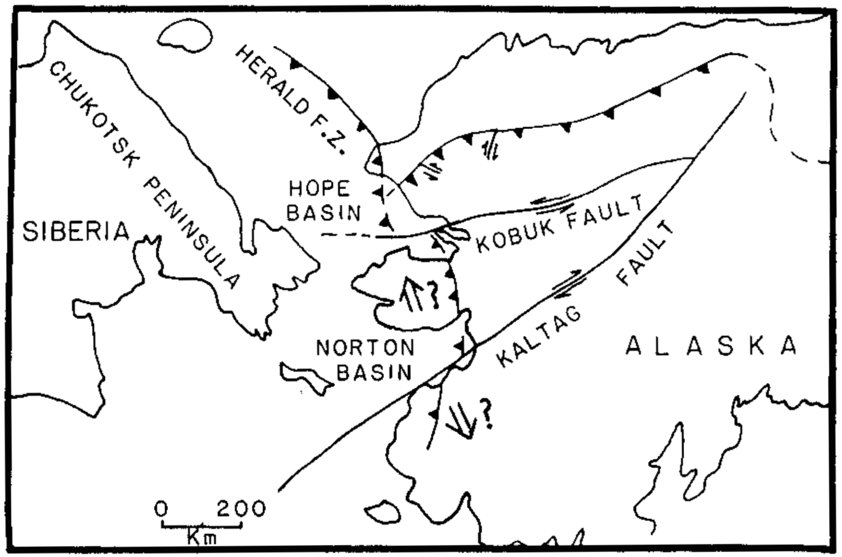


FIGURE 3C. Latest Cretaceous / early Tertiary tectonic framework of the Bering Strait region. Diagram modified from Holmes and Creager, 1981.

In middle Late Cretaceous time, east-west compression accompanied by oroclinal bending rotated the Seward Peninsula counterclockwise approximately 90 degrees (Patton and Tailleur, 1977) to its present position in relation to the Brooks Range (fig. 3A). Rotation of the peninsula resulted in eastward-directed thrusting of Paleozoic and Precambrian age rocks along the eastern margin of the Seward Peninsula. On the basis of faunal distributions, Sachs and Strelkov (1961) postulate that the Pacific and Arctic basins were connected by a seaway across the eastern Seward Peninsula during middle Late Cretaceous time, then later isolated by closure of the seaway in response to east-west compression. The initial subsidence of the Norton Basin may have been initiated in the Late Cretaceous during this east-west compressive period by right-lateral strike-slip movement along the newly formed Kaltag fault (Fisher and others, 1982) (fig. 3B).

Compression ceased in latest Cretaceous and early Paleogene time and was followed by a period of regional extension in west-central Alaska (fig. 3C). Regional extension in the Norton Basin area triggered major subsidence by block-faulting along master faults, and is believed to be the primary tectonic mechanism for the initial formation of the basin. Alluvial fans were deposited along the margins of uplifted fault blocks, which indicates that early in the history of the basin the rate of subsidence exceeded the rate of sediment input from flanking areas (Fisher and others, 1982). The Yukon horst, which separates the two subbasins of the Norton Basin, was active by early Paleogene time, as evidenced by the presence of alluvial deposits along its flanks that predate other Tertiary sequences. After major, local, fault-controlled basin subsidence ceased, epeirogenic regional subsidence (inferred to stem from thermal contraction of the crust and upper mantle as well as isostatic compensation for the newly emplaced sediment load) prevailed in the Norton Basin area (Fisher and others, 1982). Epeirogenic regional subsidence of this area has persisted through Holocene time.

Basaltic volcanism occurred in the northern Bering Sea region during latest Miocene, Pliocene, and Pleistocene time. Volcanic rocks were extruded locally onto land areas along the margin of the Norton Basin (Hoare and Coonrad, 1980). Miocene and Pliocene flood basalts located near an east-trending zone of rifting along the axis of the Seward Peninsula suggest that the peninsula and immediate areas may have undergone a period of renewed north-south extension beginning in latest Miocene or earliest Pliocene (Fisher and others, 1982). Common-depth-point seismic reflection data in Norton Basin indicate the presence of several domed structural features that appear to be laccoliths. The ages of these intrusives, as tentatively deduced from their structural and stratigraphic relationships with horizons extrapolated from Norton Basin COST No. 1 and No. 2 wells, range from early Miocene to mid-Pliocene.

3

Structural Geology

BASIN DEVELOPMENT

The Norton Basin is an extensional basin located adjacent to the Kaltag fault. The Kaltag fault, a right-lateral strike-slip fault, extends southwestward through west-central Alaska where its trace disappears along the southern margin of Norton Sound. Although the role of the Kaltag fault in the development of Norton Basin is unclear, Fisher and others (1982) suggest that movement along the fault during a period of regional extension may have served to localize subsidence.

Interpretation of CDP seismic data indicates two distinct stages in the development of the Norton Basin. In the first stage, rifting resulted in subsidence along master and secondary normal faults. The presence of possible Paleocene strata encountered in the Norton COST No. 1 and No. 2 wells suggests an early- or pre-Paleocene age for the rifting. A secondary stage of development consisted of regional, epeirogenic downwarping, beginning in the late Oligocene (figs. 13 and 14, post-horizon C) and continuing into the Holocene.

These two stages of basin development correspond to the simple extensional model for the evolution of sedimentary basins envisioned by McKenzie (1978). McKenzie proposed an initial stage characterized by rapid crustal attenuation in response to extensional stress. Thinning of the crust would then permit upwelling of hot asthenospheric material. Isostatic adjustment in response to the replacement, at depth, of the shallow crust by dense asthenosphere then results in fault-controlled initial subsidence at the surface. A positive thermal anomaly is associated with the thinning of the lithosphere and the subsequent upwelling of the hot asthenosphere (McKenzie, 1978). A secondary stage of cooling of both lithospheric and asthenospheric material by heat conduction to the surface then results in gradual, regional, non-fault-related subsidence.

McKenzie (1978) illustrates how fault-controlled subsidence, heat flow, and the resulting thermally controlled subsidence can be predicted as a function of the factor by which the surface length increases as the result of crustal stretching. Calculations of the extension factor in the Norton Basin by Helwig and others (1984) and Y. M. Chang (personal commun., 1985) provided the following values:

NORTON BASIN LEASE SALE 100

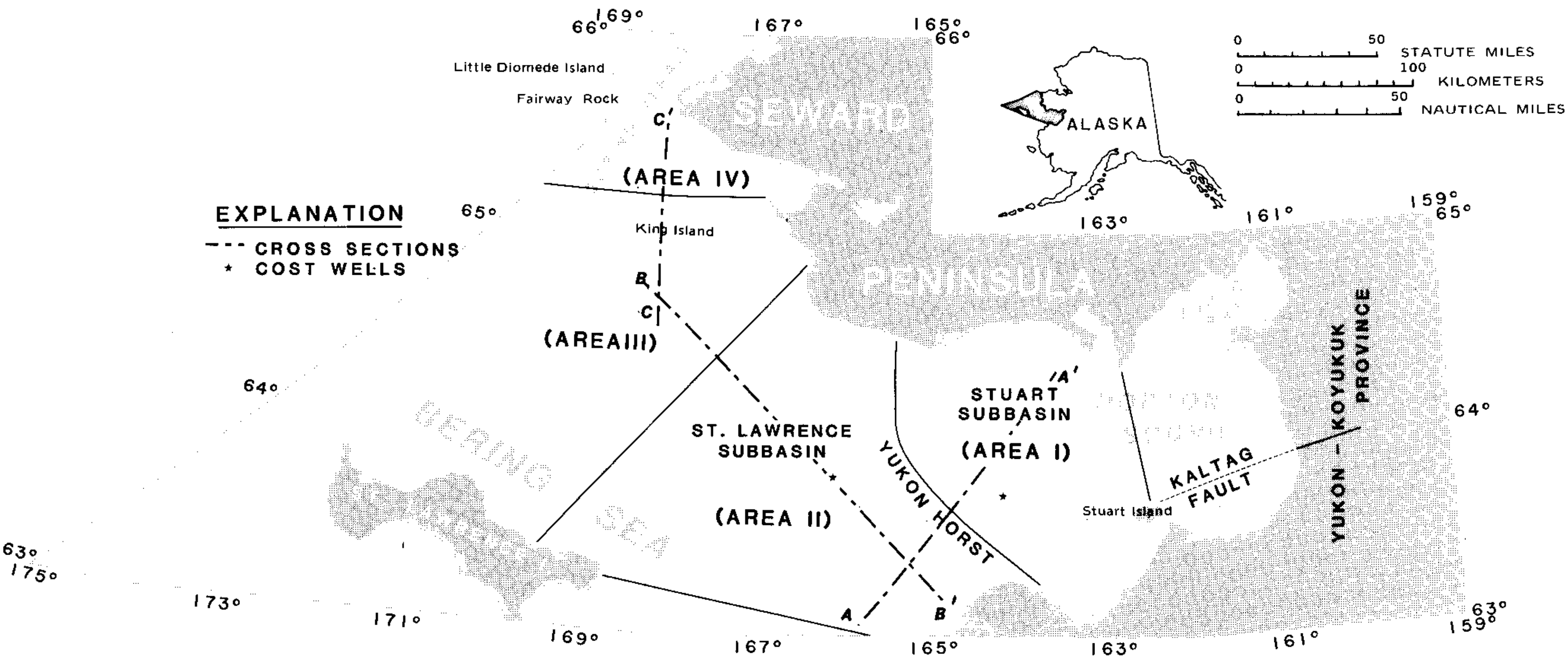


FIGURE 4. Structural provinces of the Norton Basin region.

Method	Extension Factor
Offset of Kaltag fault	1.9
Extension of basement from seismic records	<1.4
Mean basin subsidence (tectonic and isostatic)	>1.1

They concluded that the higher extension factor value (1.9) is supported by the state of maturation and present temperature gradient in the basin.

BASIN STRUCTURE

The Norton Basin area can be subdivided into four separate structural and geographic provinces based on the type and orientation of major geologic features and the segmentation of the basin by positive, intrabasinal structural features (figs. 4 and 5). Area I, the Stuart subbasin, lies east of the Yukon horst and west and north of Stuart Island. Area II, the St. Lawrence subbasin, lies west of the Yukon horst and east and northeast of St. Lawrence Island. The third structural province, area III, lies to the north of St. Lawrence Island, south of King Island, and west of a line at approximately longitude 168° W. Area IV is bordered on the east by the Seward Peninsula, on the south by a shallow platform extending northward from King Island, and on the north by Fairway Rock and Little Diomede Island.

Area I, the Stuart subbasin, is bounded on the west by a north-south-trending arcuate structural high termed the "Yukon horst" by Fisher and others (1981) (figs. 6 and 7). Seismic profiles over the basement horst reveal overlying arched strata that display drape or compaction features. The northern section of the horst is bounded on the east by a series of westward-dipping rotated fault blocks. These blocks are bordered on their downdip sides by a series of en echelon normal faults (fig. 7). Towards the south, the Yukon horst is less pronounced and assumes a more northwest-southeast orientation. The absence of seismic data from the shallow-water areas of the Yukon Delta does not permit definition of the southern margin of the Stuart subbasin. However, gravity data from this area indicate that only about 3,000 feet of Cenozoic sediment is present near the north lobe of the delta (Fisher and others, 1980; Barnes, 1977) (fig. 8). This estimate of sediment thickness was calculated from the relationship between depth-to-basement and free-air gravity values, which in the Norton Basin was determined by Fisher and others (1982) to approximate a quadratic curve (fig. 9). Low land elevations on the Yukon Delta permit, with negligible error, a direct comparison between free-air gravity and Bouguer gravity values, thus allowing the use of Bouguer gravity values in the gravity relationship illustrated in figure 9 (Fisher and others, 1982).

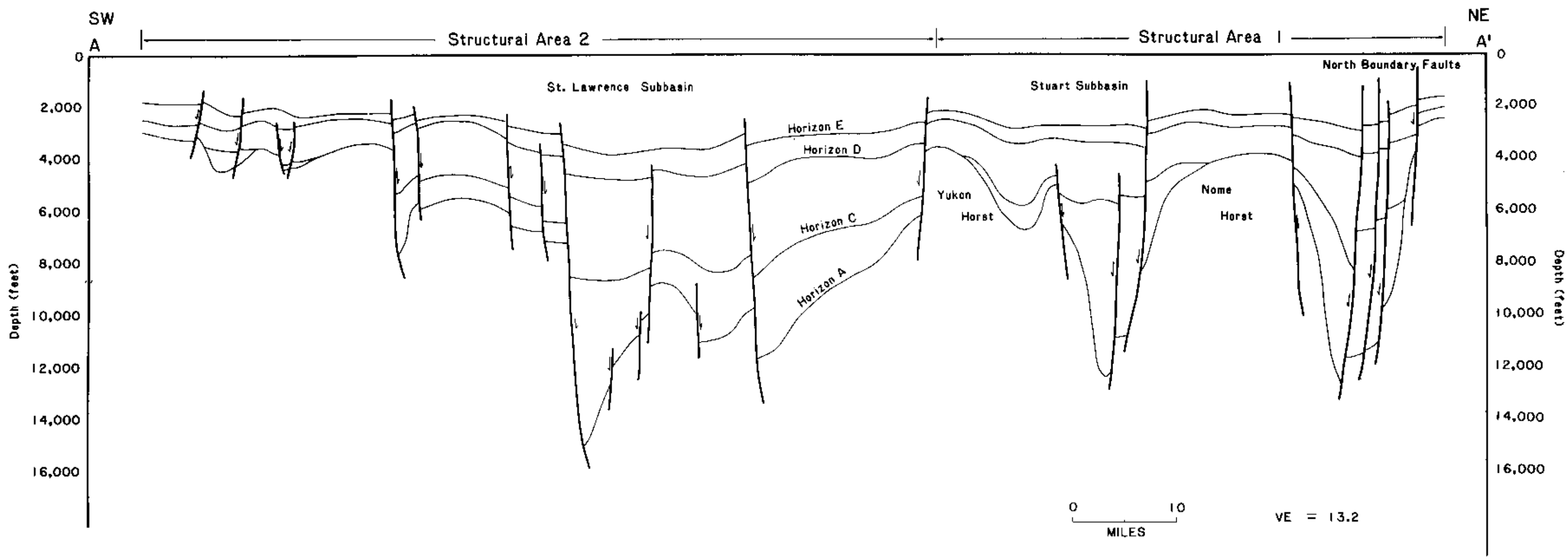


FIGURE 5 . Generalized stratigraphic cross sections across Norton Basin showing major structural features and structural provinces. Cross sections based on Western Geophysical Company of America common-depth-point seismic data. Location diagram situated on accompanying page.

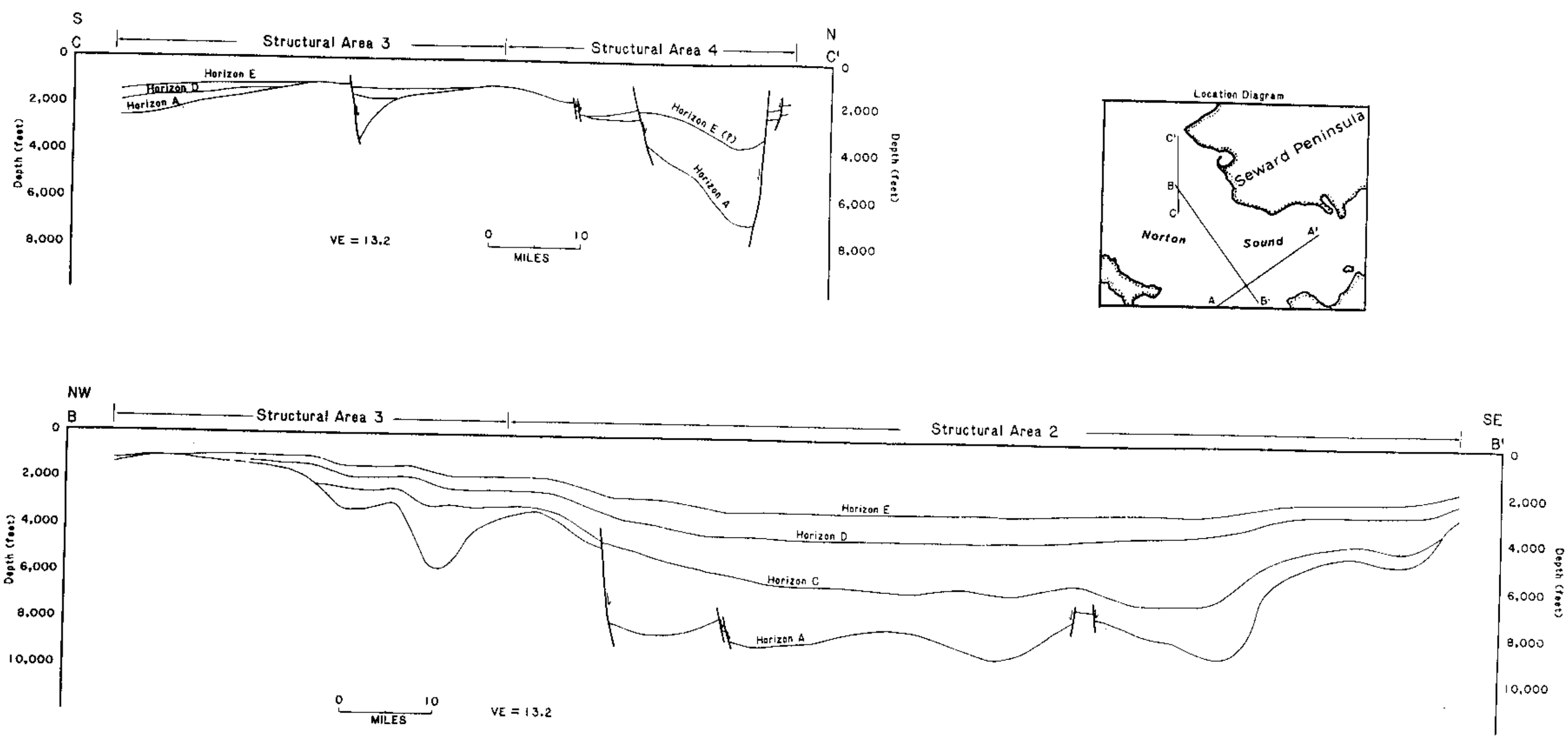


FIGURE 5(continued)

The Stuart subbasin is bounded on the north and east by a smooth, nearly featureless basement platform covered by 2,500 feet or less of sediment (fig. 7). An east-west-trending normal fault (or fault zone), informally referred to as the "north-boundary fault" by Fisher and others (1981), marks the termination of the northern basement platform against a deeper, more structurally complex area of the subbasin to the south. The total throw on the north-boundary fault and subordinate faults along the north edge of the subbasin locally exceeds 7,000 feet.

An arcuate anticlinal structure informally referred to as the "Nome horst" by Fisher and others (1981) is present in the north-central section of the Stuart subbasin (fig. 7). Along the crest of the "horst," the seismically determined depth to basement is approximately 4,000 feet. The seismically derived depth to basement is confirmed by a range of free-air gravity values from +2 to -5 milligal (mgal), which corresponds to a sediment thickness of 3,700 to 4,400 feet (fig. 9). Northeast of the Nome horst and adjacent to the north-boundary fault, lies a basin low characterized by a free-air gravity value of -36 mgal (fig. 8), which is unusually low for most structural depressions within the Stuart subbasin, and indicates a maximum depth of 17,000 feet. The depth to basement, as determined from seismic reflection data, is 16,400 feet.

The deepest area of the Norton Basin is in the central part of the Stuart subbasin south of the Nome horst. This basement low is bounded to the northwest and southeast by northeast-southwest-striking normal faults. The COST No. 2 well was drilled on the southwest flank of this structural depression, where it encountered metamorphic rocks of the Precambrian to Paleozoic miogeoclinal belt at a depth of 14,460 feet. Seismic data indicate that the sedimentary fill in the central area of the subbasin approaches a maximum thickness of 23,000 feet. Free-air gravity values over this central structural low only reach a minimum of -34 mgal (Fisher and others, 1980), which corresponds to an apparent sediment thickness of 15,800 feet. This discrepancy in the calculated depths to basement may involve a number of factors, including the possible occurrence of local high-density and/or overcompacted Paleogene strata. The presence of underlying high-density (oceanic?) type crustal material could also be in part responsible for this anomalous situation.

Area II, the St. Lawrence subbasin, lies west of the Yukon horst and east of a shallow basement platform extending northeast across Norton Basin from St. Lawrence Island to the Seward Peninsula (fig. 4). The predominant strike of faults in the St. Lawrence subbasin is to the northwest (figs. 6 and 7). A north-south-trending fault zone in the southeastern part of the subbasin bounds a half-graben to the east, where it rises northeastward onto the southwestern flank of the Yukon horst. This half-graben contains up to 14,000 feet of sediment above acoustic basement and has an associated free-air gravity value of -24 mgal, which corresponds to an apparent sediment thickness of 10,750 feet.

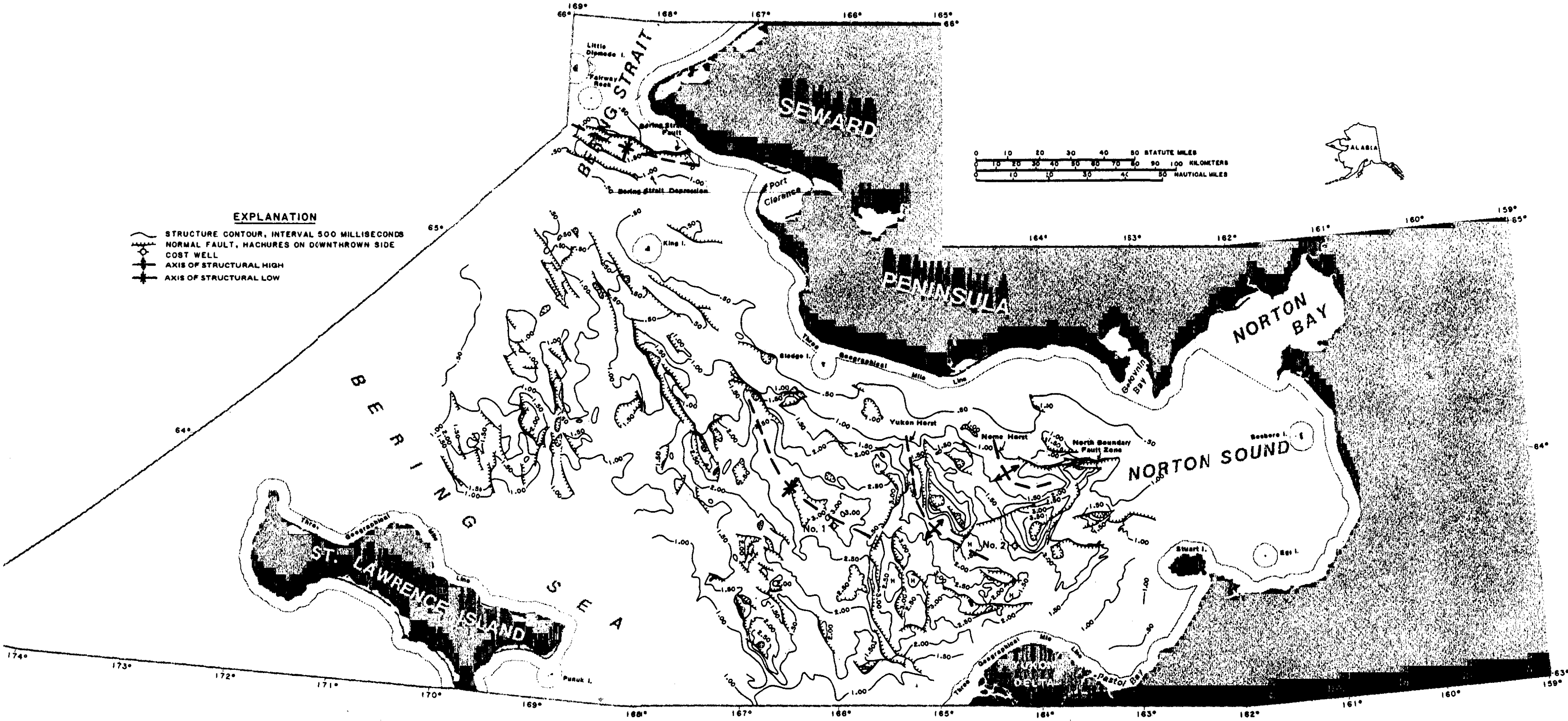


FIGURE 6. **Structure contours (in time) on horizon A in Norton Basin. Horizon A is an unconformity between probable Precambrian and Paleozoic basement rocks below and lower Paleogene rocks above. Interpretation is based on Western Geophysical Company of America common-depth-point seismic data.**

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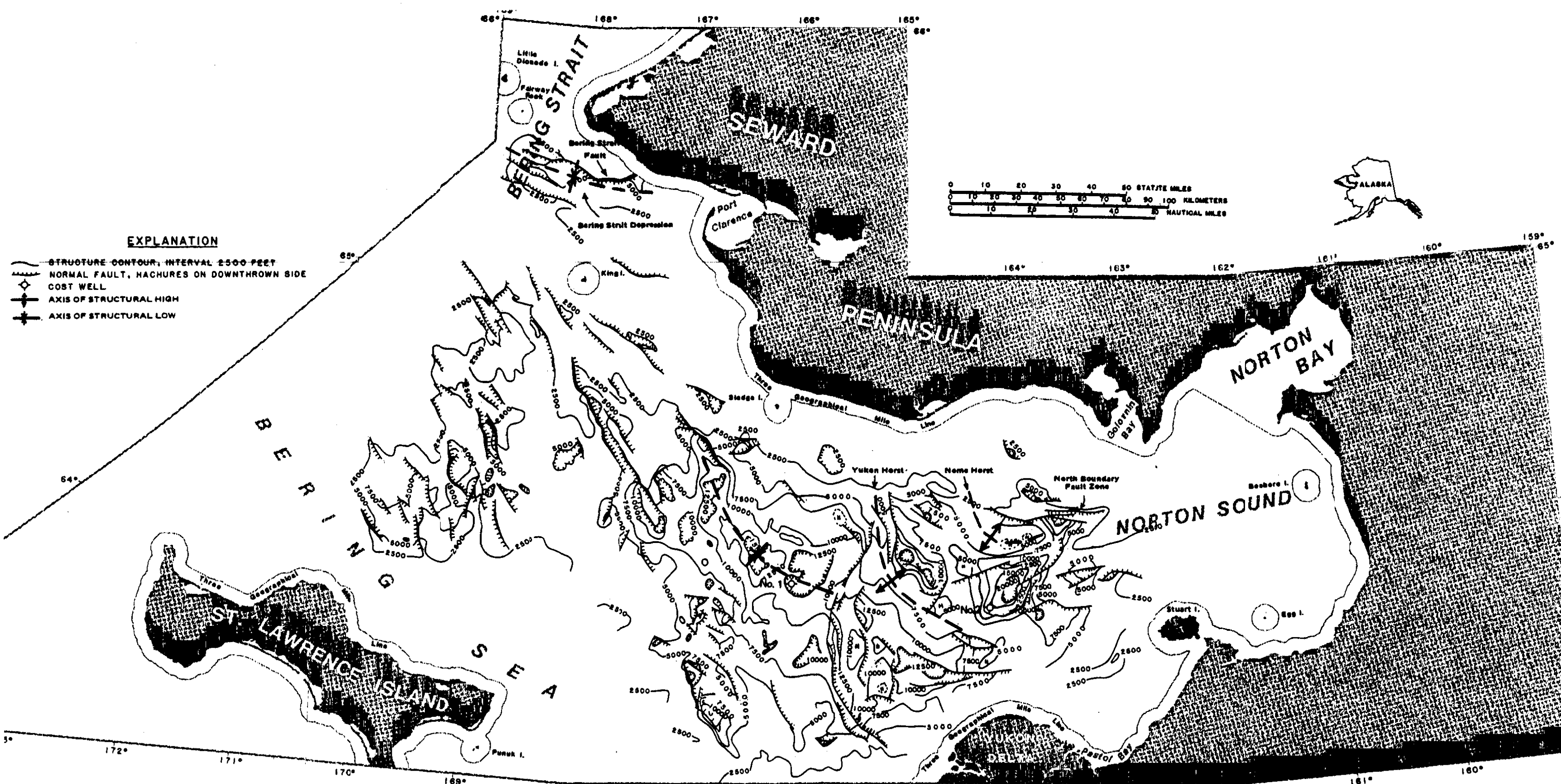

FIGURE 7. Structure contours (in depth) on horizon A in Norton Basin. Horizon A is an unconformity between probable Precambrian and Paleozoic basement rocks below and lower Paleogene rocks above. Interpretation and time-depth relationship derived from Western Geophysical Company of America common-depth-point seismic data.

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The central area of the St. Lawrence subbasin is occupied by a large northwestwardly elongated structural low that is primarily the result of minor faulting and major regional tilting and subsidence of the basement. Time-depth calculations using stacking velocities derived from seismic reflection data indicate a maximum sediment thickness of more than 16,000 feet in the center of the subbasin. To the southeast, the COST No. 1 well was drilled along the axis of the St. Lawrence subbasin and encountered cataclastically deformed and metamorphosed sedimentary rocks of probable Precambrian age at a depth of 12,545 feet (fig. 7).

Several large normal faults extend northwestward from the northwest corner of the St. Lawrence subbasin into area III. Area III consists of a relatively shallow basement platform cut by predominantly northwest-southeast-trending grabens and half-grabens. The depth to this basement platform throughout the mapped area averages between 1,500 and 3,500 feet (fig. 7). Sediment thickness in the grabens locally exceeds 7,500 feet. The western boundary of the subbasin is an extremely shallow, featureless platform with less than 2,500 feet of sediment cover. A small, faulted low just north of St. Lawrence Island approaches a basement depth of 9,000 feet.

An airborne high-sensitivity magnetic survey conducted in the western part of the Norton Basin by Aero Service Division, Western Geophysical Company of America, revealed several groups of high-amplitude magnetic anomalies, many of which exceed 200 gamma, along with several isolated low-amplitude anomalies (Vixo and Prucha, 1983). Based on similarities of the magnetic disturbances, the high-amplitude magnetic anomalies have been interpreted by Vixo and Prucha to represent Cretaceous silicic plutonic rocks analogous in composition and genesis to those found on the Darby Peninsula of southeastern Seward Peninsula, and to the Cretaceous intrusions in the Yukon-Koyukuk province. Magnetite has been found to be a common accessory mineral in the Cretaceous silicic plutonic rocks in the Norton Basin region (Miller and others, 1966; Miller and Bunker, 1976) and is, in large part, responsible for producing the magnetic anomalies associated with the plutons (Decker and Karl, 1977). The low-amplitude magnetic anomalies observed in the western area of the Norton Basin are considered to stem from two separate magnetic horizons (Vixo and Prucha, 1983): the weakly magnetic metamorphic and sedimentary rocks of the basement and a weakly magnetic suprabasement horizon, probably containing local Donovan anomalies, which are thought to result from concentrations of diagenetic magnetite associated with hydrocarbon microseepage (Donovan and others, 1979).

A shallow, relatively featureless basement shelf separates areas III and IV. Area IV, located north of King Island, consists of a small, isolated structural graben termed the "Bering Strait depression" (BSD) by Greene and Perry (npub., cited in Johnson and Holmes, 1980) that is bounded by major east-southeast-striking normal faults (fig. 7). Johnson and Holmes (1980) concluded that the east-southeast-striking faults of area IV appear to intersect and offset the northwest-trending faults and structures that extend

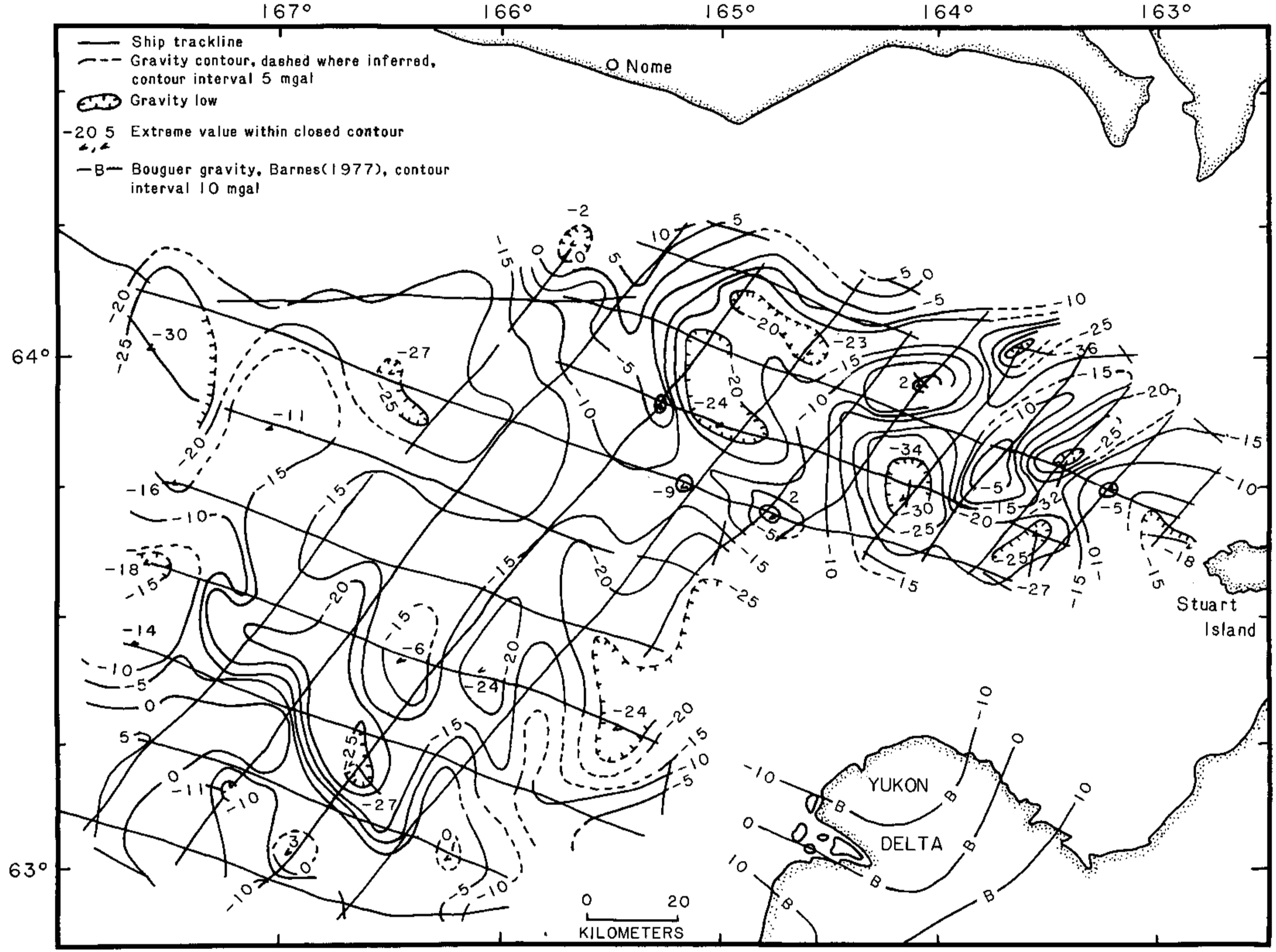


FIGURE 8. **Contours of Bouguer gravity over the Yukon Delta (Barnes, 1977) and of free-air gravity over Norton Basin (Fisher and others, 1980). From Fisher and others, 1982.**

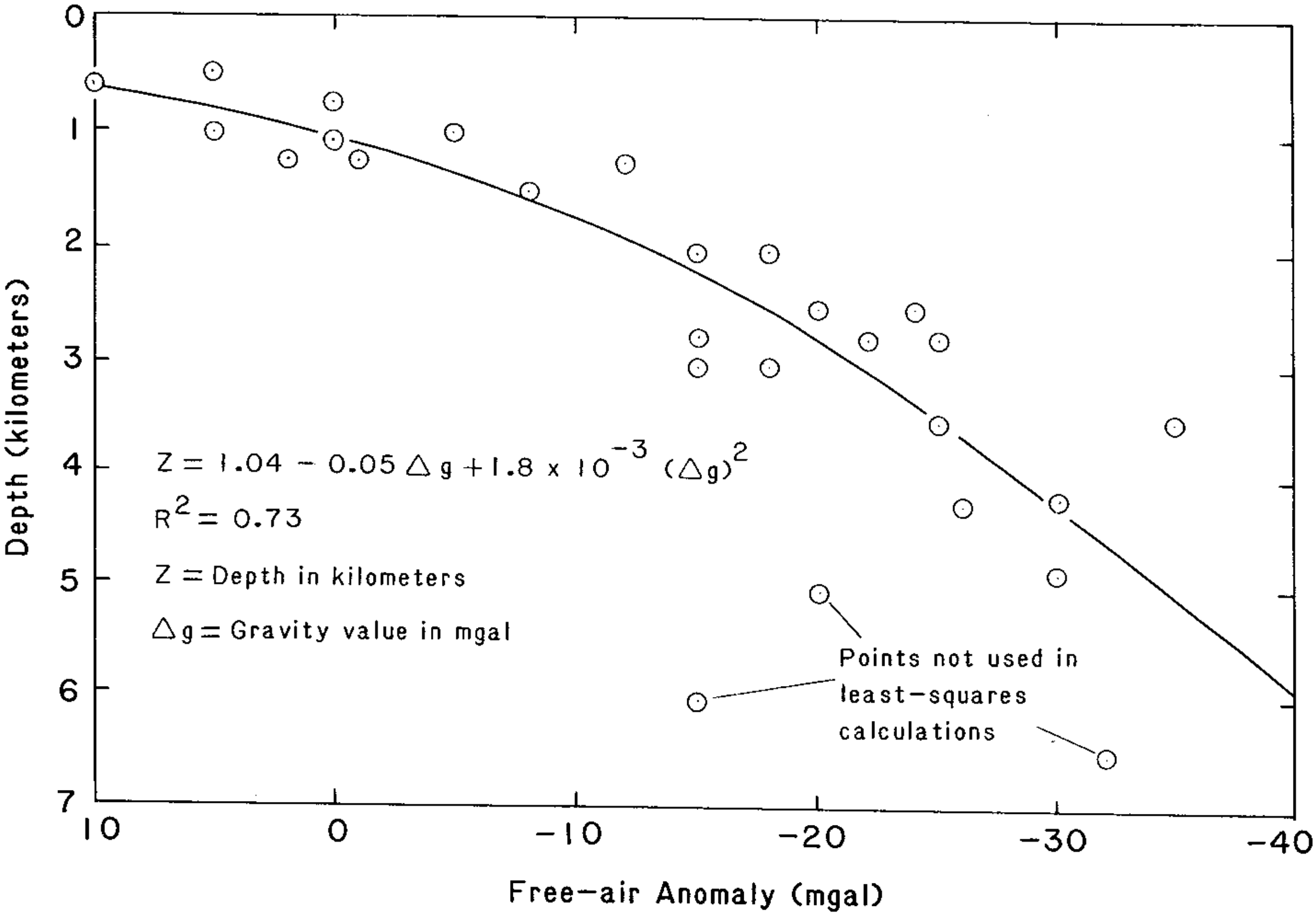


***FIGURE* 9. Relationship between free-air gravity value and depth to basement. Diagram from Fisher and others, 1982.**

from area III. This implies that the structural development of the BSD postdates earlier deformation in the main Norton Basin (Johnson and Holmes, 1980). Sediment thickness near the center of the BSD approaches 7,000 feet. The northern perimeter of the BSD is defined by a major east-trending normal fault, labeled the "Bering Strait fault" by Hopkins (unpub., cited in Johnson and Holmes, 1980). The lack of seismic coverage precludes a better definition of the Bering Strait fault further to the east, where it may merge with a structure known as the Port Clarence rift (Hopkins, unpub., cited in Johnson and Holmes, 1980).

4

Biostratigraphy

A fine-scale stratigraphic zonation of the Norton Basin based on microfossil ranges is difficult at this juncture because of the paucity of data and the imperfect state of biostratigraphic knowledge of the Bering Sea area. In addition, there has been considerable controversy concerning the several zonal schemes so far proposed, most particularly, the nature and extent of the Oligocene section. In the Norton Basin, high-resolution zonations are difficult to construct because of the poor representation of key microfossil groups such as planktonic foraminifers and calcareous nannoplankton. Even when these taxa are present there is some uncertainty involved in the extrapolation of their ranges from lower to higher latitudes. For these reasons, the biostratigraphy described in this report should be considered preliminary. Nevertheless, reinvestigations of the COST well data have already resulted in tighter and better substantiated zonations. In general, the new data support our previous interpretations (Turner and others, 1983a,b).

Paleoecologic and biostratigraphic determinations in the Norton Basin COST wells are based on detailed analyses of microfossil assemblages containing Foraminifera, ostracodes, silicoflagellates and diatoms, calcareous nannoplankton, and marine and terrestrial palynomorphs (chiefly spores, pollen, and dinoflagellates). Rotary drill-bit cuttings were examined at 30-foot intervals from the first samples taken to the total depths of the wells. Data from conventional and sidewall cores were also examined and utilized. Slides, processed samples, and reports prepared for the participants by consultants (Anderson, Warren and Associates, 1980; Biostratigraphics, 1982) were examined, interpreted, and integrated into this report.

The COST No. 2 well was reprocessed and reexamined for palynomorphs by Jonathan P. Bujak of the Bujak Davies Group and the preliminary results (J. Bujak, personal commun., 1985) integrated into this report. The COST No. 1 well is currently being restudied. In addition, both wells were reprocessed for ostracodes which were subsequently identified by Elisabeth Brouwers of the USGS (E. Brouwers, written commun., 1985). Discrepancies between Minerals Management Service and consultant interpretations, principally the location of biostratigraphic tops, for the most part can be attributed to sample

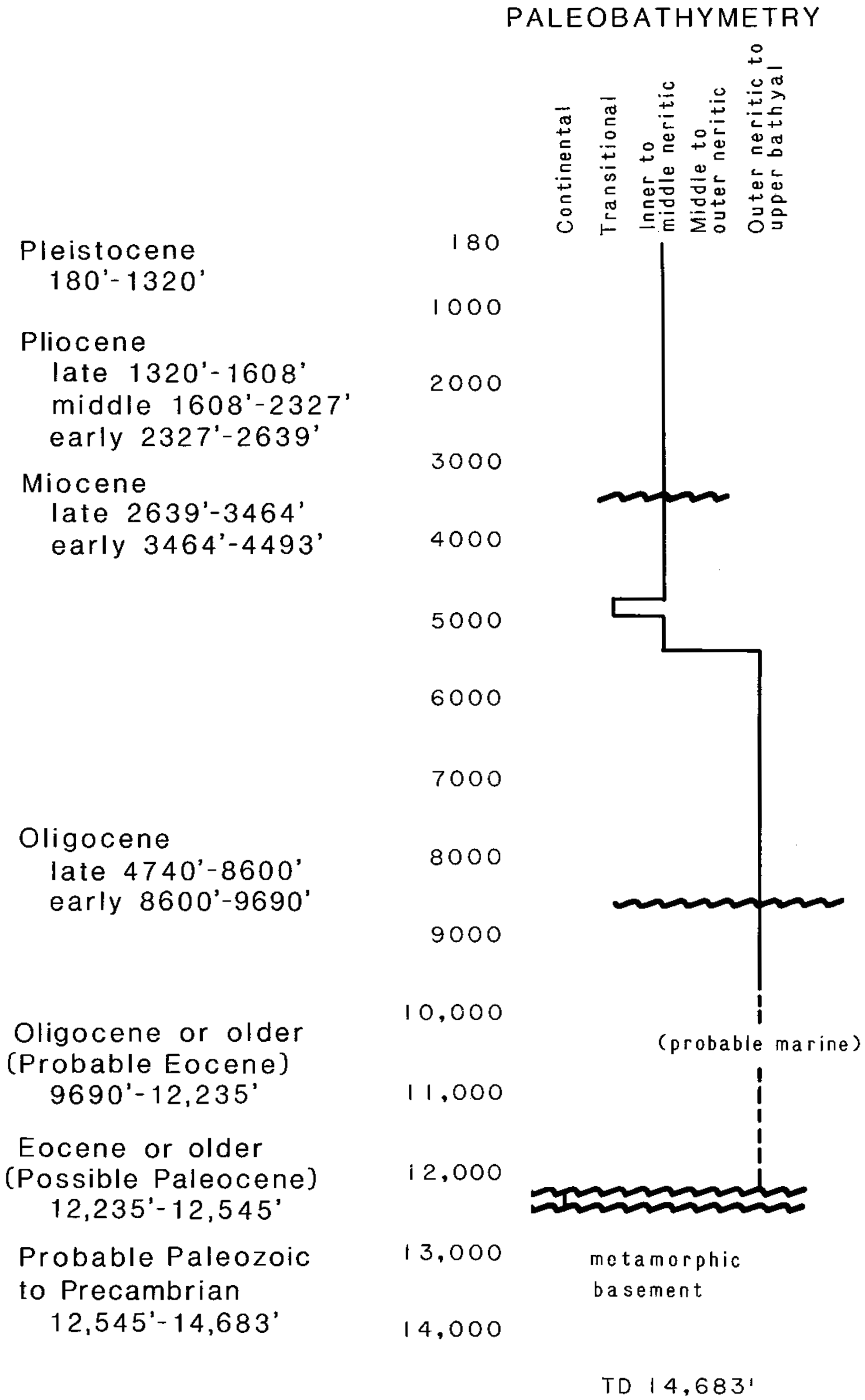


FIGURE 10. **Stratigraphic and paleobathymetric summary of Norton Basin COST No. 1 well.**

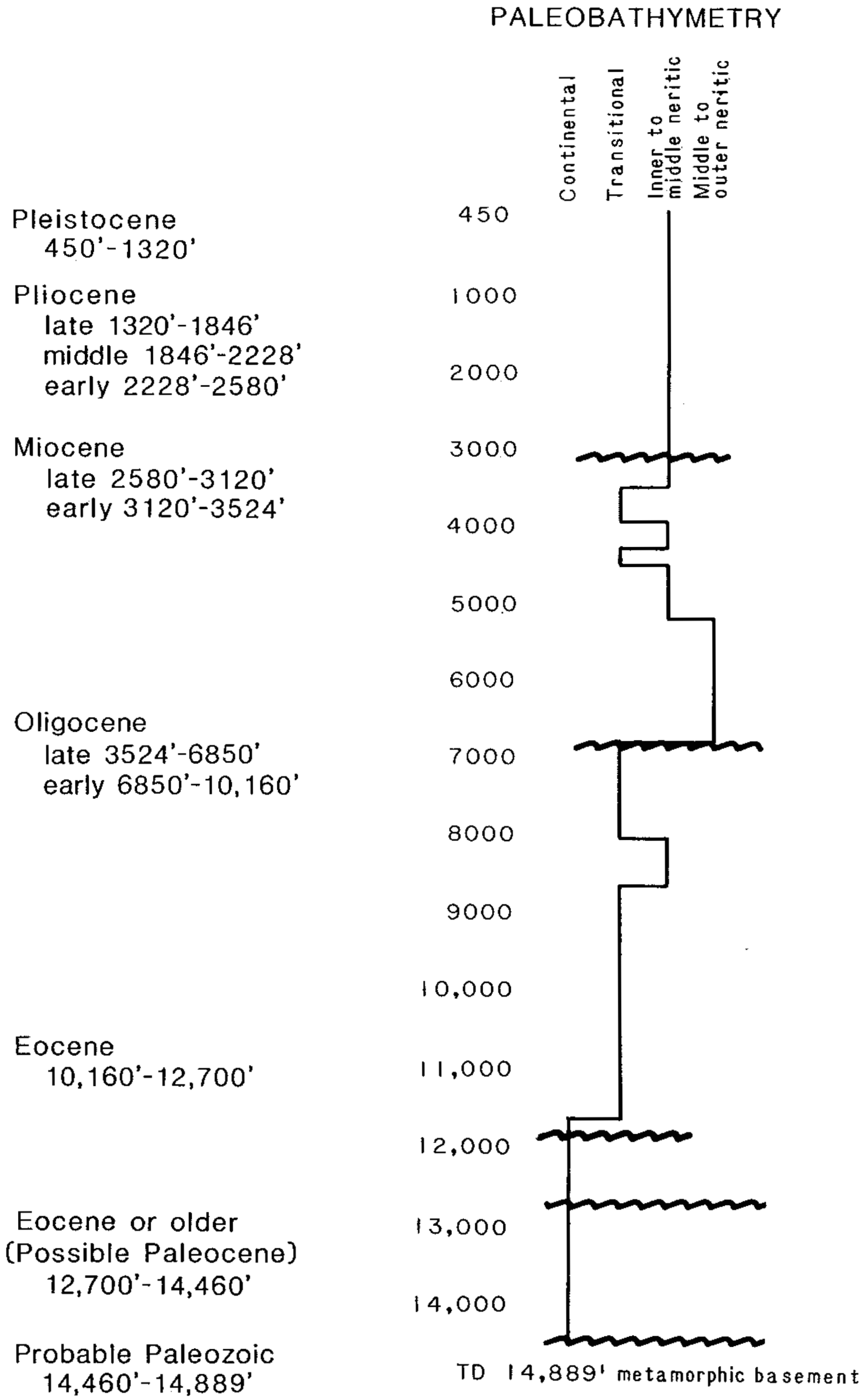


FIGURE 11. **Stratigraphic and paleobathymetric summary of Norton Basin COST No. 2 well.**

preparation techniques. Foraminiferal analysis, interpretation, and synthesis of other data were done by Ronald F. Turner of MMS. Siliceous microfossil analysis was done by Donald L. Olson of MMS.

Strata are discussed in the order that they were penetrated. The biostratigraphic units delineated often represent a synthesis of data derived from various subdisciplines that often do not agree in every particular. Following convention, fossil occurrences are listed as highest and lowest rather than the potentially confusing first and last. Sample depths were measured from the kelly bushing. Data obtained from conventional cores are given somewhat more weight than those from cuttings.

Paleoenvironmental determinations, chiefly water depth and energy, are based on the entire microfossil and macrofossil suites. Paleoclimatological interpretations are based on spore and pollen assemblages and, to a lesser extent, on diatoms, silicoflagellates, and Foraminifera. Fluvial, lacustrine, and paludal environments are classified as continental or nonmarine. Transitional environments include brackish estuaries, marshes, and lagoons. For sediments deposited in marine environments, the paleoenvironment is expressed in terms of bathymetry. Paleobathymetric determinations are primarily based on foraminiferal criteria, but dinoflagellates and other marine organisms such as bryozoans, echinoids, ophiuroids, and cirripeds were also utilized. The marine environment is divided into inner neritic (0 to 60 feet), middle neritic (60 to 300 feet), outer neritic (300 to 600 feet), and upper bathyal (600 to 1,500 feet).

The paleontology of the two Norton Basin COST wells is discussed separately (figs. 10 and 11), then correlated at the end of the chapter (fig. 12). In the absence of onshore outcrop data or other well control, these interpretations are the basis for most of the other correlations, for example, figures 13 and 14 in the Lithostratigraphy and Seismic Stratigraphy chapter of this report.

COST NO. 1 WELL

Pleistocene

The interval from 180 to 1,320 feet is Pleistocene in age on the basis of a foraminiferal fauna containing *Elphidium bartletti*, *Elphidium clavatum*, *Elphidium incertum*, *Protoelphidium orbiculare*, *Elphidiella gorbunovi*, *Elphidiella oregonense*, *Elphidiella sibirica*, *Buccella frigida*, *Quinqueloculina seminulum*, and *Dentalina baggi*.

A moderately diverse, though sparse, ostracode fauna containing specimens of *Paracyprideis pseudopunctillata*, *Heterocyprideis sorbyana*, *Normanicythere leioderma*, *Rabilimis septentrionalis*, *Rabilimis* cf. *R. paramirabilis*, *Acanthocythereis dunelmensis*, *Cytheretta* "*edwardsi*," *Sarsicytheridea* sp. A, and *Elofsonella concinna* substantiates this age (E. Brouwers, written commun., 1985).

Although the siliceous microfossil assemblages in this interval contain a high percentage of reworked material, the presence of the diatoms Melosira sulcata, Coscinodiscus marginatus, Actinocyclus curvatulus, and Biddulphia aurita in association with the silicoflagellates Distephanus octangulatus and Distephanus octanarius also indicates a Pleistocene age.

Environment

The foraminiferal fauna and diatom flora indicate an inner neritic (0 to 60 feet) cold-water environment for the Pleistocene interval. Abundant molluscan fragments, barnacle plates, echinoid plates and spines, and fragments of erect bryozoan colonies (adeoniform and vinculariiform) generally support this interpretation, although the bryozoans suggest possible middle neritic water depths (60 to 300 feet). The ostracode fauna indicates that these environments were characterized by periods of reduced or fluctuating salinities. The admixture of stenohaline and euryhaline forms can be explained by the complex interplay of glacio-eustatically controlled fluvial and marine processes.

Pliocene

The interval from 1,320 to 2,639 feet is Pliocene in age. Although the Pliocene siliceous microfossil assemblage contains a substantial number of older, reworked forms as well as Pleistocene species caved from uphole, the interval can be provisionally subdivided into late, middle, and early on the basis of diatom and silicoflagellate distributions. The late Pliocene, 1,320 to 1,608 feet, is identified by the highest occurrence of the diatoms Coscinodiscus marginatus fossilis, Stephanopyxis inermis, Actinocyclus ehrenbergii, Thalassiosira usatchevii, and Nitzschia fossilis. The middle Pliocene, 1,608 to 2,327 feet, is defined by the first occurrence of Thalassionema robusta, Thalassionema convexa aspinosa, Cosmiodiscus intersectus, Denticulopsis kamtschatica, and Distephanus boliviensis boliviensis. The early Pliocene, 2,327 to 2,639 feet, is defined by the lowest occurrences of Actinocyclus ochotensis and Ammodochium rectangulare. Siliceous microfossil zonations for all parts of the well are based on Koizumi (1973), Schrader (1973), and Barron (1980).

The foraminiferal fauna is essentially the same as that of the overlying Pleistocene with the exception of the highest occurrence of Pseudopolymorphina cf. P. suboblonga at 1,500 feet.

The ostracode fauna is also quite similar to that of the overlying Pleistocene, with the addition of Rabilimis paramirabilis, Cytheretta teshekpukensis, Cytherura sp. A, Robertsonites tuberculata, Heterocyprideis fascis, Elofsonella concinna concinna, and Eucytheridea punctillata. Most of these species have heretofore been considered Pleistocene with the exception of Rabilimis paramirabilis (1,380 to 1,410 feet), which has been reported only from Beringian-age sediments (late Pliocene-early Pleistocene).

The sparse terrestrial palynoflora contains Alnipollinites sp. and rare specimens of Betulaceae, Polypodiaceae, Polmoniaceae, and Chenopodiaceae. The marine palynoflora is characterized by common specimens of Tasmanaceae and the dinoflagellates Lejeunia spp., Paralecanicella indentata, and Operculodinium sp. 2. The latter species first occurs in a sidewall core taken at 1,494 feet and marks the approximate position of the Pliocene-Pleistocene boundary in Alaska according to Hideyo Haga (Anderson, Warren and Associates, 1980).

Environment

The Pliocene microfossil and macrofossil assemblages are indicative of cold-water, inner neritic deposition.

Miocene

The interval from 2,639 to 4,740 feet represents the Miocene section of the well. This interval can be further subdivided into late and early Miocene sections on the basis of siliceous microfossils. The absence of definitive middle Miocene siliceous microfossil taxa in conjunction with the relatively good late and early Miocene assemblages suggests that this time may be represented by a hiatus, although the foraminiferal data appear to contradict this interpretation. In fact, on the basis of preliminary palynological investigations, Bujak (personal commun., 1985) believes that the top of the middle Miocene is at 3,120 feet. Much of the "missing section" may be the result of the diagenetic loss of the opaline silica of diatom frustules (see discussion in the Lithostratigraphy and Seismic Stratigraphy chapter).

Several distinctive foraminiferal species previously reported from the Miocene of Sakhalin Island, U.S.S.R., are present in the well at 3,630 feet. The strata from which these forms were reported initially were considered to be late Miocene in age (Voloshinova and others, 1970). More recently, these strata were assigned to the middle Miocene (Serova, 1976; Menner and others 1977; Gladenkov, 1977). The age determinations of these units are still unsettled, and it is quite possible that they may prove to be older than middle Miocene (L. Marincovich, personal commun., 1983).

The late Miocene, defined on the basis of siliceous microfossil assemblages recovered from sidewall cores over the interval from 2,639 to 3,464 feet, is recognized by the lowest continuous occurrence of Melosira sulcata; the lowest occurrences of Thalassiosira zabelinae, Thalassiosira convexa aspinosa, Pseudopyxilla americana, and Ebriopsis antiqua antiqua; the highest occurrences of Coscinodiscus temperei, Coscinodiscus vetustissimus, and Goniothecum tenue; and the ubiquitous presence of Actinocyclus ingens.

The interval from 3,464 to 4,493 feet is early Miocene in age on the basis of the lowest occurrences of Thalassionema nitzschioides, Stephanopyxis turris, Stephanopyxis schenckii, and Actinocyclus ingens.

The Miocene foraminiferal fauna first encountered at 3,630 feet is characterized by Porosorotalia clarki, Elphidiella katangliensis, Elphidiella cf. E. tenera, Elphidiella cf. E. crassorugosa, Elphidiella cf. E. nagaoi, Cribroelphidium cf. C. vulgare, Cribroelphidium cf. C. paromaense, Cribroelphidium crassum, Ellipsoglandulina cf. E. subobesa, Pseudoglandulina sp., Glandulina cf. G. japonica, Buccella frigida, Buccella aff. B. mansfieldi, Buliminella cf. B. curta, and Pyrgo williamsoni.

The very sparse ostracode fauna in this interval consists of pyritized molds, carapace fragments, and rare juvenile cytherideids.

The terrestrial palynoflora over this interval is quite similar to that of the Pliocene section. New elements include Ulmipollenites sp., Tiliaepollenites sp., Juglanspollinites sp., Pterocaryapollenites sp., and Bosiduvalia sp.

The dinoflagellate assemblage includes Spiniferites cingulatus, Spiniferites cf. S. crassipellis, Spiniferites cf. S. incertus, Impagidinium spp., Lejeunia spp., and Tuberculodinium vancampoae. Although the latter species is often considered diagnostic of the Miocene, it also occurs in Oligocene strata in the Bering Sea area and in younger strata elsewhere. Overall, both the spore-pollen and dinoflagellate assemblages suggest a Miocene age for this interval.

Environment

Evidence from all of the microfossil groups suggests deposition in sublittoral to middle shelf (300 feet) depths. Paleotemperatures were colder during the late Miocene than in the generally temperate early Miocene.

Oligocene

The interval from 4,740 to 8,600 feet is late Oligocene in age; the interval from 8,600 to 9,690 feet represents the early Oligocene section. The base of the Oligocene is somewhat arbitrary. The unconformable boundary between the early and late Oligocene (8,600 feet) is placed at the top of seismic horizon C, which is also the boundary between lithologic zones To-2 and To-3. However, a single specimen of the pollen Saxonipollis saxonicus at 7,950 feet, if in place, suggests that the early Oligocene may be somewhat higher than 8,600 feet, as does the presence of a specimen of the dinoflagellate Phthanoperidinium sp. from a conventional core at 7,937.7 feet (J. Bujak, personal commun., 1985). The top of the

Oligocene is marked by the lowest occurrence of several species of the dinoflagellate Impagidinium and the highest occurrence of Heteraulacysta campanula (J. Bujak, personal commun., 1985). The previously assigned top of the Oligocene section (Turner and others, 1985a) was placed at the highest occurrence of the dinoflagellate Achomosphaera aff. A. alcicornu. According to Hideyo Haga (Anderson, Warren and Associates, 1980), this species has been previously recorded in Oligocene strata in western Alaska. Achomosphaera alcicornu ranges from middle Eocene to middle Miocene in Europe and from late Paleocene through the Eocene in eastern Canada. The "old top" of 4,493 feet (from a sidewall core) may have been based on a reworked specimen or mudcake-contamination from downhole. It is also possible that 4,493 feet is the actual top, although the "new top" is supported by better paleontological evidence and fits the lithologic, well log, and seismic data better. Other dinoflagellates present include Tenua cf. T. decorata, Systematophora placacantha (early Eocene through late Miocene), and Distatodinium ellipticum (middle Eocene through early Oligocene), and several species of Millioudodinium. These all tend to support to an Oligocene age for the interval.

The calcareous nannoplankton recovered from the well are rare, poorly preserved, and on the whole relatively nondiagnostic. None are present above 5,100 feet. The interval from 5,101 to 10,590 feet is characterized by sporadic appearances of the long-ranging species Braarudosphaera bigelowi associated with rare coccoliths and placoliths of a small, somewhat problematical form with affinities to species in the Coccolithus miopelagicus plexus. These forms suggest a middle Miocene to late Oligocene age. Braarudosphaera bigelowi is often present in times characterized by geologic crises (Prothero, 1985). The presence of Thoracosphaera heimi at 9,150 feet suggests an age within the Sphenolithus ciperoensis zone. The lower part of this zone correlates with the NP 24 zone of Martini (1971), the base of which is late early Oligocene. This somewhat scant evidence lends support to the subdivision of the Oligocene section at seismic horizon C, our "mid"-Oligocene unconformity.

The foraminiferal assemblage supports an Oligocene age, although a number of the species present range up into the Miocene and down into the Eocene. The upper part of the interval (4,493 to 5,400 feet) is characterized by a fauna that contains dominantly shallow-water forms such as Elphidiella katangliensis, Elphidiella nagaoi, Elphidium spp., Cribroelphidium spp., Buccella frigida, Miliammina fusca, Rotalia cf. R. katangliensis, Rotalia japonica, and Rotalia japonica varianta. A deeper water assemblage, present from 5,400 to 9,690 feet, contains most of the above listed species as well as Psammosphaera carnata, Ammodiscus tenuis, Ammodiscus sakhalinicus, Libusella laevigata, Martinottiella cf. M. communis, Martinottiella bradyana, Hippocrepinella variabilis, Haplophragmoides spp., Haplophragmoides tortuosus, Gaudryina quadrangularis, Plectina sp., Dorothia sp., Rhabdamminina aspera, Reophax spp., Bathysiphon edurus, Bathysiphon sp., Tritaxilina aff. T. colei, Pullenia sp., Cyclammina cf. *C. tumiensis*, *Cyclammina* cf. *C. pacifica*, *Cyclammina* sp., *Eponides* cf. *E. dorfi*, *Eponides* cf. *E. gaviotaensis*, *Pseudoglandulina nallpeensis*, *Sigmomorphina suspecta*, *Sigmoidella pacifica*, *Fissurina marginata*, *Trichyohyalus bartletti*, *Silicosigmoilina* sp., *Buccella mansfieldi*, *Porosorotalia clarki*, *Elphidiella* cf. *E. californica*, *Elphidiella* cf. *E. problematica*, *Globobulimina* sp., *Robulus* cf. *R. midwayensis*, *Lagena laevis*, *Quinqueloculina sawanensis*, *Quinqueloculina sachalinica*, *Ellipsoglandulina subobesa*, *Buliminella subfusiformis*, and several species of *Caucasina*.

The presence of *Caucasina* is significant. *Caucasina schwageri* (highest occurrence at 6,570 feet), *Caucasina eocenica kamchatica* (highest occurrence at 6,960 feet), and *Caucasina bullata* (highest occurrence at 8,640 feet) characterize the *Caucasina eocenica kamchatica* Zone in the Ilpinsky and Kamchatka Peninsulas in the U.S.S.R. This zone is thought by Serova (1976) to define the Eocene-Oligocene boundary. Microfossil evidence obtained from the Norton Basin COST No. 1 well, however, indicates that the aforementioned species of *Caucasina* range into Oligocene time.

The sparse ostracode fauna in this interval (chiefly between 6,930 and 9,450 feet) is characterized by *Acanthocythereis* cf. *A.* sp. B, *Krithe* sp. B, "*Robertsonites*" sp. C, *Palmenella* sp. A, *Cytherura* sp. B, *Leguminocythereis* sp. A, ?*Australimoosella* sp. B, *Cytheropteron* sp. A, *Schuleridea* sp. A, and several unknown genera (E. Brouwers, written commun., 1985). By and large, these specimens are representatives of taxa that range from late Eocene to early Miocene, although some extend back into the Cretaceous. The systematics of most of the taxa present are imperfectly understood even at the generic level. However, many of the genera present exhibit morphological trends in the Neogene that are quite distinct from those in the Paleogene. Of the ostracodes recovered from lithologic zones To-2 and To-3 that exhibit such trends, all are characterized by Paleogene morphologies, particularly "*Robertsonites*", *Acanthocythereis*, and *Leguminocythereis*. This evidence tends to support an Oligocene age for this section. In addition, the presence of *Schuleridea* at 9,450 feet suggests an earlier Tertiary age than do the other taxa (E. Brouwers, written commun., 1985), which, taken in conjunction with the nannoplankton evidence, bolsters the placement of lithologic zone To-3 in the early Oligocene.

Environment

The Oligocene section of the COST No. 1 well is dominantly marine in aspect. A transitional, nearshore, coal-bearing section is present between 4,740 and 4,980 feet. The interval from 4,980 to 5,400 feet is inner to middle neritic and represents a shoaling event transitional between the upper, nearshore marine section and the deep-water section below 5,400 feet. Outer neritic to upper bathyal depths (600 to 1,500 feet) prevailed over the interval from 5,400 to 9,690 feet. The most diverse deep-water microfossil assemblages are present between 8,130 and 9,690 feet. The terrestrially derived spore-pollen assemblage indicates that warm-temperate climatic conditions prevailed during most of Oligocene time.

Oligocene or Older (Probable Eocene)

Microfossil recovery and preservation from 9,690 to 12,235 feet was quite poor. Most of the rare foraminiferal occurrences appear to represent caved material. Most of the in situ palynomorphs are of terrestrial origin. Abundant plant material is disseminated through the massive sandstone units and as subparallel partings. Mica flakes and plant material are common in the fine-grained laminae. The age, boundaries, and environment have not yet been unequivocally determined.

Jonathan Bujak (personal commun., 1985) indicated that he had recovered a relatively rich marine microflora from this section of the well. Unfortunately, the samples he had at the time were too widely scattered to allow the picking of a definitive top. Nevertheless, the preliminary reinvestigation yielded a late Eocene age from a sample at 12,150 feet. This age is based on the presence of the dinoflagellates *Trinovantedinium boreale* and *Hystrichokolpoma salacium*, and to some extent follows the zonation Bujak (1984) erected for the Bering Sea from DSDP leg 19 core data. Although the new *Trinovantedinium boreale* concurrent range zone may be valid, it is at variance with calcareous nannoplankton data (Worsley, 1973) that suggest an early Oligocene age for the same Bering Sea cores. Bujak (personal commun., 1985) now believes that *Trinovantedinium boreale* ranges into the early Oligocene. Much of the uncertainty will probably be eliminated when the restudy of this interval is completed.

It is probable that this section is in part equivalent to the late and middle Eocene sections of the Norton Basin COST No. 2 well. Sedimentary features such as graded bedding and flame structures seen in cores 8 and 9 (11,960 to 11,988 and 12,071 to 12,091 feet) suggest deposition by turbidity currents. Bioturbation is neither extensive nor diagnostic; the infrequent burrows present in the massive sandstone units cannot be unequivocally related to a particular ichnofacies. However, rare traces observed on bedding planes in the laminated sequences of core 8 resemble to some degree the ichnogenus *Planolites* and the "scribbling grazing traces" of a trace fossil assemblage typical of distal turbidites. The dinocyst assemblage at 12,150 feet tends to rule out a lacustrine origin for this section.

Eocene or Older (Possible Paleocene)

No age diagnostic microfossils were recovered from the interval between 12,235 and 12,545 feet. Rare, poorly preserved spores and pollen are present. The 310-foot-thick section, bounded above and below by unconformities, appears to be roughly correlative with a much thicker coal-bearing sequence in the nearby Norton Basin COST No. 2 well. Helwig and others (1984) suggest that this section is, at least in part, Paleocene in age.

Environment

The presence of terrestrial spores and pollen in association with abundant coal indicates that the sediments are continental (fluvial and paludal) in nature. The paleoclimate was probably tropical to subtropical.

Metamorphic Basement

The No. 1 well penetrated a 2,135-foot-thick section of cataclastically deformed pelitic and psammitic metasedimentary rocks of undetermined age. Several lines of evidence suggest that these rocks may be related to rocks exposed in the York Mountains in the western part of the Seward Peninsula that are considered to be Precambrian to Paleozoic (Sainsbury and others, 1970; A. Till, J. Dumoulin, personal commun., 1985).

COST NO. 2 WELL

Pleistocene

The interval from 450 to 1,320 feet is considered to be Pleistocene in age on the basis of a foraminiferal fauna characterized by *Elphidium clavatum*, *Elphidium bartletti*, *Protoelphidium orbiculare*, *Elphidiella gorbunovi*, *Elphidiella oregonense*, *Elphidiella hannai*, *Buccella frigida*, and *Quinqueloculina akneriana*.

Rare, poorly preserved and broken ostracodes assignable to *Paracyprideis pseudopunctillata*, "*Acanthocythereis*" *dunelmensis*, *Heterocyprideis sorbyana*, and *Rabilimis septentrionalis* substantiate a Pleistocene age.

The diatom assemblage is quite sparse, but the presence of *Melosira sulcata* to some degree supports a Pleistocene age. Spores and pollen are also rare, but an assemblage composed of *Sphagnumsporites* spp., *Alnipollenites* sp., and Betulaceae and Compositae (*Helianthus* type) is consistent with a Pleistocene age. No calcareous nannoplankton or radiolarians were recovered in this interval.

Environment

The microfossil assemblage indicates that the Pleistocene sediments were deposited in cold water at inner neritic depths (0 to 60 feet). Salinity varied from normal marine to brackish.

Pliocene

The interval from 1,320 to 2,580 feet represents the Pliocene section of the well. The siliceous microfossil zonation utilized hereafter follows that of Koizumi (1973), Schrader (1973), and Barron (1980). The Pliocene section can be only provisionally further subdivided owing to the poorly known biostratigraphy of the area and to complications caused by extensive reworking and downhole sample contamination.

The late Pliocene (1,320 to 1,846 feet) is defined by the highest occurrences of the diatoms *Coscinodiscus marginatus fossilis*, *Coscinodiscus pustulatus*, *Stephanopyxis horridus*, and *Thalassiosira zabelinae*. Rare specimens of *Denticulopsis kamtschatica* recovered from a sidewall core at 1,846 feet mark the top of the middle Pliocene. The base of this interval is tentatively placed at 2,228 feet on the basis of the highest occurrence of the early Pliocene forms *Cosmiodiscus insignis* and *Thalassiosira punctata*. The early Pliocene section (2,228 to 2,580 feet) is based on the highest occurrences of the aforementioned diatom species and an assemblage characterized by *Coscinodiscus temperei* and the silicoflagellate *Ebriopsis antiqua*.

The terrestrial palynoflora contains relatively abundant specimens of *Alnipollenites* sp., *Osmundacites* sp., and rare to frequent Betulaceae, Polypodiaceae, Polemoniaceae, Compositae, and Malvaceae.

The marine component of the Pliocene palynoflora includes the dinoflagellates *Lejeunia* spp., *Spiniferites* spp., and *Cannosphaeropsis* aff. *C*. sp. A Williams and Brideaux 1975. The highest occurrence of the latter species, 2,310 feet, is considered to be a possible Miocene marker by Biostratigraphics (1982) on the basis of the occurrence of *Cannosphaeropsis* sp. A Williams and Brideaux 1975 in the Miocene of eastern Canada. They also identify a Tasmanaceae zonule between 2,040 and 2,670 feet that they consider to be Pliocene to Miocene in age. The No. 2 well was recently reprocessed and reexamined utilizing fluorescence microscopy. This analysis yielded abundant specimens of the algal cyst *Leisophaeridia* and the brackish-water dinoflagellate *Peridinium* sp. B (J. Bujak, personal commun., 1985) and tends to support a Pliocene age.

The foraminiferal fauna contains all of the species present in the overlying Pleistocene section as well as specimens of *Pseudopolymorphina* sp., *Dentalina* sp., *Quinqueloculina seminulum*, *Globobulimina* sp., *Elphidiella sibirica*, *Elphidiella* cf. *E*. *brunescens*, *Elphidium incertum*, *Cassidulina* cf. *C*. *minuta*, *Pullenia* sp., and *Oolina melo*.

Environment

Deposition took place at inner neritic depths in a cold-water environment characterized by fluctuating salinities. The cheilostome bryozoan fragments recovered include both encrusting and erect colonies. The presence of cellariiform and catenicelliform zoarial types (erect with flexible internodes) suggests a depositional environment characterized by moderately strong currents and a relatively high sedimentation rate. Strongly stenohaline forms such as echinoids and ophiuroids are present throughout the interval but are neither diverse nor numerous.

Miocene

The interval from 2,580 to 3,524 feet is Miocene in age. The section is subdivided into late and early Miocene on the basis of siliceous microfossil assemblages. The late Miocene (2,580 to 3,120 feet) is based on the lowest occurrence of Thalassiosira zabelinae and the highest occurrences of Rhaphoneis surirella and Goniothecum tenue associated with Coscinodiscus vetustissimus, and Coscinodiscus temperei. No in situ middle Miocene forms are present and it is possible that this time is represented by a hiatus. The early Miocene (3,120 to 3,524 feet) is characterized by Thalassiothrix longissima, Rhaphoneis miocenica, Rhaphoneis cf. R. fossilis, and Actinocyclus ingens.

The spore-pollen assemblage is quite similar to that identified in the overlying Pliocene section with the addition of the pollen Tsuga veridifluminipites (J. Bujak, personal commun., 1985). The dinoflagellate assemblage contains Lejeunia paratenella, Lejeunia spp., Spiniferites cingulatus, Spiniferites ramosus, Tuberculodinium vancampoae, and Hystrichosphaeropsis sp. The dinocyst stratigraphy supports that derived from diatoms and silicoflagellates.

The foraminiferal assemblage is similar to the Elphidium-Elphidiella-dominated faunas seen higher in the well and contains all of the same species. New taxa include Cribroelphidium crassum, Quinqueloculina sachalinica, Dentalina aff. D. nasuta, Elphidiella simplex, Elphidiella katangliensis, Pseudoglandulina sp., Pseudoglandulina aff. P. nallpeensis, Ellipsoglandulina cf. E. subobesa, Sigmoidella pacifica, and Porosorotalia clarki. This assemblage, here considered to represent middle to early Miocene, is best developed from 3,200 to 3,540 feet. Species such as Elphidiella katangliensis, Porosorotalia clarki, and Quinqueloculina sachalinica were described from deposits of supposed late Miocene age on Sakhalin Island, U.S.S.R. (Voloshinova, and others, 1970). Subsequent stratigraphic revisions (Serova, 1976; Gladenkov, 1977; Menner and others, 1977) place these strata in the middle Miocene and it is quite possible that they may prove to be older. Several of the species appear to range through the Oligocene section and may extend into the Eocene as well.

Environment

The late Miocene interval was deposited in inner to middle neritic depths in a cold climate. The early Miocene interval represents a shallower (inner neritic) and warmer (warm-temperate?) environment.

Oligocene

The interval from 3,524 to 6,850 feet is late Oligocene in age; the interval from 6,850 to 10,160 feet is early Oligocene. The palynofloras over this interval are abundant, diverse, and relatively diagnostic. The uppermost coal-bearing portion of the sequence (3,524 to 3,930 feet) is characterized by an assemblage composed of Alnipollenites sp., Betulaceae, and rare to frequent Ulmipollenites sp., Pterocaryapollenites sp., and Momipites sp. From 3,930 to 6,520 feet, the spore-pollen and dinocyst assemblages are much more diverse and age diagnostic. Additional terrestrial palynomorphs include common Caryapollenites sp., Juglanspollenites sp., Tiliaepollenites sp., and less abundant specimens of Faguspollenites sp., Ilexpollenites sp., and Liquidamberpollenites sp. The dinocyst assemblage contains Tenua cf. T. decorata, Distatodinium ellipticum, Deflandrea sp., and Paralecanicella indentata. A reprocessing and reexamination of the cuttings from 3,750 to 4,910 feet yielded a rich, relatively long-ranging dinoflagellate assemblage containing Lingulodinium machaerophorum, Systematophara ancyrea, Oliogsphaeridium centrocarpum, and Reticulatosphaera stellata (J. Bujak, personal commun., 1985).

Below 6,890 feet, the presence of an abundant palynoflora characterized by the heath pollen Ericipites indicates an early Oligocene age (J. Bujak, personal commun., 1985). The unconformable boundary between early and late Oligocene is placed at 6,850 feet on the basis of this paleontological evidence as well as well log, lithological, and seismic data. Fungal palynomorphs, particularly species of Striadiporites, are an increasingly important floral element below 7,900 feet. Biostratigraphics (1982) suggests that some of the fungal taxa recovered below 9,300 feet may have Eocene affinities.

Calcareous nannoplankton are represented in the No. 2 well by a single, incomplete placolith of Coccolithus pelagicus from 7,250 to 7,340 feet. The morphology of the specimen suggests that it is older than Miocene.

The foraminiferal assemblage contains Elphidiella katangliensis, Elphidiella cf. E. problematica, Elphidiella cf. E. tenera, Elphidiella cf. E. californica, Cribroelphidium cf. C. crassum, Cribroelphidium cf. C. vulgare, Buccella mansfieldi, Porosorotalia clarki, Rotalia japonica, Rotalia japonica varianta, Quinqueloculina sp., Miliamnia fusca, Buliminella curta, Caucasina eocenica kamchatica, Caucasina bullata, Caucasina schwageri, Reophax spp., Plectina sp., Haplophragmoides spp., Cyclammina cf. C. pacifica, Sigmomorphina suspecta, Sigmoidella pacifica, Pseudoglandulina inflata, Martinottiella sp., Pyrgo williamsoni, Trichyohyalus bartletti, Saccammina sp., and Psammosphaera carnata.

Shallow-water forms such as Elphidiella katangliensis and Porosorotalia clarki dominate over much of the interval. Shelf forms such as Caucasina and deeper water forms such as Cyclammina are far less common. The Caucasina eocenica kamchatica Zone is restricted to the late Eocene in the U.S.S.R. and defines the Eocene-Oligocene boundary on the Kamchatka and Ilpinsky Peninsulas (Serova, 1976). However, the several species of Caucasina recovered from the No. 2 well range well up into the Oligocene.

Environment

The climate of the Oligocene was at least warm-temperate and the bathymetry fluctuated from possible outer neritic to continental. Coal-bearing strata are present in the upper part of the section from 3,524 to 4,570 feet. This continental to transitional sequence contains a predominantly inner neritic section from 3,930 to 4,250 feet containing shallow-water foraminifers that are common in hyposaline environments. Inner to middle neritic conditions prevailed from 4,570 to 5,150 feet. Middle to outer neritic conditions obtained from 5,150 to 6,770 feet. Although rare, isolated specimens of Cyclammina cf. C. pacifica and Martinottiella sp. are present, they are not associated with a definitive deep-water faunal assemblage. The presence of a dominantly shallow-water fauna and minor amounts of coal in drill cuttings suggest that outer shelf-upper slope depositional depths were not obtained. Below 6,770 feet, the environment is characterized by numerous fluctuations from continental and transitional to inner neritic. There are numerous thin coal seams, as well as coal beds as much as 5 feet thick, between 6,850 and 8,450 feet. There is some indication that the unconformity at 6,850 feet is bracketed by middle neritic pulses. Overall, the interval from 6,770 to 10,160 feet appears to represent deltaic to inner shelf paralic deposits.

Eocene

The interval from 10,160 to 12,700 feet is Eocene in age. A suite of distinctive and diagnostic fungal palynomorphs, including Striadiporites sp., Ctenosporites wolfei, Dicellaesporites sp. A Rouse 1977, and Pesavis tagluensis is present. Published ranges suggest that these species generally occur earlier in the Canadian Arctic than in British Columbia. The known ranges in the Norton Sound area are somewhat intermediate. On the basis of fungal palynomorph ranges, the interval above 11,960 feet is no older than early to middle Eocene and may be late Eocene in age. The spore-pollen assemblage is essentially the same as that in the overlying early Oligocene. Marine palynomorphs are rare in the samples and most were probably caved.

Foraminifera are quite sparse over this entire interval and occur most frequently between 10,160 and 12,000 feet. Many are probably caved from uphole. The assemblage contains rare specimens of Porosorotalia clarki, Elphidium spp., Elphidiella katangliensis, Elphidiella cf. E. californica, Psammosphaera cf. P. carnata, Saccammina sp., Ammodiscus sp., Loxostomum sp., and fragmentary polymorphinids.

A dermal scute from a juvenile sturgeon was recovered from cuttings at 10,160 feet. Comparisons with material in the fossil collections of the University of California at Berkeley indicate that it is a species of Acipenser that has affinities with an unnamed species from the early Tertiary of Montana (Patrick McClellan, personal commun., 1983).

Environment

The Eocene depositional environments fluctuated between continental (predominantly fluvial and paludal), transitional (marshes, bays, and estuaries), and inner neritic. Depositional environments in the upper part of the section (10,160 to 12,000 feet) may have occasionally been as deep as middle neritic. Thick coal beds are not present above 12,700 feet. The presence of euryhaline Foraminifera associated with terrestrial pollen and fungal palynomorphs, pelecypod shards, sturgeon scutes, and scattered coal suggests a transitional environment. Although sturgeon are anadromous, the juveniles commonly inhabit sloughs near river mouths. The interval from about 12,000 to 12,700 feet (lithologic zone Te-2) is dominantly continental in aspect. The climate in the Eocene was at least subtropical.

Eocene or Older (Possible Paleocene)

The interval from 12,700 to 14,460 feet is Eocene or older. Helwig and others (1984) consider this section to be in part Paleocene in age, probably on the basis of palynological data. Palynomorph recovery from cuttings is poor in this part of the well and the specimens are poorly preserved. Seismic and geochemical investigations indicate an unconformity at approximately 11,960 feet. Another unconformity is placed at 12,700 feet on the basis of lithologic and dipmeter criteria.

Eocene fungal palynomorphs were recovered from sidewall cores in this interval but not from conventional cores. This leaves open the possibility that the sidewall cores may have sampled contaminated mud cake.

Environment

The thick coal sequences indicate a continental environment. The paleoclimate was probably no cooler than that of the overlying Eocene section.

Metamorphic Basement

The interval from 14,460 to 14,889 feet consists of phyllite, quartzite, and marble similar to rocks of probable Paleozoic age exposed on the Seward Peninsula. No in situ fossils were recovered from this part of the well.

CORRELATION

The strata identified in the Norton Sound COST No. 1 and No. 2 wells can be biostratigraphically correlated (fig. 12) despite the fact that they are located approximately 49 nautical miles apart and were deposited in geographically distinct and tectonically independent subbasins characterized by different depositional environments (figs. 10 and 11). The depositional environments of the St. Lawrence subbasin, the site of the No. 1 well, are far more marine than those of the Stuart subbasin, the site of the No. 2 well. Nevertheless, similarities between the two wells are more pronounced than differences, particularly in the marine sequences seen above seismic horizon C (figs. 13 and 14). Below this horizon, which is the unconformable boundary between early and late Oligocene, correlations are somewhat more difficult because the nonmarine and transitional strata of the No. 2 well must be compared with the predominantly shelf and slope deposits of the No. 1 well. With the exception of the Eocene or older (possible Paleocene) section, which is far thicker in the No. 2 well, time-equivalent units are of roughly equivalent thicknesses in the two wells. Sedimentation rates were not calculated because of the tentative nature of some of the biostratigraphic boundaries, particularly below 9,660 feet in the No. 1 well.

Pleistocene

The first sample in each COST well is Pleistocene in age, although it is probable that a thin Holocene section was penetrated. Sample quality is poor. The base of the Pleistocene was placed at 1,320 feet in both wells. Microfossil assemblages, lithology, and depositional environments are essentially identical in both wells. Shallow seismic evidence indicates that there may be a slight unconformity between the Pliocene and the Pleistocene sedimentary sections.

Pliocene

The top of the Pliocene is at 1,320 feet in each well, the base of the Pliocene is at 2,639 feet in the No. 1 well and 2,580 feet in the No. 2 well. The Pliocene was subdivided into early, middle, and late in both wells on the basis of siliceous microfossil assemblages, but the chaotic mixture of reworked and caved forms renders such a subdivision provisional at best. In general, the microfossil assemblages in both wells reflect similar paleo-environments.

Miocene

The top of the Miocene is at 2,639 feet in the No. 1 well and at 2,580 feet in the No. 2 well. There may be a middle Miocene hiatus in both wells, possibly in part correlative with the NH4 hiatus of Barron and Keller (1982). This interval appears to be represented by an unconformity (seismic horizon E) on the basin flanks and a zone of biogenic silica dissolution and diagenesis in the subbasins (see Lithostratigraphy and Seismic Stratigraphy chapter, figs. 13 and 14). The base of the early Miocene is at 4,740 feet in the No. 1 well and at 3,524 feet in the No. 2 well. There may be a middle Miocene top present at 3,120 feet in the No. 1 well (J. Bujak, personal comm., 1985). Microfossil assemblages and lithologies are quite similar in both wells, although there are some indications that deposition was at shallower depths in the No. 2 well and that the Stuart subbasin was subject to greater fresh-water influence.

Oligocene

Strata assigned to the Oligocene epoch account for roughly half of the sedimentary section penetrated by the wells, approximately 5,000 feet in the No. 1 well and 6,644 feet in the No. 2 well. In the No. 1 well, the Oligocene section (4,740 to 9,690 feet) is represented almost entirely by marine deposition, much of it outer shelf and upper slope. By way of contrast, in the Oligocene section of the No. 2 well (3,524 to 10,160 feet) almost half of the sediments are coal bearing and were deposited under transitional, nearshore to nonmarine conditions.

The boundary between the early and late Oligocene in both wells (8,600 feet in the No. 1 well, 6,850 in the No. 2) corresponds to the top of seismic horizon C and the boundary between lithologic zones To-2 and To-3. This unconformity may represent the major "mid"-Oligocene sea level drop (event TO 2.1 of Vail and others, 1977) approximately 30 million years ago. The age of the unconformity is generally corroborated by the available palynological and nannoplankton data.

There is a small but pronounced coal-bearing transitional environment present near the top of the Oligocene section in the No. 1 well (4,740 to 4,980 feet) that is correlative with the coal-bearing strata seen in the No. 2 well at 3,524 to 4,570 feet.

Eocene

Definite late to middle Eocene strata are present from 10,160 to 12,700 feet in the No. 2 well. Some late Eocene palynomorphs were found in the No. 1 well in a sample at 12,150 feet. It is probable that part of the problematic Oligocene or older section (9,690 to 12,235 feet) is correlative with the Eocene section in the No. 2 well.

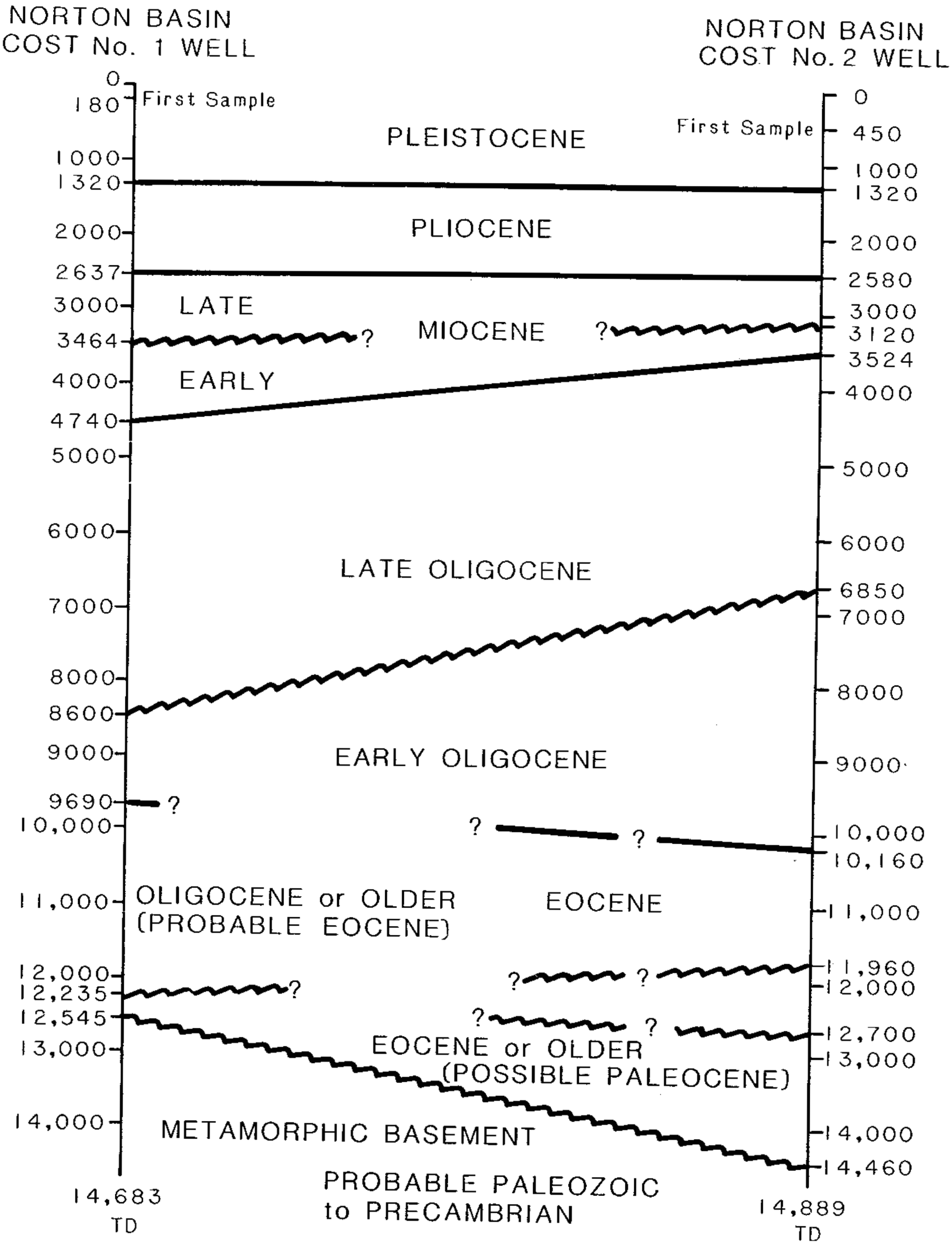


FIGURE 12. **Biostratigraphic correlation of Norton Basin COST wells.**

Eocene or Older (Possible Paleocene)

In both wells, a coal-bearing section unconformably overlies the regional early Cenozoic to late Mesozoic erosional surface (seismic horizon A). This continental section, 310 feet thick in the No. 1 well and 1,760 feet thick in the No. 2 well, is truncated by an unconformity at 12,235 feet in the No. 1 well and at 11,960 feet in the No. 2 well. Because of the variable lithologic character of the strata underlying this surface in two subbasins that are separated by a large positive tectonic element, this unconformity is not characterized by a continuous seismic reflector. Nevertheless, it is reasonable to assume that the unconformities are approximately coeval. Likewise, on the basis of lithology, depositional environment, stratigraphic position, and the similar preservational state of the palynomorphs, it seems likely that the Eocene or older sections in the two wells are in part correlative. Helwig and others (1984) consider this section to be in part Paleocene in age.

Basement Complex (Probable Late Precambrian to Paleozoic)

Both wells penetrated metasedimentary sections below the regional unconformity that marks acoustic basement. The 2,135-foot-thick sequence of cataclastic rocks in the No. 1 well appears quite similar to slate of late Precambrian to early Paleozoic age described from the York Mountains of the Seward Peninsula; the 429 feet of quartzite, phyllite, and marble identified in the No. 2 well appears to be quite similar to metamorphic rocks of probable Paleozoic age described from the central and eastern parts of the Seward Peninsula. At present, it is not possible to more closely relate the metamorphic sections of the two wells on the basis of either age or genesis. Several samples from the No. 1 well were recently reprocessed for acritarchs and chitinozoans but yielded negative results.

5

Lithostratigraphy and Seismic Stratigraphy

The offshore lithostratigraphy of the Norton Basin is based on the integration of well log and lithologic data from the Norton Basin COST No. 1 and No. 2 wells with paleontologic and CDP seismic data. A stratigraphic section of 12,500 to 14,400 feet of Quaternary, Neogene, and Paleogene clastic sediments was penetrated by the Norton Basin COST wells. At both wells, the Tertiary basin fill unconformably overlies a Precambrian to Paleozoic metasedimentary section of slate, schist, quartzite, and marble similar to outcrops on the Seward Peninsula. These metasedimentary rocks are included in the miogeoclinal belt of Fisher and others (1979) and appear to form the basement complex beneath much of Norton Basin.

The Norton Basin is divided into two structural subbasins by a northwest-trending anticlinal structure termed the Yukon horst (Fisher and others, 1982). The COST No. 1 well sampled a stratigraphic section west of the horst in the St. Lawrence subbasin and the COST No. 2 well penetrated a section east of the horst in the Stuart subbasin (fig. 7). Both wells were located on basement lows near subbasin depocenters. Over 16,000 feet of Tertiary sediment is present near the COST well site in the St. Lawrence subbasin and over 24,000 feet is present near the well site in the Stuart subbasin.

The Neogene strata in both subbasins are similar and consist primarily of marine shelf deposits. Paleogene strata penetrated in the COST No. 1 well (St. Lawrence subbasin) are generally finer grained and more marine in character than those encountered in the COST No. 2 well (Stuart subbasin). This sediment size distribution probably reflects the closer proximity of the Stuart subbasin to sediment source areas. Most of the potential reservoir sandstones encountered in the COST No. 2 well represent alluvial, deltaic, and shallow shelf deposits, whereas most of the coeval sandstones in the St. Lawrence subbasin COST No. 1 well appear to be outer shelf to upper slope turbidite deposits.

The strata encountered in the two Norton Basin COST wells are here divided into informal stratigraphic units or lithologic zones that can be correlated on the basis of microfossil assemblages, seismic stratigraphy, lithology, inferred depositional environments, large-scale patterns of regression and transgression, and wireline log petrophysical characteristics (figs. 13 and 14).

Lithologic zones are discussed in the order they were penetrated in the wells. Most depths referred to in this section were measured from the kelly bushings. Minor discrepancies occur between depths given for seismic horizons and depths given for nearly equivalent lithologic and time-stratigraphic boundaries. Those discrepancies not attributable to datum differences (kelly bushing versus sea level) are probably the result of differences in the vertical resolution of seismic, well log, and paleontological techniques.

PLIOCENE AND MIOCENE: LITHOLOGIC ZONE TMP

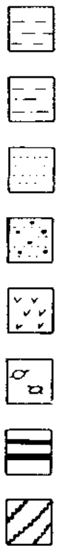
The Neogene section, lithologic zone Tmp, extends from 1,320 to 4,700 feet in the COST No. 1 well, and from 1,320 to 3,524 feet in the COST No. 2 well. The section consists of Miocene and Pliocene diatomites, diatomaceous mudstones, siltstones, and sandstones. In both subbasins, lithologic zone Tmp consists of fine-grained sediments that grade upward into coarser, sandier lithologies. The depositional environment of zone Tmp was largely inner to middle shelf, as indicated by the micro- and macrofossil assemblages and the presence of glauconite.

The Neogene strata of this zone (as well as the overlying Quaternary section in the unlogged portions of the two COST wells) make up seismic sequences I and II (figs. 13 and 14). Sequence I is characterized by flat-lying, parallel, moderate- to high-amplitude, continuous reflections that can be traced throughout the basin. Sequence II reflections are characterized by variable amplitude, moderate to high continuity, and lower frequency than sequence I horizons. The high continuity and parallelism of these reflections suggest that an open marine shelf depositional environment existed over most of the basin.

A somewhat enigmatic reflector, seismic horizon E, separates seismic sequences I and II. At the COST wells, horizon E may represent a change from dominantly terrigenous sediments to sediments with a significant biogenic fraction, a diagenetic zone, an unconformity, or some combination of these features. In both COST wells, horizon E corresponds to the top of a zone marked by the rapid disappearance of abundant siliceous diatom tests, an increase in bulk density and acoustic velocity on well logs (figs. 15 and 16), and high-amplitude, low-frequency seismic reflections. Although these changes could indicate an unconformity, some well data suggest that silica dissolution and redistribution as cement may be a significant contributing factor. The observed physical changes, although relatively abrupt, span an interval of several hundred feet. If an unconformity alone were responsible, a sharp transition would be expected in the well.

The diagenetic conversion of biogenic opaline silica, chiefly the opal-A of diatom tests, to other forms of silica and silica-rich minerals has previously been noted in other Bering Sea wells (Turner and others, 1984). This phase change appears to be primarily a

Lithologic Symbols for Figures 13 and 14



Mudstone or Shale

Siltstone

Sandstone

Conglomerate

Volcanics: Diabase, Basalt and Tuff

Diatoms

Coal

Phyllite, Schist and Marble

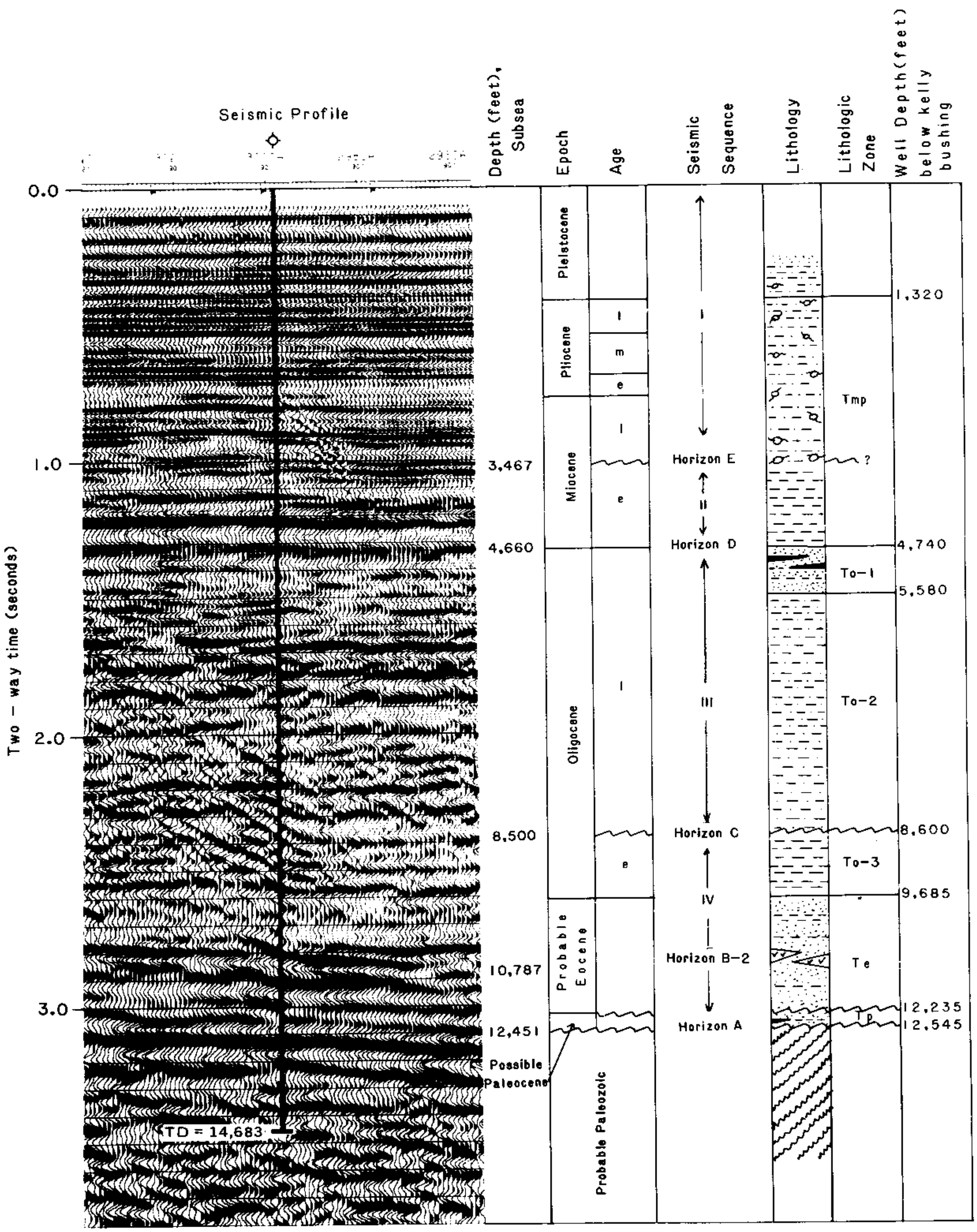


FIGURE 13. **Seismic profile, time-stratigraphic column, seismic sequences, lithology, and lithologic zones of COST No. 1 well, in the St. Lawrence subbasin.**

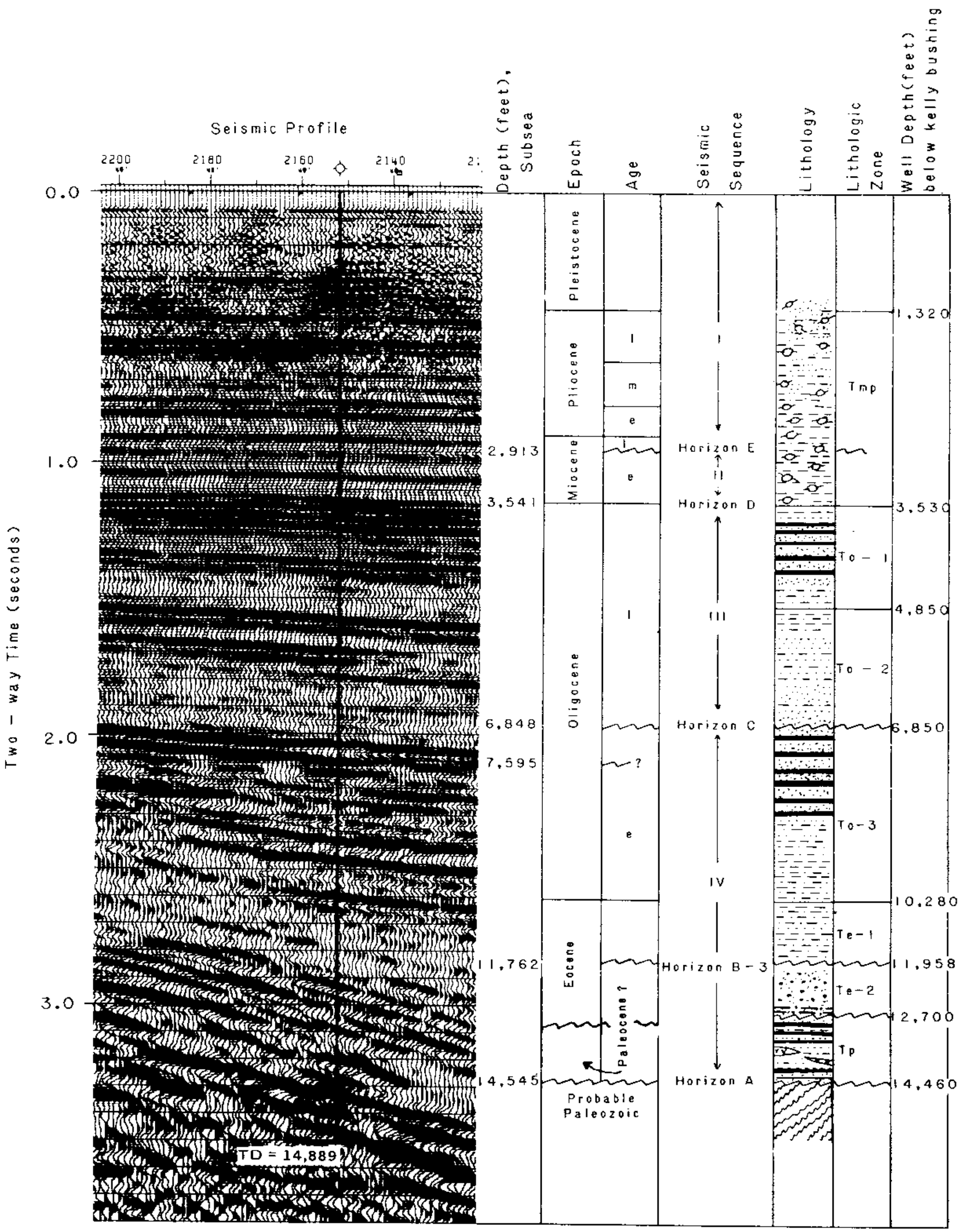


FIGURE 14. **Seismic profile, time-stratigraphic column, seismic sequences, lithology, and lithologic zones of COST No. 2 well, in the Stuart subbasin.**

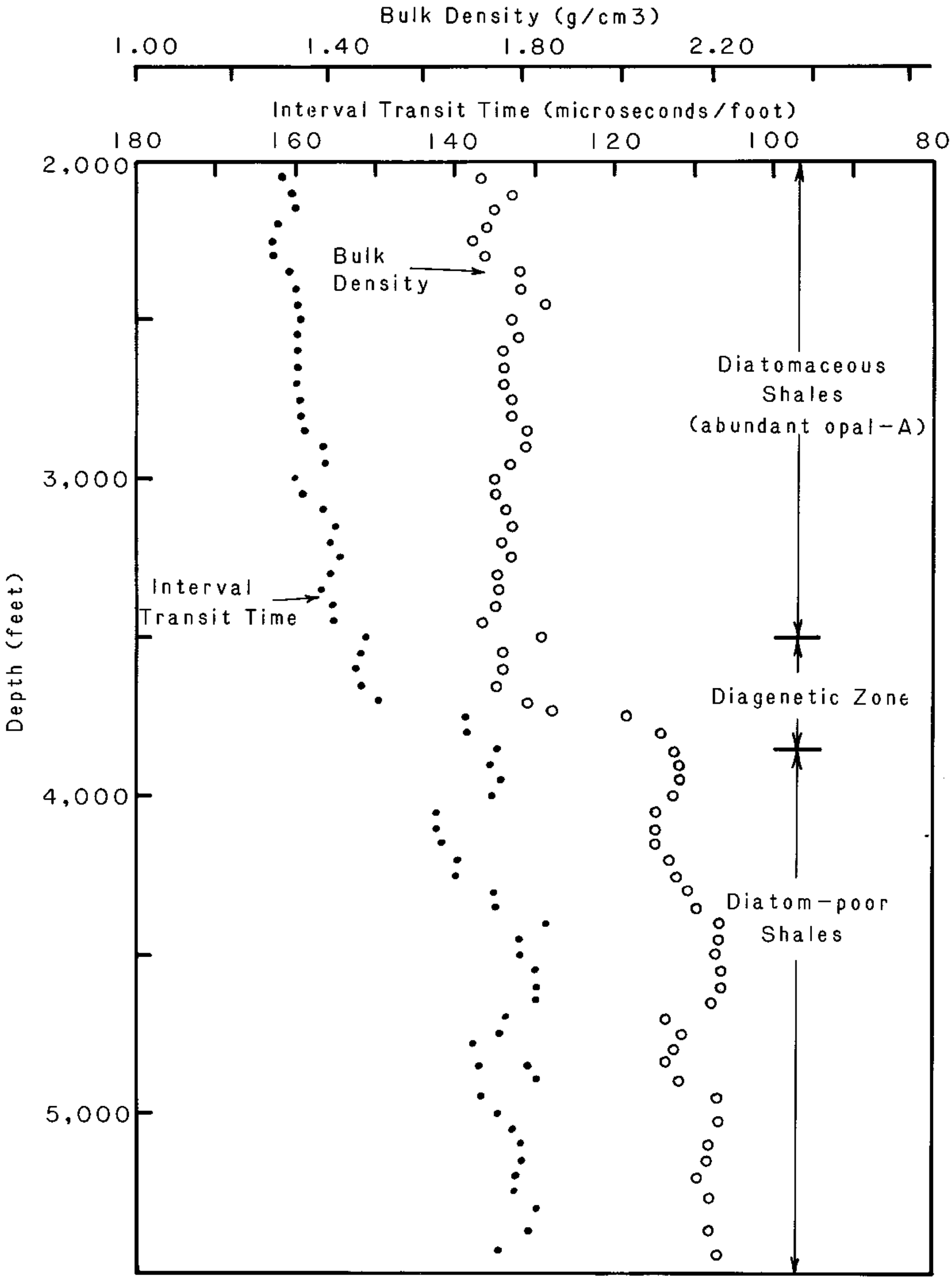


FIGURE 15. **Pattern of decrease in acoustic interval transit time and increase in bulk density for diatomaceous shales and their diagenetic equivalents, Norton Basin COST No. 1 well, St. Lawrence subbasin.**

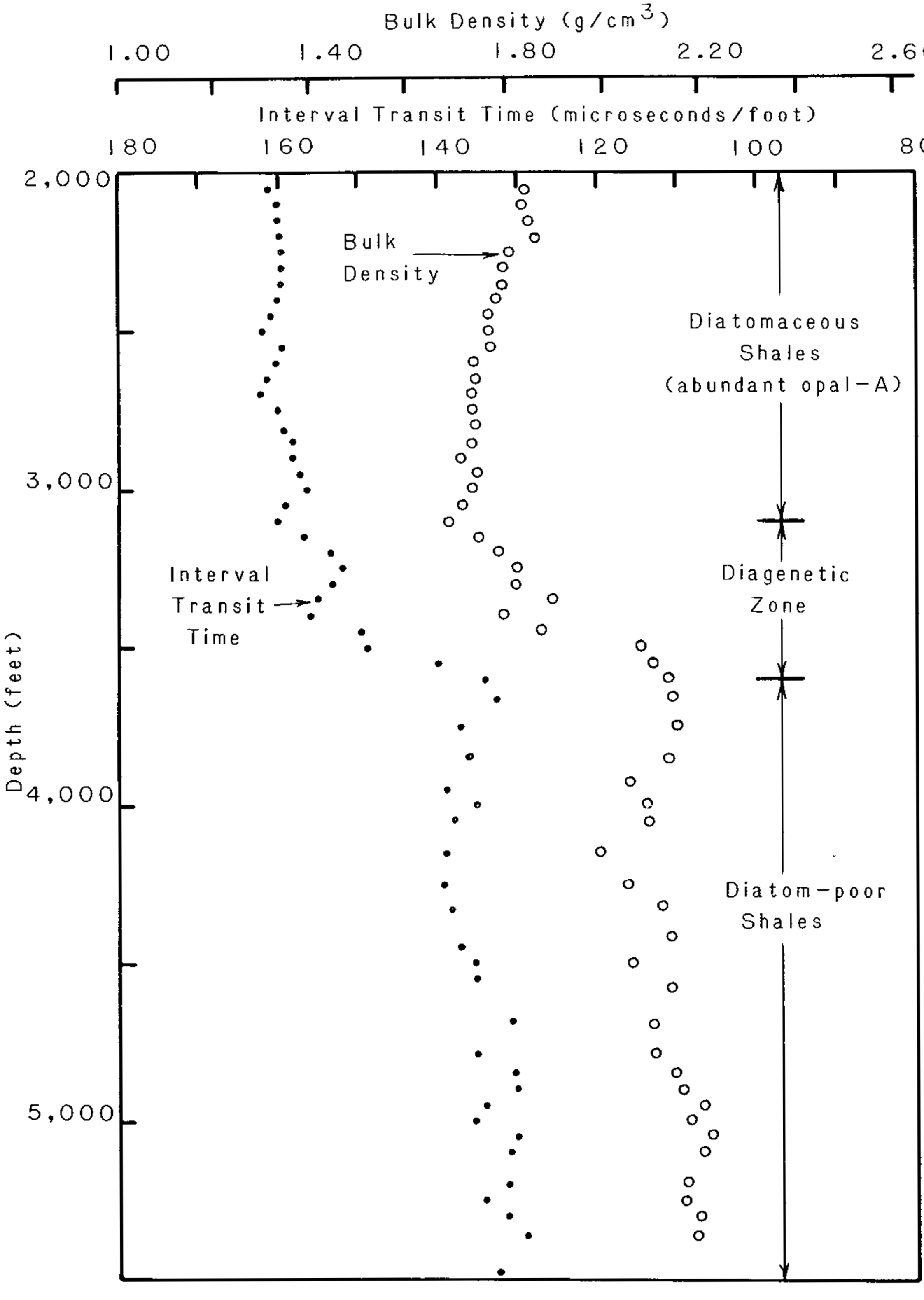


FIGURE 16. Pattern of decrease in acoustic interval transit time and increase in bulk density for diatomaceous shales and their diagenetic equivalents, Norton Basin COST No. 2 well, Stuart subbasin.

function of temperature and requires a range of 95 to 125 °F to initiate large-scale conversion (Hein and others, 1978). Petrophysical changes associated with the transformation of opal-A in diatomaceous sediments include marked increases in compaction, cementation, bulk density, hardness, cohesion, and brittleness. These changes are primarily due to the reprecipitation, recrystallization, and collapse of the biogenic silica fraction (Isaacs and others, 1983; Hein and others, 1978). In both COST wells in the Norton Basin, changes in lithology and diatom abundance, and corresponding wireline log responses, occur at depths that would be within the requisite temperature range to initiate opal-A instability.

In some parts of the Bering Sea, a bottom-simulating reflection (BSR) attributed to a silica diagenetic zone occurs at a depth between 1.0 and 2.0 seconds two-way travel time (Hammond and Gaither, 1983). Fisher and others (1982) suggested that in the Norton Basin (St. Lawrence subbasin), horizon E might represent a BSR. Horizon E consistently produces refracted arrivals, has a lower frequency than adjacent reflections, and, in the central part of the basin, occurs between 1.0 and 1.5 seconds. However, the definitive seismic characteristic of a BSR is that because it mimics the sea floor topography it appears discordant with dipping reflectors. A BSR, if present in the Norton Basin area, is extremely subtle and could not be unequivocally identified on seismic data.

Fisher and others (1982) speculated that terrigenous sediment input into the basin might have diluted the diatom fraction of the sediment to the point that a diagenetic boundary would not be detectable. This does not appear to be the case. The diagenetic zone in the Stuart subbasin (at the COST No. 2 well) spans an interval which includes the upper part of a deltaic sequence in which terrigenous input was high, yet the paleontological and petrophysical changes there and in the St. Lawrence subbasin COST well, where the diagenetic zone spans an interval of fine-grained shelf deposits, are quite similar.

In shallower parts of the Norton Basin, seismic horizon E may coincide with a late Miocene unconformity. The discordant reflections above and below horizon E in these areas suggest the presence of an unconformity. In these structurally shallower areas, horizon E is probably too shallow (above 1.0 second) to be within the necessary temperature range for opal-A transformation to occur. Some interpretative difficulties in deeper parts of the basin, and at the COST wells, may be due to the approximate coincidence of an unconformable stratigraphic surface and a diagenetic boundary. This relationship would probably generate a family of seismic reflections caused in great part by constructive interference. Similar interpretative difficulties were encountered in the Navarin Basin (Turner and others, 1984) and other Bering Sea areas where the zone of biogenic silica diagenesis often generates a strong regional reflector which may obscure structural interpretation of seismic horizons in the shallow subsurface.

Similarities between the diagenetically altered Miocene diatomites of the Bering Sea basins and those of the Monterey Formation, which is an important hydrocarbon source rock and reservoir in California, suggest that seismic sequence II could be a prospective exploration target. If fractured, the siliceous rocks in sequence II could function as a reservoir; if unfractured, the same rocks could serve as a seal for underlying reservoirs.

OLIGOCENE

Strata of probable Oligocene age account for much of the Tertiary section in the Norton Basin. Sedimentary strata of Oligocene age reflect several regressive and transgressive episodes which are considered in the subdivision of these strata into three stratigraphic units designated, from top to bottom, To-1 to To-3.

Lithologic Zone To-1

Zone To-1 (4,700 to 5,580 feet in the COST No. 1 well; 3,524 to 4,850 feet in the COST No. 2 well) is composed of interbedded deltaic to shallow-shelf sandstones, siltstones, mudstones, and coals. In both subbasins, the sequence consists of a lower sandy unit, a middle fine-grained unit of siltstone and mudstone, and an upper sandy unit. The zone consists of an overall regressive sequence that reflects the progradation of deltaic deposits into the subbasins. The fine-grained middle unit probably records a minor transgressive episode which interrupted deltaic progradation.

Sandstones from this zone fall into the feldspathic litharenite category of Folk's classification (1974). Framework grains consist of 45 to 60 percent quartz, 15 to 25 percent feldspar (primarily plagioclase), and 25 to 30 percent lithic fragments. Sandstone compositions from the two subbasins differ primarily in the composition of their lithic components. Lithic fragments in the St. Lawrence subbasin (COST No. 1 well) are composed chiefly of ductile metamorphic grains (mica and quartz-mica schist), whereas in the Stuart subbasin (COST No. 2 well), the lithic clasts include grains of feldspars, carbonates, micas, shale, and schist that were derived from volcanic, metamorphic, and sedimentary source terranes.

Zone To-1 sediments in the Stuart subbasin (COST No. 2 well) contain nearly equal contributions from volcanic, metamorphic, and sedimentary source terranes (AGAT, 1982, D-281-PI,), whereas equivalent sediments deposited in the St. Lawrence subbasin (No. 1 well) were derived from a metamorphic source terrane and reflect only a minor input from volcanic sources (AGAT, 1980, p. 9). This suggests that during Oligocene time, the Stuart subbasin received sediment from two major lithostratigraphic provinces, the miogeoclinal belt and the Okhotsk-Chukotsk volcanic belt. The St. Lawrence subbasin, however, received terrigenous sediment primarily from a single province, the miogeoclinal belt.

Nonmarine deltaic facies are more prevalent in strata of the Stuart subbasin than in the St. Lawrence subbasin. Lithologic zone To-1 in the COST No. 2 well contains a number of relatively thick coal beds. In contrast, the COST No. 1 well contains a more marine facies and has only a few thin, shaley coals near the top of the zone. Sandstone beds in the COST No. 2 well are coarser grained, thicker, and more numerous than those in the COST No. 1 well. Zone To-1 microfossil assemblages indicate a greater freshwater influence in the COST No. 2 well, as compared to the more marine section in the COST No. 1 well.

Lithologic zone To-1 comprises the upper part of seismic sequence III (figs. 13 and 14). Sequence III contains both medium-amplitude, moderately continuous reflections and high-amplitude, discontinuous reflections. These seismic characteristics are often associated with strata formed in marginal marine and fluviodeltaic environments. Seismic sequence III is bounded at the top by seismic horizon D, which is an unconformity mapped at or near the top of the Oligocene section across the Norton Basin (figs. 17 and 18). Horizon D and seismic sequence III are laterally continuous throughout the basin and onlap basement on structural highs. Syndepositional faulting is common in sequence III.

Lithologic Zone To-2

In the COST No. 1 well, zone To-2 extends from 5,580 to 8,600 feet; in the COST No. 2 well, from 4,850 to 6,850 feet. The sediments of lithologic zone To-2 consist of marine mudstones, siltstones, and sandstones. In the St. Lawrence subbasin, the COST No. 1 well penetrated a section of predominantly deepwater marine mudstones, siltstones, and muddy sandstones; in the Stuart subbasin, the COST No. 2 well penetrated an equivalent sequence characterized by shelf sandstones and siltstones. The strata of zone To-2 comprise roughly the lower two-thirds of seismic sequence III (figs. 13 and 14). In the St. Lawrence subbasin, sequence III reflections are more discontinuous and have lower and more variable amplitudes than equivalent strata to the east in the Stuart subbasin. Sequence III reflectors typically onlap underlying strata over pre-existing structures and along basin margins.

Seismic horizon C is mapped near the base of lithologic zone To-2 and represents the unconformable, lower boundary of seismic sequence III (figs. 13 and 14). Horizon C forms the approximately flat summits of horsts in the Norton Basin, which are almost all at about the same depth. Strata above horizon C are laterally continuous between subbasins and over the Yukon horst, whereas strata below this horizon are not. Horizon C may reflect a sea level drop during the "mid"-Oligocene which exposed intrabasin highs to erosion. Erosive truncation of these highs eventually allowed the expansion of more open-marine conditions across the Yukon horst and into the Stuart subbasin.

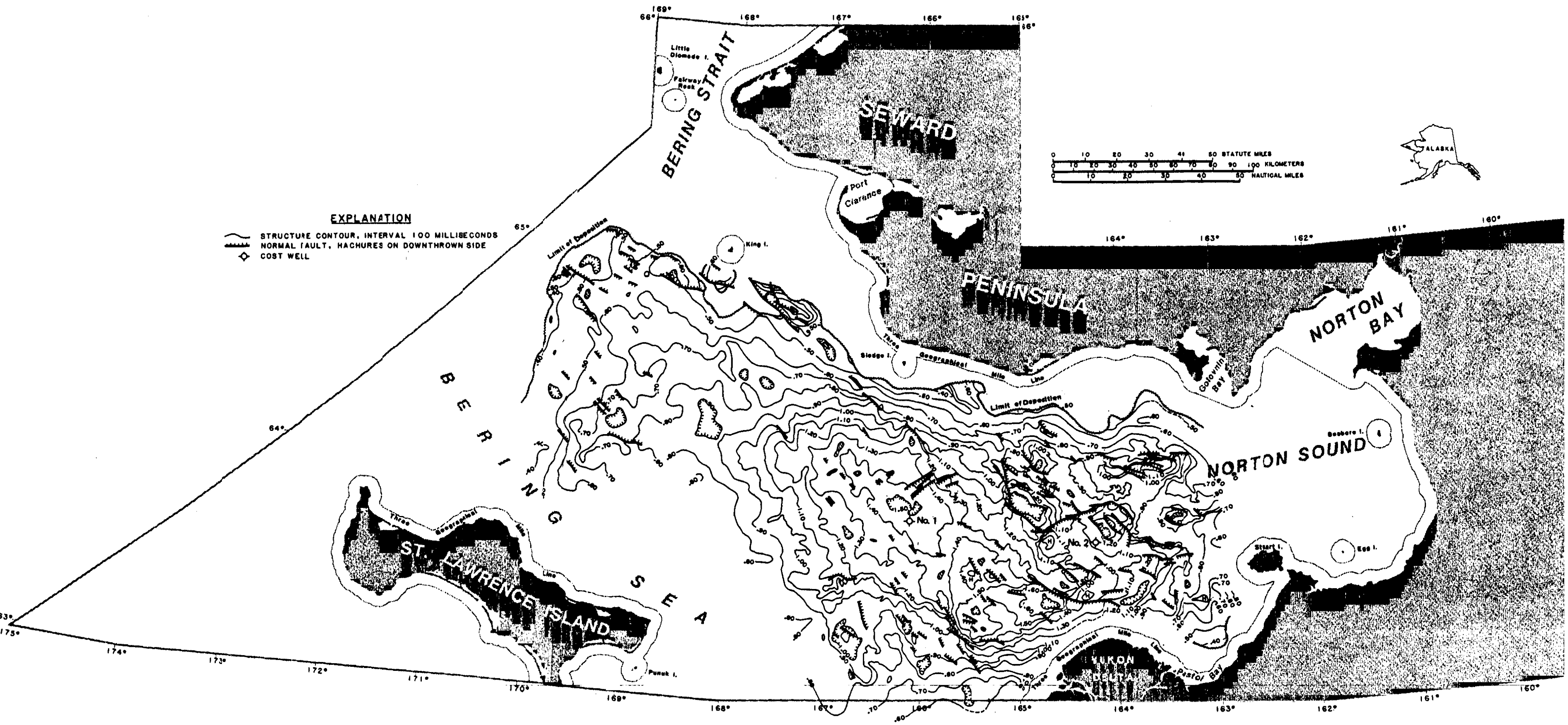


FIGURE 17. Structure contours (in time) on horizon D in Norton Basin. Horizon D represents a stratal surface at or near the top of the Oligocene. Interpretation is based on Western Geophysical Company of America common-depth-point seismic data.

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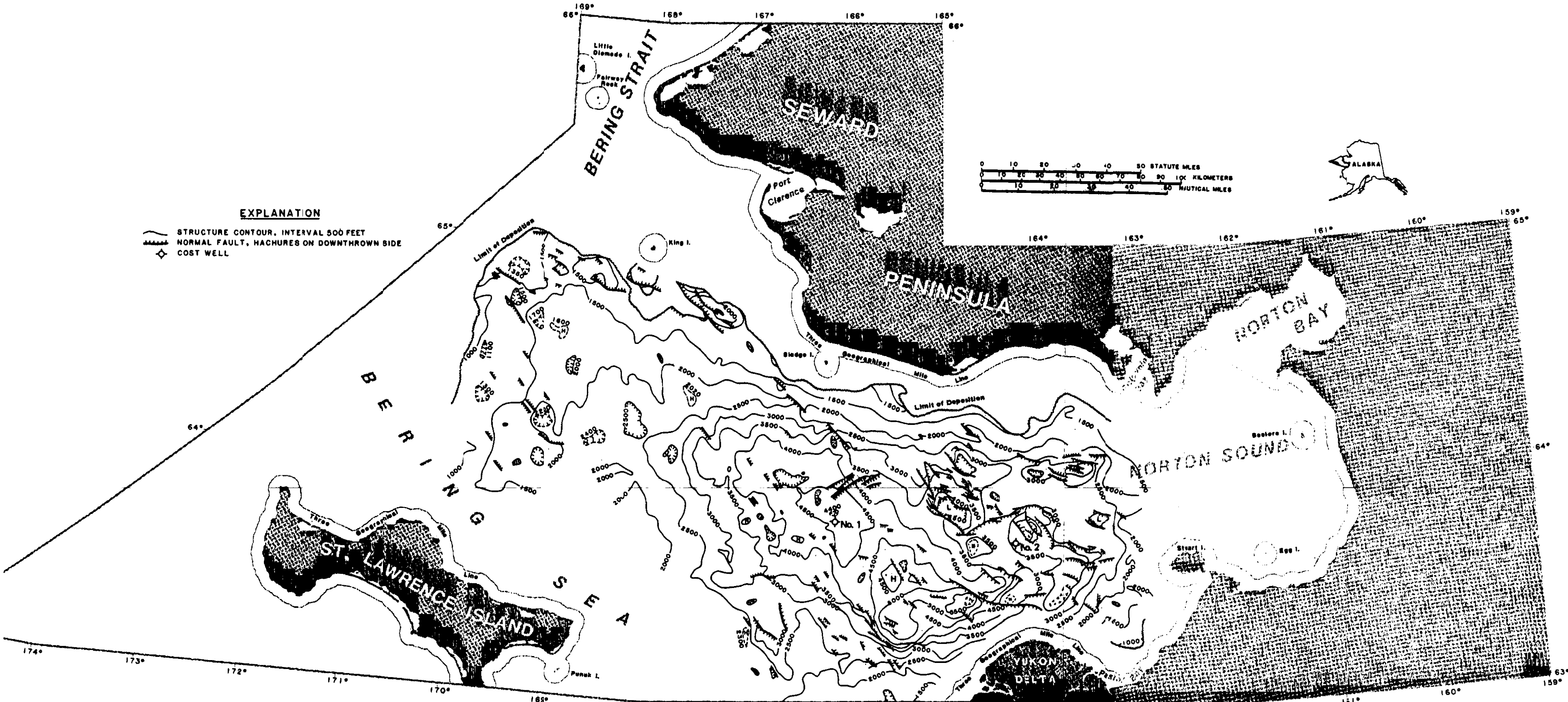

FIGURE 18. Structure contours (in depth) on horizon D in Norton Basin. Horizon D represents a stratal surface at or near the top of the Oligocene. Interpretation and time-depth relationship derived from Western Geophysical Company of America common-depth-point seismic data.

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The upper part of zone To-2 in the COST No. 1 well consists of probable prodelta mud and silt deposits. This interpretation is in part based on the stratigraphic position of the zone subjacent to a deltaic sequence. The dark-gray to black color of the mudstones is typical of organically rich prodelta sediments (Fisher and others, 1974). A conventional core from this interval recovered 25 feet of bioturbated, olive-gray, silty and sandy mudstone containing fossil fragments, carbonaceous debris, mica, pyrite, and traces of glauconite. Some of the bedding exhibits small-scale soft-sediment deformation structures that suggest deposition on a slope.

The lower part of zone To-2 is a sequence of rhythmic cycles of thin (5 to 10 feet), coarsening-upward shaley sandstones which grade upward into thick (20 to 110 feet), blocky, stacked, shaley sandstones (fig. 19). The depositional environment of these sandstones is uncertain. On a large scale, the upward-thickening, upward-coarsening sequence appears analogous to the basin-plain facies of Mutti and Ricci Lucchi (1972) for a progradational submarine fan (fig. 19). The log signatures of the cyclic, thin, coarsening-upward sandstones are similar to those of turbiditic distal-fan sand lobes; the thicker blocky sands with abrupt bases suggest middle- to inner-fan channel deposits (Selley, 1978, figs. 54 and 55). The hypothesis that zone To-2 was deposited in deep water is supported by the presence of upper bathyal microfossils and the close relationship with the underlying marine shale of zone To-3.

The lithic components of the sand fraction of zone To-2 in the COST No. 1 well (St. Lawrence subbasin) suggest a similar provenance to that of the overlying deltaic deposits of zone To-1, that is, chiefly metamorphic grains derived from older miogeoclinal belt rocks. The mudstones of zone To-2 consist of about 60 percent smectite, illite, and mica, with the remaining 40 percent composed of equal parts of chlorite and kaolinite.

In the COST No. 2 well, the sandstone framework grains consist of 50 to 60 percent quartz, 10 to 20 percent feldspar, and 25 to 35 percent lithic fragments. These sandstones are classified as lithic arkoses (AGAT, 1982, D-281-2). The lithic fraction contains about twice as many plutonic and volcanic grains as metamorphic grains. This suggests that terrigenous input from the Okhotsk-Chukotsk volcanic belt predominated in the Stuart subbasin in the late Oligocene.

Wireline logs from the COST No. 2 well indicate that zone To-2 represents a generally fining-upward and thinning-upward sequence. Sandstone beds are thicker and more numerous in the lower half of the sequence; thin beds of siltstone, silty sandstone, and mudstone predominate in the upper half. This pattern suggests an overall transgressive sequence.

The thicknesses of individual sandstone beds are generally 7 to 20 feet, with one at least 65 feet thick. Although coal is reported in samples from this sequence, no coal beds thick enough to be detected by wireline logging tools were observed. The coal present in drill cuttings appears to be predominantly disseminated carbonaceous detritus from terrestrial plants. The presence of an inner neritic microfossil assemblage, abundant shell shards, bioturbation traces, and glauconite supports a dominantly marine origin for zone To-2.

Lithologic Zone To-3

In the Stuart subbasin (COST No. 2 well), zone To-3 consists of fluviodeltaic deposits of interbedded sandstone, siltstone, coal, and prodelta mudstone. In the St. Lawrence subbasin (COST No. 1 well), the inferred equivalent Oligocene section consists of basinal marine shale deposits. Zone To-3 is separated from the superjacent zone To-2 by the "mid"-Oligocene unconformity, which is represented by horizon C (figs. 13 and 14).

The strata of zone To-3 comprise the upper third to two-thirds of seismic sequence IV. These strata do not appear to be continuous across the Yukon horst that separates the two subbasins. There are marine fossils in the Stuart subbasin, however, which suggest a marine connection between the subbasins at the time of deposition of zone To-3.

St. Lawrence Subbasin

In the COST No. 1 well, zone To-3 (8,600 to 9,685 feet) is characterized by a uniform sequence of light- to dark-gray pyritiferous mudstones containing a deepwater microfossil assemblage (Turner and others, 1983a). The gamma-ray, SP, and resistivity logs all display a monotonous shale response with few deflections from the shale baseline except near the base of the interval. Deposition probably took place in a deepwater basin-plain environment. The seismic reflections that correspond to these strata are discontinuous and weak. These strata overlie what, on a regional scale, appear to be alluvial fan deposits that grade basinward into submarine fan deposits. These seismically defined sedimentary packages display onlapping relationships with basement rocks on horsts and other structural highs.

Stuart Subbasin

In the COST No. 2 well, zone To-3 extends from 6,850 to 10,280 feet. The zone consists of a sequence of three genetically related units of strata representing a single depositional system. These units are interpreted (from top to bottom) to be largely delta-plain, delta-front, and prodelta deposits that prograded into a shallow-water marine basin.

The sediments in the upper unit of zone To-3 in the COST No. 2 well (6,850 to 8,450 feet) consist of a complexly interbedded deltaic sequence of sandstone, siltstone, shale, and coal. Samples from this interval yielded a continental to marginal marine microfossil assemblage. The lithic-clast fraction of the framework grains of

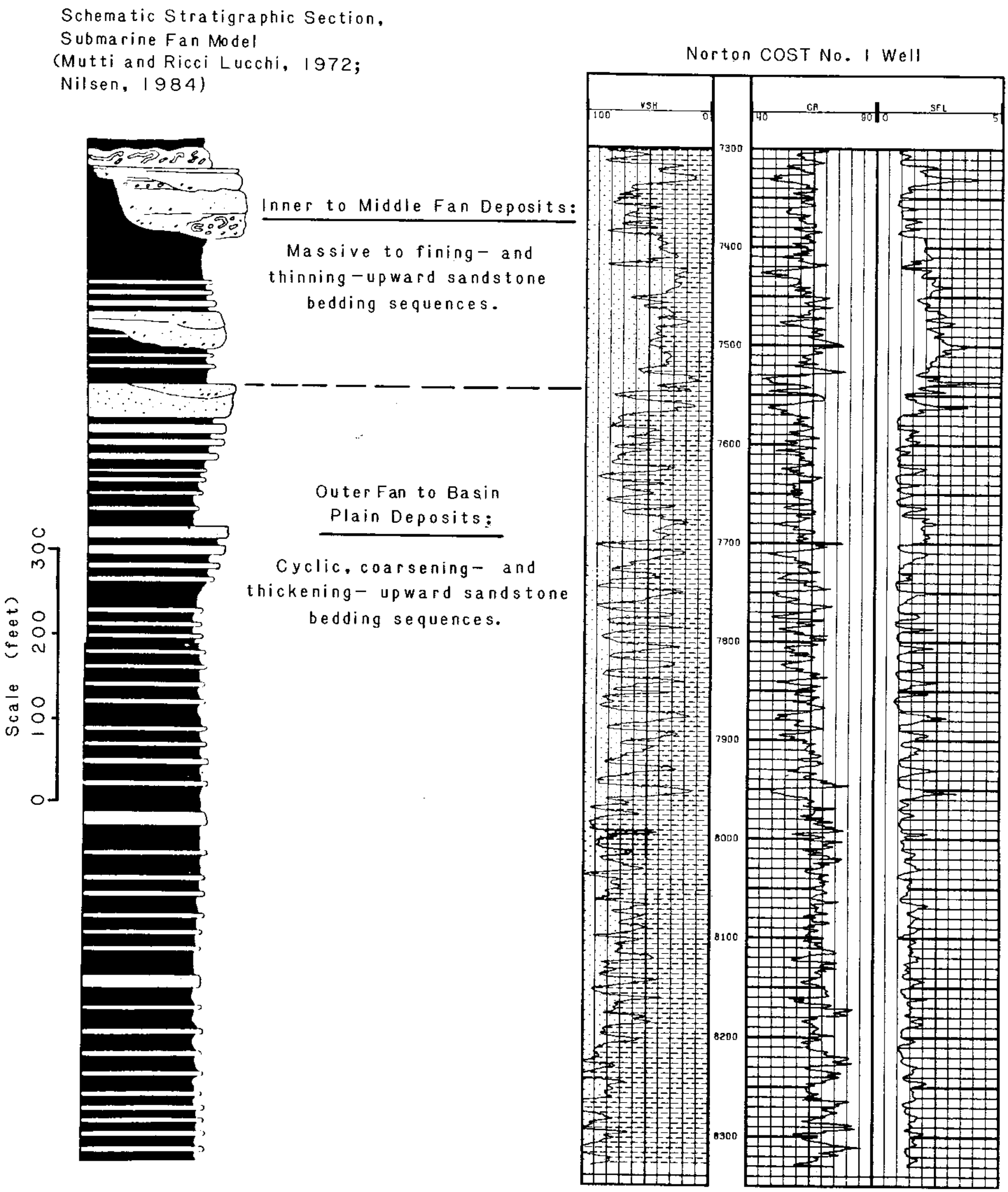

FIGURE 19. **Comparison of large and small-scale vertical wireline log patterns of rock unit To-2, St. Lawrence subbasin, and characteristic vertical cycles of submarine fan turbidite facies. (Log heading abbreviations: VSH=shale volume, GR=Gamma Ray, SFL=Spherically Focused Resistivity Log)**

these sandstones indicates a dominantly metamorphic source terrane (AGAT, 1982). This suggests that a major shift from a metamorphic to a volcanic source area occurred subsequent to the deposition of zone To-3.

Wireline logs of the upper unit indicate numerous thin coal beds (5 feet thick or less) throughout the interval. Sandstone beds are generally 5 to 20 feet thick and appear to be relatively clean based upon large SP and gamma-ray log deflections as well as core and petrographic data. The depositional environments represented by two cores from this interval were interpreted as point bar, channel fill, levee, overbank and swamp deposits on the basis of abundant carbonaceous debris and coal, plant impressions, fining-upward character, moderate sand sorting, the presence of ripple to parallel laminations, and the absence of marine bioturbation traces (AGAT, 1980). This sedimentary unit probably represents a fluvially dominated delta-plain system. This interpretation is based on the preponderance of fluvially influenced aggradational delta-plain facies and the relative paucity of strongly marine facies. Notably absent are the thick shoreface to foreshore delta-front sands (smooth, funnel-shaped log profiles) that are typically developed in wave-dominated destructional marine settings (Fisher and others, 1974; Balsley and Parker, 1983).

Seismic reflections corresponding to the strata of the upper unit of zone To-3 in the Stuart subbasin display moderate to high amplitudes and are relatively continuous. Laterally, these reflections become divergent away from basement horsts. These divergent seismic reflections may represent alluvial fan deposits (Fisher and others, 1982) genetically related to the fluviodeltaic sandstones penetrated in the COST No. 2 well.

Below the fluviodeltaic sequence, the middle unit of zone To-3 (from 8,450 to 9,230 feet) is characterized by thin-bedded, fining-upward and thinning-upward sequences of very fine grained sandstone, siltstone, and shale. The dipmeter log indicates uniform dips with little variation in magnitude and direction, which suggests deposition in quiet water below wave base (Schlumberger, 1981, p. 36). The sparse microfossil assemblages, chiefly shallow-water Foraminifera, indicate an inner neritic to transitional (estuarine) depositional environment (Turner and others, 1983b). The micaceous mudstone, shale, and siltstone recovered from drill cuttings and cores are chocolate brown to dark gray or black and contain abundant coaly and carbonaceous material. Seismic reflections corresponding to these strata are generally weaker and less continuous than those of the overlying fluviodeltaic sequence. A conventional core from the middle unit contained very fine grained, massive to fining-upward bedding sets of carbonaceous sandstone which graded upward into thin, interbedded carbonaceous sandstone and mudstone, capped by mottled carbonaceous mudstone. Sedimentary structures included current ripple, wavy, parallel, and mudstone-inclined laminations, disturbed bedding (soft-sediment deformation), and load casts (AGAT, D-281-5, 1982). These types of sedimentary structures and sequences, as well as patterns observed on the wireline logs (fig. 20), suggest deposition on a slope by turbidity currents (Bouma, 1962; Walker, 1965). However, the dominantly shallow-water foraminiferal fauna contains no in situ deeper water elements that would support a downslope transport origin for this fossil assemblage. If these facies represent deposits generated by density currents, then deposition may have occurred in relatively shallow water.

Fisher and others (1974) and Balsley and Parker (1983) characterize distal distributary mouth bar deposits as consisting of fine-grained sediments in graded beds that resulted from rapid sediment influxes during floods. These sedimentary structures include parallel and ripple lamination, graded to massive bedding, thin Bouma sequences, sole marks and load casts, and local burrowing in bed tops. The facies profiles from the COST well logs and the sedimentary features described in the core from this middle unit compare closely with the diagnostic characteristics of ancient and modern distal mouth bar deposits. It is reasonable to conclude that zone To-3 was probably deposited by similar processes.

Strata in the lower unit of lithologic zone To-3 (9,230 to 10,300 feet in the COST No. 2 well) consist of thin-bedded shale, siltstone, and minor amounts of silty sandstone that contain a sparse, shallow-water foraminiferal assemblage. The dipmeter log indicates uniform dips with little variation in magnitude or direction, which suggests quiet-water deposition (Schlumberger, 1981, p. 36). Drill cuttings from these rocks consist of carbonaceous, chocolate-brown to dark-gray or black micaceous mudstone, shale, and siltstone. A conventional core from the COST No. 2 well, which sampled the basal part of the lower unit, contains thinly interbedded carbonaceous mudstones, siltstones, and silty sandstones in coarsening-upward sequences. Sedimentary structures include ripple lamination, high-angle planar cross-lamination, and abundant contorted bedding, suggesting deposition on a slope. The facies characteristics of this lower package are typical of prodelta deposits (Fisher and others, 1974; Sheriff, 1980).

EOCENE

Over 2,400 feet of strata of Eocene or probable Eocene age are present at both COST well locations. The upper contact of these strata with the overlying Oligocene in both COST wells is marked by a large shift on the gamma-ray logs. An increase in radioactivity of 30 to 50 API units occurs in the siltstones and shales of Eocene or probable Eocene age relative to those of the overlying Oligocene. Offsets in trends of the thermal maturity of organic matter (fig. 30) and in dipmeter data at or near this gamma-ray log shift in the No. 1 well, suggest the possibility of an unconformity. However, in the No. 2 well, no such offsets (fig. 33) were observed at the upper contact where the gamma-ray log shift occurs.

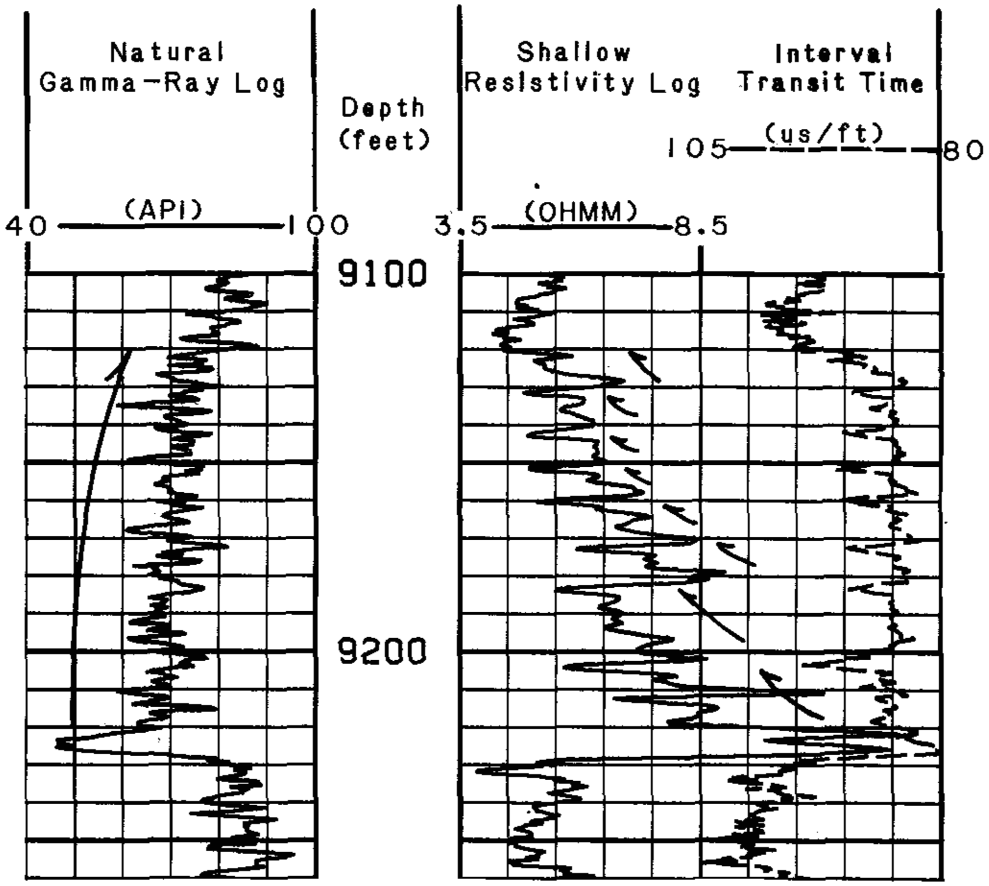

FIGURE 20. **Wireline log details of large and small-scale bedding cycles of the inferred distal facies of a distributary mouth bar sandstone, zone To-3, Norton COST No. 2 well. Small-scale fining- and thinning-upward bed cycles are well-defined on the resistivity and sonic logs and are interpreted to reflect Bouma Ta-e sequences. Each sequence is inferred to represent a turbidity event fed by distributary mouths during storm and flood events.**

The probable Eocene age section in the St. Lawrence subbasin is represented by a single lithologic sequence at the COST No. 1 well (fig. 13). In the Stuart subbasin (COST No. 2 well), however, the Eocene section is divided into two distinct lithologic units separated by an unconformity (fig. 14). The unconformity is mainly indicated by a large offset in the vitrinite reflectance trends with depth (fig. 33).

St. Lawrence Subbasin: Lithologic Zone Te

Lithologic zone Te strata in the COST No. 1 well extend from 9,685 to 12,235 feet and consist of very micaceous, fine-grained sandstones which are interbedded with brown to dark-gray, sparsely burrowed, micaceous shale and siltstone. The sandstone framework grains consist of 40 to 60 percent quartz, 30 to 55 percent micas, and 2 to 12 percent fragments of micaceous schist. These sandstones are classified as litharenites (AGAT, 1980) and were probably derived from metamorphic rocks of the miogeoclinal belt. In the upper third of this zone there are three basaltic sills that range in thickness from 6 to over 140 feet. Igneous rocks such as these probably account for many of the strong discontinuous reflections in seismic sequence IV.

Sandstone beds in zone Te, which vary from a few inches to over 100 feet in thickness, generally increase in frequency of occurrence, thickness, and overall grain size downward. Sedimentary structures and features observed in sandstones in five conventional cores (which collectively recovered over 90 feet of section) include sharp erosional bed bases with occasional groove casts and flame structures (AGAT, 1980). Bedding styles include thin, graded beds, fining-upward Bouma cycles, and massive bedding in the thicker units. Burrows are present in the tops of some beds. Although only rare marine palynomorphs were recovered from zone Te (at 12,150 feet), the sedimentary structures suggest deposition as marine turbidites.

Seismic reflections in sequence IV corresponding to zone Te make up most of the reflections between horizon B2 and A at the COST No. 1 well (fig. 13). Away from the COST No. 1 well, reflections from this interval vary in amplitude and continuity and dip basinward from the Yukon horst and other positive basement structures. Near the basement highs, these dipping reflections probably represent alluvial fan deposits (Fisher, 1982). The possible turbidites in the COST No. 1 well may represent a distal-basin facies genetically related to an alluvial fan and deltaic depositional system.

Stuart Subbasin

Lithologic Zone Te-1

In the COST No. 2 well, lithologic zone Te-1 (10,280 to 11,958 feet) consists of a sequence of thinly interbedded micaceous sandstones, siltstones, and shales derived mainly from a metamorphic terrane (AGAT, 1980). These rocks unconformably overlie the remainder of the Eocene section. Zones Te-1 and Te-2 are separated by seismic horizon B-3, which occurs in the lower part of seismic sequence IV (fig. 14). Reflections from this interval are generally of low amplitude, with poor to fair lateral continuity. Strata from this interval terminate against the flanks of the Yukon horst and other positive basement structures.

Sandstones in this zone are chiefly fine- to very fine-grained, poorly to moderately sorted, and micaceous, although thin, well-sorted, medium- to coarse-grained sandstones are locally present. Wireline logs indicate that the individual beds are generally less than 5 feet thick and that fining-upward sequences predominate. Sedimentary structures observed in cores include thin, graded beds, small-scale hummocky(?) crossbedding, and ripple cross-lamination. Microfossil assemblages indicate a paleobathymetry from transitional (estuarine?) to middle neritic. The graded bedding and lack of bioturbation suggest rapid deposition in quiet water. Dipmeter data show little variation in dip magnitude and direction, which also suggests generally quiet water deposition (Schlumberger, 1981, p. 36). The hummocky(?), cross-stratified, well-sorted sands are suggestive of strong episodic currents (Harms and others, 1975) and imply that the depositional environment was shallow enough to be affected by storm-generated currents.

Lithologic Zone Te-2

In the COST No. 2 well, lithologic zone Te-2 extends from 11,958 to 12,700 feet. The upper 420 feet of this zone consists of a sequence of thick, fining-upward, conglomeratic sandstones. Most of the pebbles and granules are volcanic in origin, which indicates a significant detrital influx from the Okhotsk-Chukotsk volcanic belt. The sequence is composed of a 180-foot-thick basal bed with an abrupt erosional base and a gradational fining-upward profile, overlain by a series of similar beds varying from 25 to 60 feet thick.

A conventional core from the upper 30 feet of the thick basal bed contains a conglomerate of matrix-supported, randomly oriented, subangular volcanic clasts; the conglomerate grades upward into medium- to very fine-grained, poorly sorted shaley sandstone. The sedimentary structures present are defined by laminae of coaly detritus and organic-rich shale clasts along bedding surfaces and include high-angle (25 to 40 degrees) inclined stratification and slightly contorted bedding. Shell fragments are reported in drill cuttings from the sandstone sequence above the cored interval. A sidewall core from a thin mudstone interbed displayed a mottled texture suggestive of bioturbation (AGAT, 1980).

Significant amounts of coal are present in cuttings from the conglomeratic sandstone sequence and from the underlying shale and siltstone which comprise the lower 322 feet of the zone in the No. 2 well. However, coal beds thick enough to be detected on wireline logs are not present. The coal is probably derived from either thin laminae, coaly detritus, or both.

The depositional environment represented by zone Te-2 is uncertain. The presence of coal, conglomerate, and a dominantly continental microfossil assemblage suggests that this section represents a nonmarine, fluvial deposit (AGAT 1980; Turner and others, 1983b). However, the presence of shell fragments and bioturbated shale interbeds are inconsistent with a fluvial deposit. The sedimentary structures and bedding sequences observed in the conglomeratic sandstone could have resulted from either fluvial or turbidite deposition. The presence of coal, particularly if it is detrital, does not exclude marine deposition. Large amounts of plant material are common in modern turbidite deposits (Nelson and Nilsen, 1984) and coaly detritus is reported from ancient turbidite deposits as well (Balsley and Parker, 1983).

POSSIBLE PALEOCENE: LITHOLOGIC ZONE TP

Lithologic zone Tp (12,235 to 12,545 feet in the COST No. 1 well; 12,700 to 14,460 feet in the COST No. 2 well) is composed of interbedded sandstone, siltstone, coal, and shale. The zone unconformably overlies metamorphic basement and is unconformably overlain by Eocene sedimentary strata. Zone Tp contains numerous coal beds (frequently up to 10 feet thick). The sandstones are generally medium to coarse grained, poorly sorted, and contain abundant detrital matrix and carbonaceous debris. Cores from this zone exhibit typical fluvial facies characteristics including pebble lags, trough to ripple cross-stratification, and small- and large-scale fining-upward bedding sequences. Abundant leaf impressions are preserved in the interbedded shales. Sandstone clast compositions suggest a source area dominated by schist and marble rock.

In the COST No. 2 well, several layers of igneous rock (varying in thickness from 5 to 25 feet) are intercalated with zone Tp strata. The drill cuttings contained a possible welded tuff and a single sidewall core from an igneous interval was classified as basalt (AGAT, 1982). The igneous intervals are characterized on well logs by high resistivities, large gamma-ray deflections (low radiation), high sonic velocities, and high bulk densities.

Strata in zone Tp make up the basal part of seismic sequence IV in both subbasins (figs. 13 and 14). Reflections from this interval are discontinuous, highly variable in amplitude, and, in places, nonparallel. The basal part of seismic sequence IV is represented by reflections that are present in wedge-shaped packages of dipping reflections that diverge away from horsts on the downthrown sides. Basinward from these wedges, the reflectors converge with and downlap basement rocks. Strata from this zone appear to represent alluvial fans deposited adjacent to faulted basement horsts early in the formation of Norton Basin.

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Part 2
Petroleum Geology

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6

Exploration History

Two deep stratigraphic test wells, the Norton Basin COST No. 1 and No. 2 wells, have been drilled in the Norton Basin, one in the Stuart subbasin and one in the St. Lawrence subbasin (fig. 21). Twenty-one oil companies participated in financing these tests; ARCO was the operator for both wells. The COST No. 1 well was spudded June 14, 1980, and completed September 16, 1980. The well site is located about 54 miles southwest of Nome at lat 63°46'48.97" N., long 166°05'10.40" W. The well was drilled in approximately 90 feet of water from the Dan Prince, a self-elevating drilling unit owned by DANTEX Inc. The total depth of the well was 14,683 feet.

The COST No. 2 well was spudded June 7, 1982, from the Key Singapore, a self-elevating drilling unit owned by Keydrill Company. It was drilled in approximately 49 feet of water. The well site is located about 68 miles southwest of Nome at lat 63°41'49.43" N., long 164°11'03.38" W. The well was completed on August 27, 1982, to a depth of 14,889 feet.

Geophysical exploration in the Norton Basin area to date has produced 49,506 line miles of common-depth-point data, 3,453 miles of high-resolution seismic data, and 8,000 miles of gravity and magnetic data.

Lease Sale 57 was held on March 15, 1983, in Anchorage, Alaska. Ninety-eight bids were received on 64 tracts. The total value of the high bids was $325 million. Fifty-nine bids were accepted and five rejected.

During the summer of 1984, three exploratory wells were drilled in the Sale 57 area, one by ARCO and two by Exxon (fig. 21). The ARCO well, the OCS-Y-0436 No. 1 well, was drilled at lat 64°4'47.56" N., long 165°37'22.49" W. to a depth of 10,950 feet in 65 feet of water. One Exxon well, the OCS-Y-0414 No. 1 well, was drilled at lat 63°42'42.80" N., long 164°43'22.44" W. to a depth of 3,636 feet in 54 feet of water. The remaining Exxon well, the OCS-Y-0430 No. 1 well, was drilled at lat 63°30'40.34" N., long 164°14'22.99" W. to a depth of 4,951 feet in 35 feet of water. All of these wells were plugged and abandoned. No discoveries were announced. The data from these three wells are proprietary.

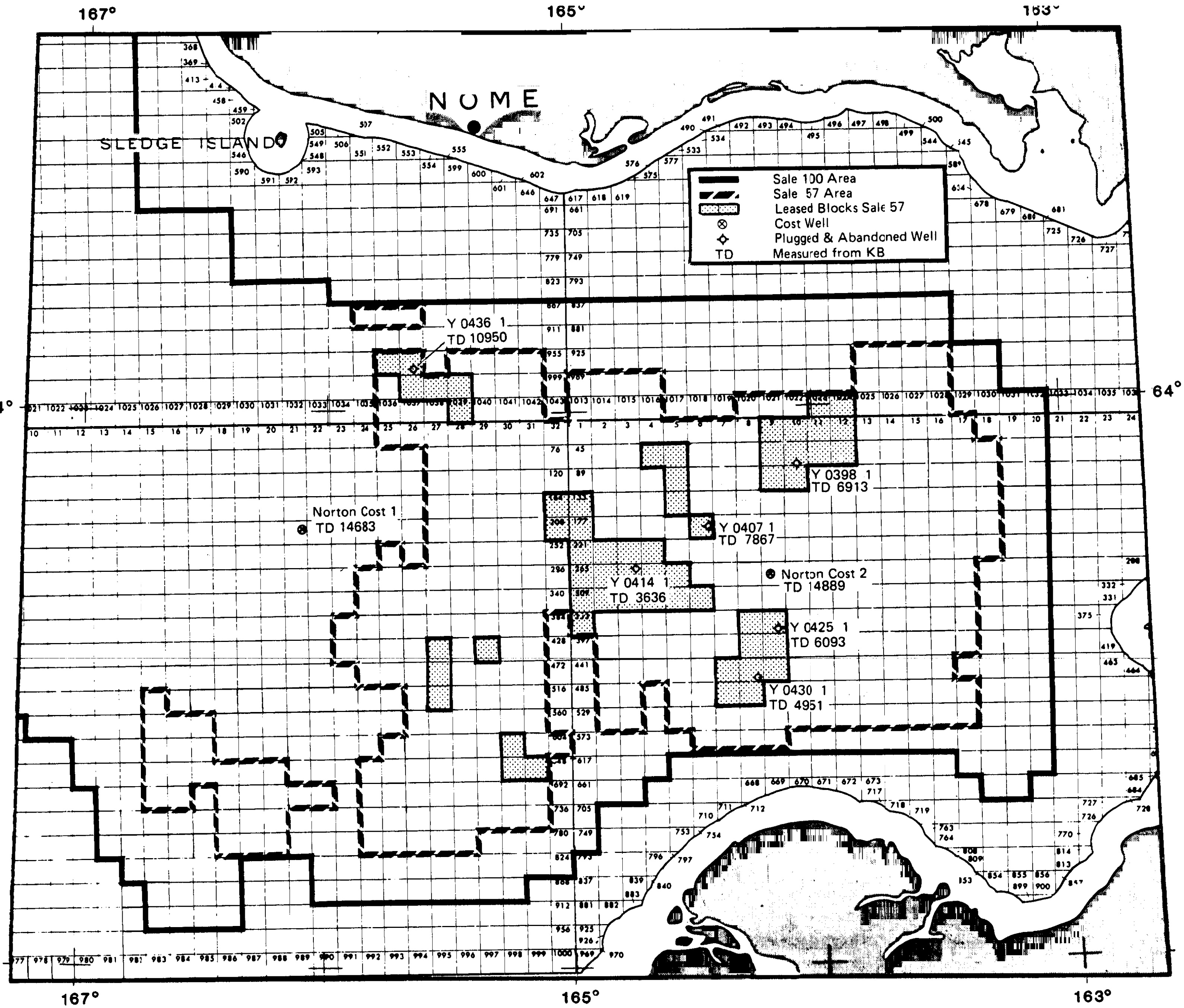

FIGURE 21. **Locations of sale areas, leased blocks, and COST and exploratory wells.**

During the summer of 1985, three more exploratory wells were drilled in the Norton Basin (fig. 21). Exxon was the operator for all three wells. The Exxon OCS-Y-0398 No. 1 well, located at lat 63°53'28.76" N., long 164°03'56.16" W., was drilled to a depth of 6,913 feet in 58 feet of water. The Exxon OCS-Y-0407 No. 1 well, located at lat 63°47'15.79" N., long 164°25'56.92" W., was drilled to a depth of 7,867 feet in 58 feet of water. The Exxon OCS-Y-0425 No. 1 well, located at lat 63°36'06.11" N., long 164°09'33.40" W., was drilled to a depth of 6,093 feet in 42 feet of water. All of these wells were plugged and abandoned. No discoveries were announced. The data from these three wells are proprietary.

Lease Sale 100 is scheduled to take place in March of 1986 (fig. 1). Tracts that were not leased during Sale 57, as well as additional tracts to the west, will be offered.

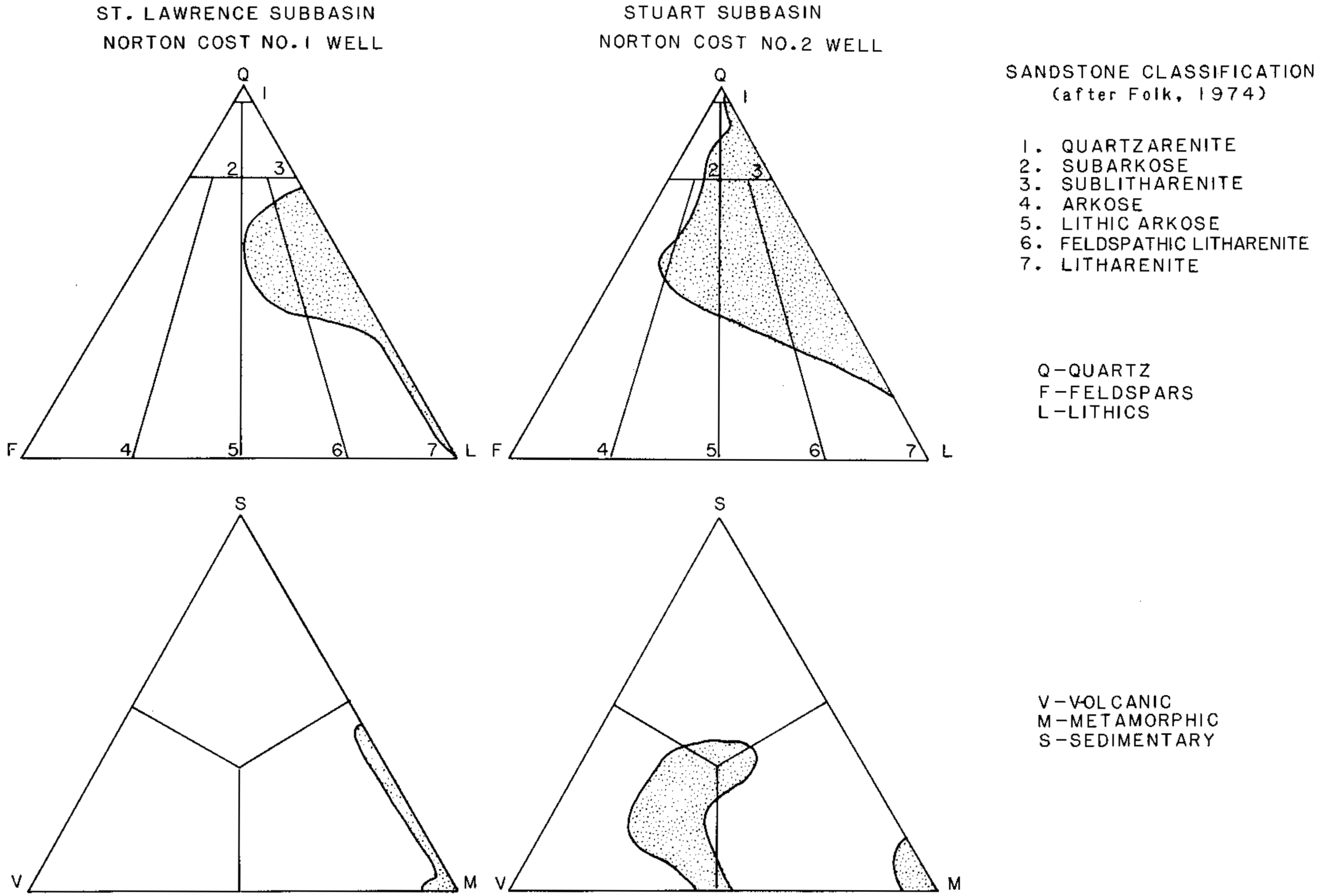

FIGURE 22. **Ternary diagrams showing the range of the principal sandstone framework constituents and the major rock types of lithic fragments in sandstones from conventional and sidewall core samples from Norton Basin COST No.1 and No.2 wells. (Modified from AGAT Consultants, Inc.,1980, 1982.)**

7

Reservoir Rocks

The reservoir quality of a sandstone in any given basin is primarily a function of provenance, depositional environment, and tectonic setting. These factors determine the sand texture (grain size, packing, and angularity) and composition, as well as most aspects of the burial and diagenetic history (Hayes, 1984). Sandstones in the Norton Basin COST wells are composed of metamorphic detritus shed from uplifted horsts in and around the basin, and from volcanic and volcaniclastic debris shed from the volcanic belt to the south and east of the basin. These sandstones contain significant fractions of chemically and mechanically unstable components. As a result, reservoir quality diminishes rapidly with increasing burial depth in the Norton Basin.

The distribution of quartz, feldspar, and lithic grains in these sands and the major rock types of the source terranes from which they were derived are shown in figure 22. The majority of the sandstones are either litharenites or feldspathic litharenites. Most of the feldspathic litharenites and the few lithic arkoses occur in lithologic zones Tmp, To-1, and To-2 (figs. 13 and 14). Sandstones below the Oligocene unconformity tend to be largely litharenites. This mineralogical difference is probably due to an increase in the input of volcanic detritus containing abundant plagioclase feldspars and to the progressive diagenesis and dissolution of these feldspars with depth.

Most of the prospective reservoir rock seen thus far in the Norton Basin is in the Oligocene section of the COST No. 2 well (lithologic zones To-1, To-2, and To-3; fig. 14). These sandstones represent fluvial to shallow-marine deposition. The relatively high depositional energy of these environments winnowed and reworked the metamorphic and volcanic detritus and ultimately deposited sandstones with sufficient quartz framework clasts to have retained significant effective porosity to considerable burial depths. These sandstones are probably representative of most of the potential reservoirs, including possible Paleocene and Eocene alluvial fan deposits, that are likely to be encountered in both subbasins. Although significant thicknesses of probable deepwater turbiditic sandstones were encountered in the COST No. 1

well (in the St. Lawrence subbasin), these sandstones appear less likely to represent significant reservoirs because they may be restricted to the central parts of the subbasin at burial depths where effective porosity and permeability are anticipated to be very low.

OLIGOCENE SANDSTONES

Potential net sandstone intervals were determined for the Oligocene sandstone section in the Stuart subbasin by wireline well log analysis. Net sands were defined as intervals with a minimum of 30 percent quartzose components and an SP log deflection from the shale baseline of at least 10 millivolts (mv). An SP deflection of this magnitude indicates that at least minimal permeability is present. Effective porosity was determined by calculating the volume of shale in the sandstone and subtracting the component of shale microporosity from the apparent total porosity of the sandstone. The component of shale and mica in the sandstones was determined from the gamma-ray log (technique from Dresser Atlas, 1979) and from neutron-density crossplots (technique from Poupoun and others, 1970). Effective porosities were calculated from acoustic, density, and neutron-density logs and the results were averaged.

The relative volume of quartz in the sand was determined by subtracting from the sand the total volume of shale calculated from neutron-density statistical crossplots. This analysis assumes that quartz is the major framework component remaining after the deletion of microporous granular and intergranular components detected as shale by the neutron-density crossplots. Although quartz is the major mechanically stable framework component, significant amounts of feldspar (mostly plagioclase) are also present. This simplified analysis of quartz content, while yielding a good general estimate, also includes feldspars and other mechanically stable grains.

The shaley component detected by wireline logs can be distributed in the sand as intergranular matrix (dispersed shale), as shaley lithic framework grains (structural shale), and as shale laminae. Dispersed shale probably has the most adverse effect on reservoir quality at depths where compaction and deformation of ductile lithic grains are not too severe. The simplified dispersed-shale model of Alger and others (1963) and Tixier and others (1968) was employed to obtain an estimate of this type of shale.

The results of the log evaluation of reservoir potential were checked against petrographic and laboratory measurements of reservoir parameters obtained from core 3 of the COST No. 2 well. The three other conventional cores in the Oligocene sand sequence (cores 1, 2, and 4) did not penetrate intervals of potential net sand. Table 1 summarizes the wireline log analysis of the interval cut by core 3 and table 2 summarizes the laboratory and petrographic analysis of the core.

Although it is seldom possible to find a significant one-to-one correspondence between discrete wireline and core analyses, when a series of analyses over an interval are averaged, the results can generally be meaningfully compared. This was done with the data shown in tables 1 and 2. The average of the effective porosities derived from the sonic log closely matches (within about 1 percent) the average of the porosities from the core analysis. In addition, the average of effective porosities from the neutron-density crossplot analysis agrees fairly well (within about 2 percent) with the average of the porosities from the petrographic analysis. These close correspondences suggest that the well log analysis is providing a reasonable evaluation of effective porosity for these sandstones.

The well log estimate of quartz content is slightly high relative to the petrographic analysis (36.6 versus 33 percent) but not unreasonable. The estimate of dispersed clay from well log analysis exhibits the least correspondence with core data, and is an average of 30 percentage points higher than that from the petrographic analysis. The logs appear to be detecting some of the structural and laminar shale in addition to dispersed shale. Most of the framework lithic fraction (structural shale) shown in table 2 consists of micas and carbonaceous fragments, both of which contain abundant microporosity (AGAT, 1982, p. D-281-3). Because of this microporosity, this material is apparently detected as intergranular clay by the wireline dispersed shale analysis. This is evident when the volume of micaceous and carbonaceous detritus is added to that of the intergranular clay, because the resulting volume of 38 percent closely agrees with the average shale volume of 38.2 percent determined by the dispersed-shale analysis (table 1). Thus, although the dispersed shale of the wireline analysis is not an exclusive measure of intergranular shale, it is a reasonable indicator of total porosity-occluding material.

Table 2 shows that the highest permeabilities occur in samples with the least amount of lithic detritus (depths 7,044.5 and 7,047.5 feet). In the interval sampled by this core, the relative amount of lithic detritus is apparently the major factor limiting reservoir potential. This then suggests that the energy of the depositional environment, hence the amount of physical winnowing, is probably one of the most significant factors in determining the ultimate reservoir quality of Norton Basin sandstones.

A plot of core analyses from core 3 (fig. 23) shows that a good correlation exists between porosity and permeability. The relation established by linear regression of the data indicates that where core porosity falls below 20 percent, permeability will be lower than 10 millidarcies. This marks the approximate point below which sandstones would be considered poor reservoirs. In terms of the wireline log analysis, a comparison of the data in tables 1 and 2 suggests that a core porosity of 20 percent approximately equals an average wireline effective porosity of 12 percent. On this basis, permeabilities of better than 10 millidarcies can be inferred from the wireline analysis for sands with effective porosities of over

Table 1. Wireline log analysis of the sandstone interval cut by core 3, Norton Basin COST No. 2 well.

Depth (feet)	Thickness (feet)	Quartz Content[1] (%)	Q Factor (Dispersed Shale)[2] (%)	Effective Porosity: Sonic (%)	Effective Porosity: Density (%)	Effective Porosity: Neutron-Density Crossplot (%)	Effective Porosity: Average (%)
7030	3	21.9	41.6	13.5	9.8	2.1	8.5
7033	1.5	45.8	20.5	19.7	17.8	9.9	15.8
7034.5	3	49.7	23.2	25.9	21.4	13.6	20.3
7037.5	2.5	33.2	43.4	17.3	10.6	1.6	9.8
7040	2	38.1	44.2	22.1	13.1	5.0	13.4
7042	2	26.1	48.0	21.6	11.7	1.7	11.6
7044	2	43.9	38.4	24.1	15.9	7.8	15.9
7046	3	37.7	43.6	19.6	12.1	4.3	12.0
Gross	19	36.6	38.2	20.3	13.9	5.7	13.3
Net[3]	13.5	40.5	36.5	22.3	15.4	7.2	15.0

1) Determined from neutron-density crossplots. Includes feldspars (chiefly plagioclase).

2) Indicates the amount of pore space occluded by shale and lithic detritus.

3) Indicates sandstone with a quartz content greater than 30 percent and effective porosity averaging more than 10 percent.

Table 2. Petrographic modal analysis of thin sections and core analysis of conventional core 3, Norton Basin COST No. 2 well (petrographic analysis from AGAT, 1982, p. D-281-3).

	Petrographic Analysis						Core Analysis	
	Framework Grains			Intergranular			(Boyle's Law - Helium Porosity)	
Depth (feet)	Quartz (%)	Feldspar (%)	Lithics (%)	Clays (%)	Siderite (%)	Porosity (%)	Porosity (%)	Permeability (millidarcies)
7030.7	31	5	41	5	8	9	20.5	11
7032.5	27	14	37	14	5	2	14.4	0.74
7034.3	32	10	37	7	6	9	21.0	7.64
7036.5	--	--	--	--	--	--	28.5	543
7038.6	28	8	37	10	12	5	17.7	1.27
7041.3	33	9	41	7	8	2	20.0	7.98
7044.4	39	6	21	11	5	18	26.3	183
7047.5	43	8	22	10	4	14	21.2	40
Average	33	9	34	9	7	8	21.2	99

Table 3. Wireline log analysis of Oligocene sandstone sequence in the Norton Basin COST No. 2 well.

Zone	Sand Thickness (feet)	Net/Gross Ratio	Quartz Content of Sand (percent)		Dispersed Shale Content (percent)		Effective Porosity (percent)	
			Range	Mean	Range	Mean	Range	Mean
To-1	285	0.65	34-83	57	5-26	15	13-36	26
To-2	400	.68	44-74	54	2-30	17	10-25	18
To-3	230	.83	34-70	53	17-44	27	12-21	16

12 percent. This assumption can be applied with some confidence to the sandstones of lithologic zone To-3, where core 3 was cut, but is less certain in zones To-1 and To-2, in which no porous sands were cut by conventional cores.

The results of the wireline log analysis of the Oligocene sand sequence are shown in table 3. The analysis indicates that significant reservoir potential exists in each lithologic zone. Lithologic zone To-1 contains a total of 285 feet of sandstone in 14 beds greater than 5 feet thick (as defined by minimum SP log deflections of 10 mv). The average bed thickness is about 20 feet; the zone contains three beds from 45 to 50 feet thick. Of these sandstones, intervals with a minimum quartz (and feldspar) content of 30 percent and a minimum effective porosity of 10 percent were considered potential reservoir rock or net sandstone. On this basis, zone To-1 contains a net to gross sandstone ratio of 65 percent. Net sand intervals average 26 percent effective porosity and range from 13 to 36 percent.

Lithologic zone To-2 contains an aggregate sand thickness of 400 feet in 16 beds greater than 5 feet thick. The average bed thickness is about 25 feet, with one bed of 45 and one of 70 feet in thickness. The net to gross sand ratio is 68 percent with net intervals averaging 18 percent effective porosity and ranging from 10 to 25 percent.

Lithologic zone To-3 contains 230 feet of sandstone in 18 beds greater than 5 feet thick. The average bed thickness is about 13 feet with a maximum thickness of 30 feet. The net to gross sand ratio in zone To-3 is 83 percent. Net intervals display an average effective porosity of 16 percent and range from 12 to 21 percent.

EOCENE OR OLDER SANDSTONES

In both COST wells, the Eocene or older sandstones occur at depths where reservoir quality has been severely reduced by the compaction of ductile grains. At depths below 9,000 feet in the COST No. 2 well, visual estimates of effective porosity (mesoporosity) from petrographic analyses of conventional cores are less than 2 percent (AGAT, 1982, p. D-281-PI). Measured permeabilities from conventional cores from both COST wells do not exceed 10 millidarcies below about 9,000 feet. The rapid reduction of porosity with depth is shown in figure 24. The lower right envelope of the porosity trend, which represents the maximum porosities that are likely to be encountered, passes below 20 percent at about 8,500 feet. As indicated in the analysis of porosity versus permeability in figure 23, this probably represents the point below which reservoir quality is likely to be poor.

However, the bulge in the porosity trend below 12,700 feet, and the anomalous point at 10,900 feet, suggest that there may be exceptions to this porosity-depth trend. Such offsets in

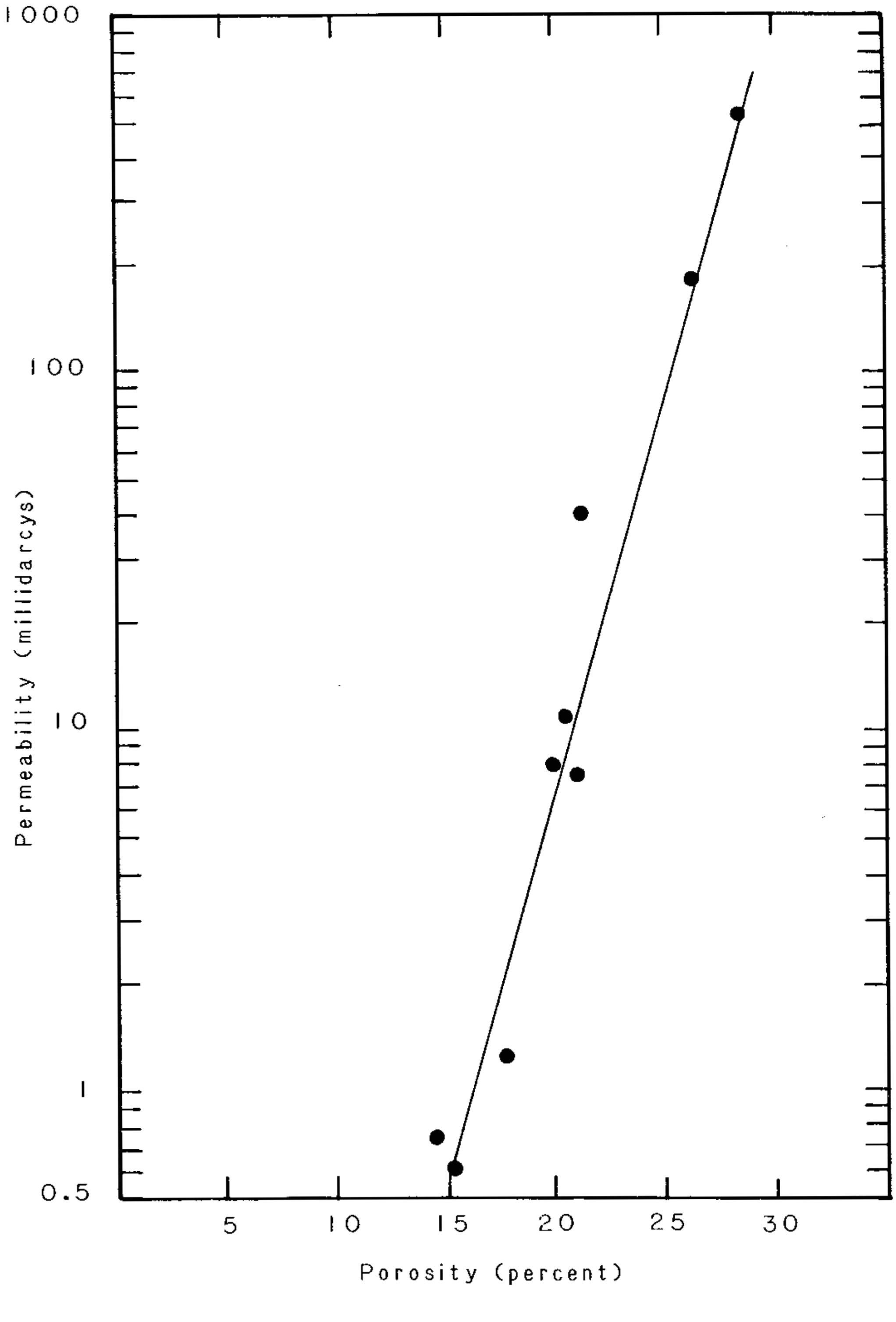

FIGURE 23. Plot of porosity versus permeability for conventional core 3 (7020.6 to 7047.5 feet), Norton Basin COST No.2 well.

porosity-depth trends are generally a result of secondary porosity enhancement. Such enhancement is thought to be attributable to the dissolution of chemically unstable grains and cements by organic acids generated by decarboxylation during the thermal maturation of kerogen (Surdam and others, 1984). Alternately, the higher apparent porosities seen below 12,700 feet may be in part due to overpressuring, spurious readings from washed-out zones in the borehole, and possible gas effects from methane generated from interbedded coal. Core measurements and petrographic analyses of sandstones from two conventional cores cut in this interval actually indicated very low porosity and permeability (AGAT, 1982, p. D-281-10, 11).

The 20-percent-porosity point at 10,900 feet appears to represent a 10-foot-thick sandstone with significant reservoir quality. A good drilling break was observed through the interval and the sandstone was described on the drill cuttings log as being "very well sorted" with "very good porosity." The SP log displayed a deflection through the interval which suggests that the sandstone is permeable. Petrographic analyses of sidewall cores from this sand indicated fair amounts (6 to 8 percent) of effective porosity, much of which was the result of the dissolution of volcanic rock fragments (AGAT, 1982, p. D-281-SC-5). Measurements on these samples indicated porosities of 23 to 25 percent and permeabilities of 48 to 147 millidarcies. If these sidewall core measurements are valid, as the petrographic analysis suggests, and not due to fabric disruption from the coring process, then there is fair to good reservoir rock present at a depth over 2,000 feet below that predicted by the general trend of figure 24. If these same conditions obtain elsewhere in Norton Basin, particularly in areas where more of this cleaner sandstone is present, then significant volumes of prospective reservoir rock could be present at depths within or in closer proximity to the oil window.

HYDROCARBON SHOWS

Traces of free oil in the drilling mud were reported in the COST No. 2 well between 11,800 and 13,000 feet. In this same interval, an increase in background gas and numerous gas peaks were recorded on the Exlog Formation Evaluation Log (mud log) and yellow-orange fluorescence "pops" were reported in cuttings between 11,820 and 11,830 feet. In the possible turbidite sequence of the COST No. 1 well, bright-yellow to gold fluorescence and fluorescence cuts were reported from about 5 percent of the drill cuttings in several intervals between 10,200 and 11,200 feet.

The most interesting show consisted of residual oil saturations of 14 to 18 percent in conventional core 9 (12,212 to 12,241.5 feet) from the COST No. 2 well. This core sampled the volcaniclastic conglomerate and sandstone sequence of lithologic zone Te. Two drilling breaks and gas peaks an order of magnitude larger than peaks elsewhere in the well were recorded between 12,180 and 12,290 feet.

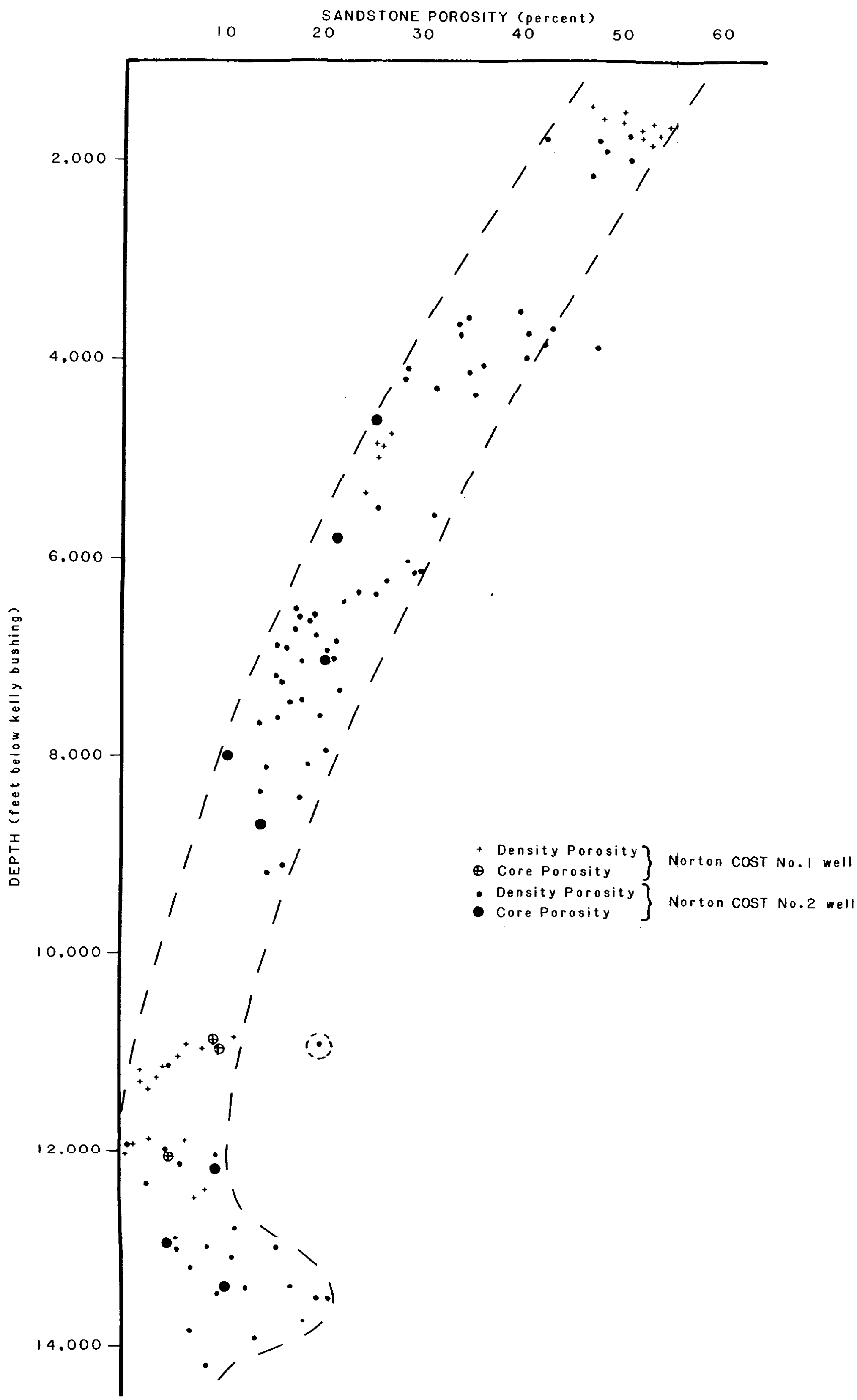

FIGURE 24. **Distribution of sandstone porosity with depth, Norton Basin COST No.1 and No. 2 wells. Porosity calculated from Compensated Formation Density log data and conventional core measurements.**

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These indications of good porosity and permeability were not corroborated by the core analysis, which measured permeabilities of less than 0.1 millidarcy and porosities of only 7 to 12 percent. However, the wireline logs suggest that the core may have sampled an interval of less prospective rock between the intervals where the drilling breaks occurred.

These two prospective zones were evaluated by well log analysis. Each of the intervals displays an annulus invasion profile on the Dual Induction Log. The annulus effect is detected by a higher resistivity reading on the deep induction curve than on the medium induction curve, which is significant because it generally denotes hydrocarbon zones (Asquith, 1982, p. 4).

A Hingle crossplot (Hingle, 1959) was constructed over the interval containing these two prospective zones (fig. 25). This type of crossplot is useful for determining the water saturation of a reservoir (SW) where the formation water resistivity (RW) is unknown. An RW of 0.045 ohm-meters and a sandstone matrix density of about 2.72 to 2.73 grams per cubic centimeter were determined from the plot. The sandstone matrix density obtained from the plot agrees well with several grain density values of 2.71 to 2.72 grams per cubic centimeter obtained from an analysis of core 9 from the interval. The close correspondence obtained from these two disparate techniques provides a positive check on the validity of the data from the crossplot.

Water saturations of less than 40 percent (60 percent oil saturation) are indicated by the Hingle plot for the upper parts of the prospective zones. The lowest water saturations on the plot (those between 15 and 25 percent) are probably not valid, however, because these values were determined from a badly washed-out interval in the borehole (which may also represent a coaly interval). The porosities in the washed-out interval were determined from the Borehole Compensated Sonic Log, which is less affected by bad hole conditions than the density log, but nevertheless probably could not compensate for the greater than 20-inch hole size of the caved interval.

Permeabilities in the prospective zones were estimated by plotting porosity versus water saturation on the Schlumberger chart (1972a) shown in figure 26. The permeability values plot approximately parallel to the hyperbolic, bulk-volume water lines, which indicates that the reservoir intervals are at irreducible water saturation. Irreducible water saturation, a condition in which all water is adsorbed on grains or held by capillary pressure, is necessary for obtaining valid permeability values from the chart (Schlumberger, 1972a). A few of the chart-derived permeability values for gas approximate the permeabilities measured from cores obtained at corresponding depths (upper left points, fig. 26). However, the points plotting to the right of the 5-millidarcy gas and 50-millidarcy oil permeability line are a washed-out zone, and these high permeability values are probably not valid. The single core

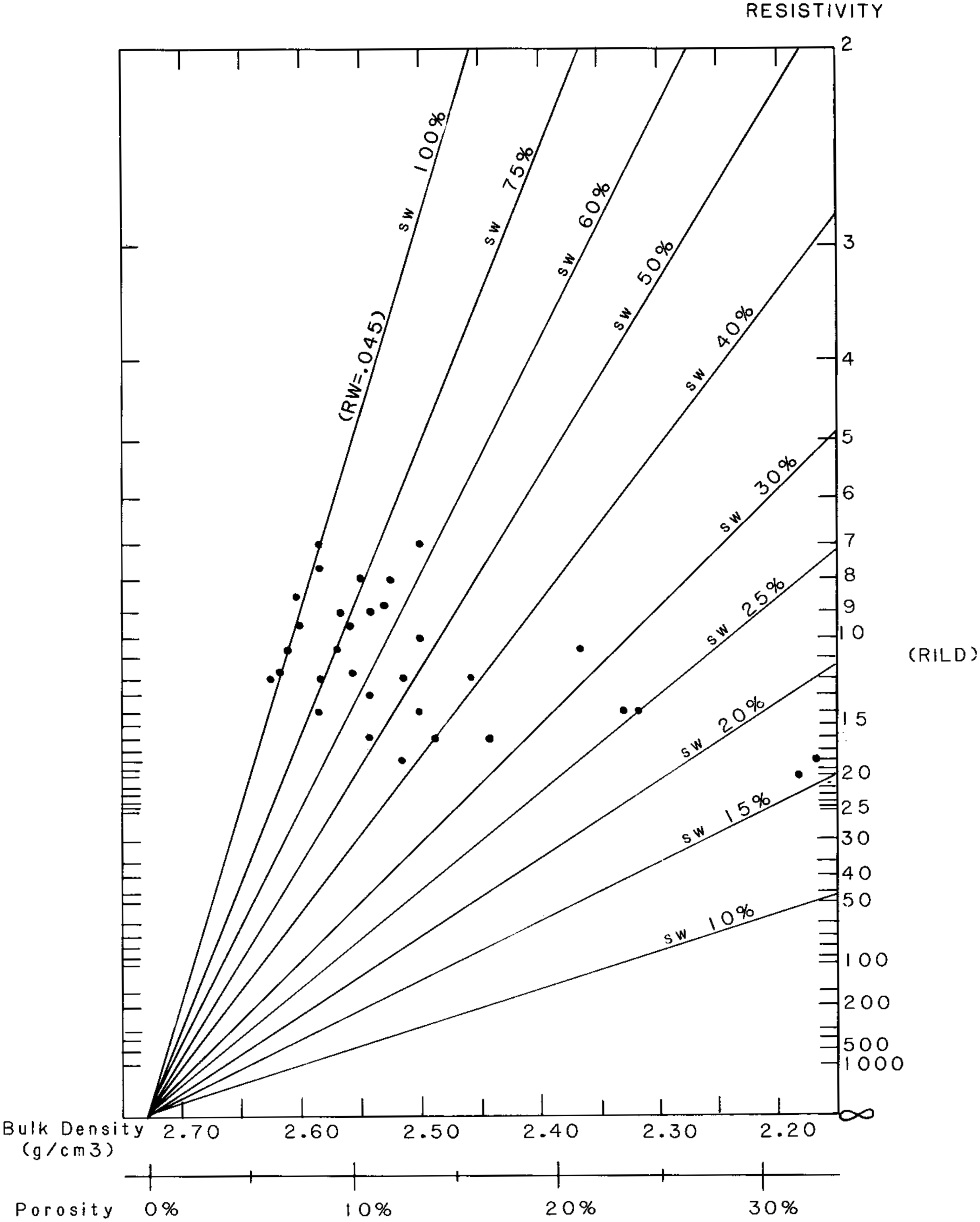

FIGURE 25. **Water saturation determinations of a suspected oil zone at 12,133 to 12,300 feet, Norton Basin COST No.2 well. Hingle (1959) crossplot of deep induction resistivity (RILD) versus density porosity (chart after Helander, 1983, fig. 9-25; cementation exponent m= 2.0).**

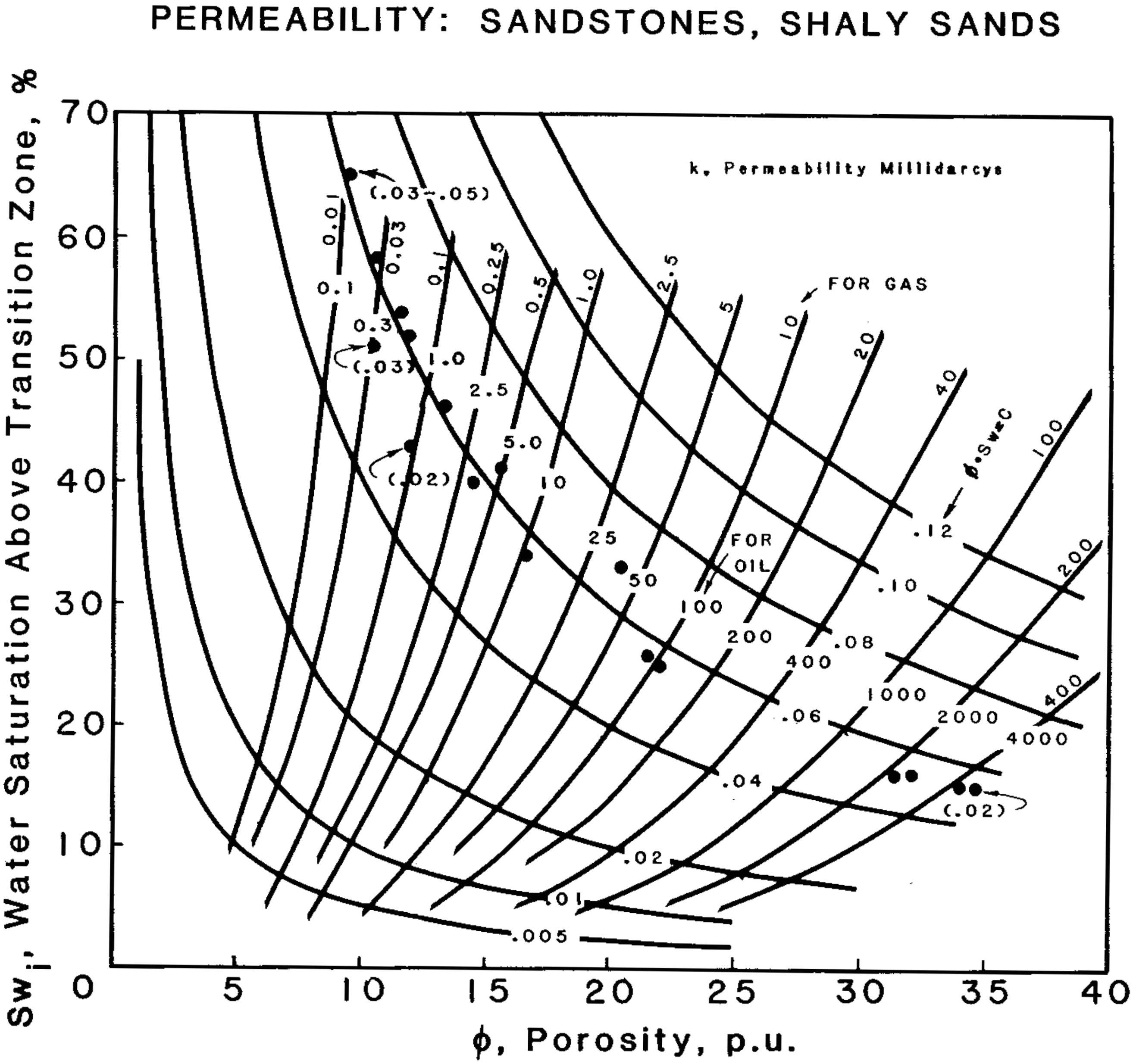

FIGURE 26. Chart of porosity (Ø) versus irreducible water saturation (swi) for estimating permeability and determining bulk volume water (c=sw x Ø) for Norton Basin COST No. 2 **well (depths 12,182 to 12,218 feet).** Numbers in parentheses adjacent to plotted points indicate measured permeability (for gas) from conventional cores (chart after Schlumberger,1972a).

permeability from this zone was much smaller (0.02 millidarcy) than the chart value (greater than 400 millidarcies). Nevertheless, the remaining values on the chart appear to be reasonably accurate and suggest permeabilities (for oil) as high as 40 millidarcies. If this analysis is valid, it not only indicates a significant show of liquid hydrocarbons, but also documents the occurrence of fair quality reservoir rock at depths where figure 24 predicts the occurrence of only very poor reservoirs.

8

Organic Geochemistry

SURFACE HYDROCARBONS AND INITIAL EXPLORATION

Traces of hydrocarbons have been reported in the vicinity of Norton Sound since the turn of the century (fig. 27). Two test wells were drilled in 1906 in the coastal plain east of Nome at Hastings Creek, and two more were drilled in 1908. They were reported to have been drilled on an oil seep. One of the earlier holes encountered gas at 122 feet which nearly blew the drill stem out of the bore hole, and the other produced a trace of oil. None of these wells were drilled much deeper than 200 feet. The gas encountered was believed to have been marsh gas.

Oil seeps have been reported in the Sinuk Valley near the junction of the Sinuk and Stewart Rivers, about 20 miles northwest of Nome, and near the mouth of the Inglutalik River, which drains into Norton Bay. Several exploratory wells are said to have been drilled in the Sinuk Valley, but there is no record of the results. Miller and others (1959) state that oil shale has been reported to occur on Besboro Island, northwest of Unalakleet in Norton Sound. These early reports remain largely unconfirmed.

In 1976, a submarine seep of natural gas was reported approximately 24 miles south of Nome by Cline and Holmes (1977). They described a plume of C_2 to C_4 alkane-rich water advecting north from a point source on the seafloor. This plume reached the coast as far east as Cape Nome, but generally spread westward past Sledge Island to at least 168° W longitude (fig. 27).

Cline and Holmes (1977) suggested that these gases were of thermogenic origin on the basis of the highly localized nature of the hydrocarbon source, the relatively low ethane-to-propane ratio (C_2/C_3), the proximity to unconformable, truncated strata that dip basinward from the seep locus, and the presence of seismically defined acoustic anomalies and numerous steeply dipping faults in the immediate vicinity. Subsequent analyses of seafloor sediments recovered from vibracores in the vicinity of the seep placed its location about 30 miles south of Nome (Kvenvolden and others, 1979; Kvenvolden and Claypool, 1980). Kvenvolden and Claypool (1980) concluded that the

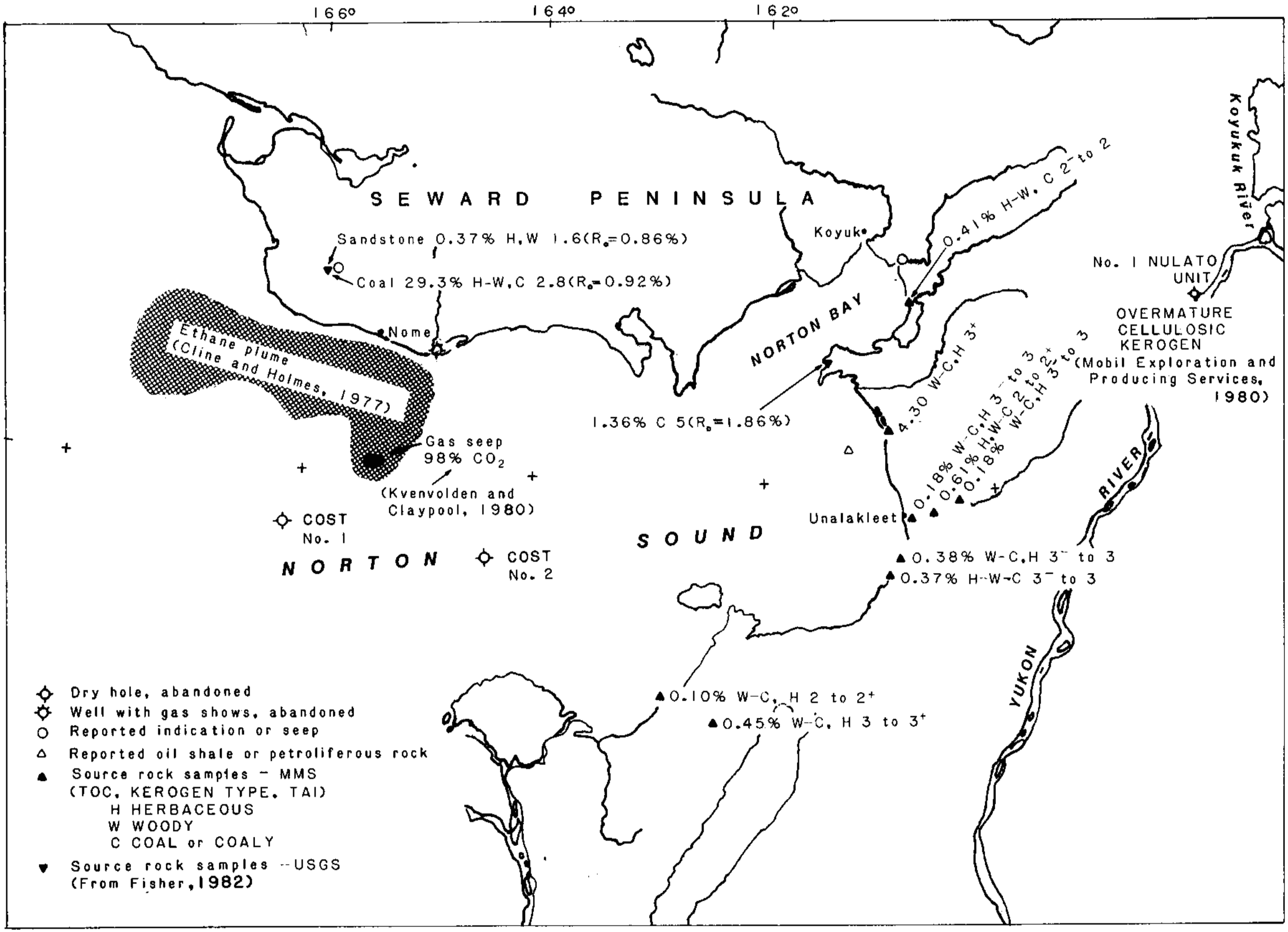

FIGURE 27. **A partial compilation of organic geochemistry from Norton Sound and the adjacent area.**

hydrocarbon compounds present were probably thermogenic based upon the following evidence:

1) The ratio of $C_1/(C_2+C_3)$ is less than 20 at sediment depths greater than 50 centimeters.

2) $\delta^{13}C_{PDB}$ for one methane sample is about -36 parts per thousand (see Bernard and others (1977) for interpretative geochemical model).

3) About 50 gasoline-range hydrocarbon compounds (C_5 to C_8) were positively or tentatively identified and three of five samples have C_7 compositions that resemble the immature, nonmarine Kenai condensate. The other two samples yielded C_7 compositions that resemble both immature nonmarine condensate and biodegraded oil from the Gulf of Mexico.

The hydrocarbon components comprised only 0.1 percent of the above methane sample; the remainder consisted of about 98 percent carbon dioxide with $\delta^{13}C_{PDB}$ equal to -2.7 parts per thousand (per mil). Kvenvolden and Claypool (1980) suggest that the CO_2 may have been produced by the decarbonization of carbonate in basement rocks by heat or fluids, and that the CO_2 acted as an extraction agent as it migrated through the sedimentary column and transported hydrocarbons to the surface.

SURFACE EXPOSURES OF POTENTIAL SOURCE ROCK

Samples of potential source rock from exposed sediments surrounding Norton Sound have been collected by the USGS (Fisher, 1982) and the Minerals Management Service and Alaska Department of Natural Resources (Lyle and others, 1982).

Five Paleozoic to Mesozoic age samples from St. Lawrence Island (Fisher, 1982) yielded thermal alteration indices (TAI) ranging from 1.6 to 3.6, which can be interpreted as a maturation range of immature to very mature (Bayliss and Smith, 1980). Fisher (1982) suggests that local heating by igneous activity may have produced a complex thermal history for these rocks. Only two shales containing woody-herbaceous kerogen were sampled and they contained about 2 percent organic carbon and yielded no more than 708 parts per million (ppm) total $C_{15}+$ extractable bitumen, probably from coal macerals. Two thermally immature limestone samples contained less than 0.3 percent organic carbon and a single mature dolomite sample contained 0.4 percent organic carbon and 439 ppm $C_{15}+$ total extract.

Three of the four Tertiary samples from St. Lawrence Island contained coal with total organic carbon contents (TOC) as high as 82 percent (Fisher, 1982). The maximum amount of $C_{15}+$ bitumen from these samples, 489 ppm, constitutes a poor anomaly (Bayliss and Smith, 1980). A calcareous sandstone sample was immature and contained only 0.4 percent total organic carbon. The Tertiary coal samples tended to be moderately mature, with a mean vitrinite reflectance (R_o) of about 0.6 percent and TAI values no greater than 2.

The limited public information from St. Lawrence Island indicates that the organic material is composed predominantly of humic, gas-prone kerogen characterized by low amounts of organic carbon except where coal is present. The thermal maturity is variable, depending, at least to some extent in the older rocks, upon the proximity of igneous activity.

Two samples of probable Tertiary age from the Seward Peninsula in the vicinity of the Sinuk River were analyzed by the USGS (Fisher, 1982). One was a sandstone with a TOC of 0.37 percent and an R_o of 0.86 percent, the other a coal sample with 29 percent TOC and an R_o of 0.92 percent. The organic material in these samples can be classified as mature humic kerogen, possibly capable of generating gas.

The USGS sampled a Paleozoic limestone at Cape Denbigh that contained 1.36 percent TOC and produced 105 ppm $C_{15}+$ total extract. It contained coaly material with an R_o of 1.86 percent. Several Oligocene coal samples from near Unalakleet yielded R_o values of about 0.3 percent (Fisher, 1982). These coals appear to be rather insignificant in total volume and are so poorly exposed that they are often difficult to locate in the field.

Considerably more sampling has been performed on the east coast of Norton Sound, particularly from sequences of late Early and early Late Cretaceous rocks (Patton, 1973) which are exposed in the vicinity of Unalakleet. Woody and herbaceous gas-prone kerogen and small amounts of coal are present in the clastic sediments. The USGS analyses (Fisher, 1982) produced total organic carbon values from 0.31 to 1.87 percent, excluding coal and coaly shale. MMS analyses for TOC from similar samples in the same area range from 0.05 to 7.88 percent, with coaly inertinite present in a few samples (Lyle and others, 1982; unpublished MMS data). Almost all samples collected from this region contain less than 1.0 percent TOC and most have less than 0.5 percent organic carbon. Samples processed for soxhlet extraction produced less than 300 ppm total extract when coal was present. The USGS evaluated the thermal maturity of the outcrop samples from the east coast of Norton Sound using both R_o and TAI values and also evaluated a few samples by Rock-Eval pyrolysis. Minerals Management Service samples from the same area were evaluated using TAI. Samples ranged from immature to severely altered on the basis of TAI values, but most could be considered capable of producing either "wet" or "dry" hydrocarbon gas depending upon the kerogen type. However, Fisher (1982) noted a discrepancy between R_o values and TAI values for some samples collected along the east coast of Norton Sound. Most of the USGS R_o values ranged from about 2 to 3 percent (very mature to severely altered kerogen), in contrast with TAI values of approximately 2 to 3 (moderately mature to mature kerogen). The USGS checked seven of their samples by Rock-Eval pyrolysis and the results compared most favorably with the R_0 data. The temperature at which maximum pyrolytic hydrocarbon generation occurs, T_2-max °C, ranged from 475 to 530 °C. If these higher values are correct, it is likely that only dry gas could survive in these rocks.

During 1959 and 1960, a test well was drilled by Benedum and Associates in the Yukon-Koyukuk clastics at Nulato, about 80 miles east of Norton Bay on the Yukon River. The sedimentary rocks of this province were described by Patton (1973) as predominately graywacke and mudstone. The visual kerogen and maturation analyses of the well samples later conducted by Mobil Exploration and Producing Services, Inc., are available from the Alaska Oil and Gas Conservation Commission. All well cuttings to a depth of 11,700 feet below the kelly bushing (elevation 865 feet) contained largely "cellulosic" gas-prone kerogen. Nearly all vitrinite reflectance measurements are in excess of 3 percent and the organic material is considered to be overmature. No oil or gas was reported.

Clastic rocks of the Yukon-Koyukuk province are exposed east of Norton Sound. Seismic studies have not resolved the relationship of these deformed rocks to the metamorphic "basement" complex of either of the Norton Basin COST wells. Cretaceous and Tertiary sediments which crop out on the coast may actually have been exposed to higher temperatures than equivalent rocks in the Norton Basin COST wells. The location and apparent shape of the Yukon-Koyukuk province, as well as the trend (220 degrees) and plunge (16 degrees) of folds in the vicinity of Unalakleet (unpublished MMS data), suggest that substantial amounts of Yukon-Koyukuk sediments are not present beneath Norton Sound, except perhaps in the extreme southeast corner. Moreover, the apparent lack of organic material and the high level of thermal maturity on the margin of the sound make these sediments an unlikely source of oil for the Norton Basin.

OFFSHORE STRATIGRAPHIC TEST WELLS

In 1980, the first Norton Basin COST well was drilled in the St. Lawrence subbasin. This was followed in 1982 by a second COST well in the Stuart subbasin. These deep stratigraphic tests provided the first opportunity for a detailed examination of the subsurface geology of Norton Sound and for a reasonable assessment of the petroleum potential of the basin. The locations of these wells are indicated on figure 27.

COST No. 1 Well, St. Lawrence Subbasin

In the COST No. 1 well in the St. Lawrence subbasin, geochemical analyses were performed by Core Laboratories, Inc., and by Geochem Laboratories, Inc. From the first sample (240 feet) to about 12,000 feet below the kelly bushing (elevation 98 feet), the total organic carbon content (TOC) generally ranged between about 0.5 and 2.0 percent (fig. 28). TOC values in excess of 2.0 percent occur most frequently below 9,000 feet and are generally associated with the occurrence of coal. The kerogen is composed mostly of gas-prone woody, coaly, and herbaceous materials. Examinations of the organic material by petrographic microscope in reflected light indicate that at least 50 percent of the kerogen in most samples belongs to the vitrinite group (fig. 28). The hydrogen index (S_2/TOC) from pyrolysis does not exceed 300 milligrams hydrocarbon per gram TOC and is generally less than 100 milligrams per gram. Traces of coal are generally present in samples producing the higher hydrogen indices in figure 29. Between 12,000 and 13,000 feet, there is an increase in the coal content of the samples and a corresponding increase in TOC and the proportion of inertinite (up to 80 percent). At 13,000 feet, the hydrogen index drops sharply, presumably in response to the low hydrogen content of the inertinite. From 13,000 feet to 14,683 feet (T.D.), the TOC is less than 1.0 percent and most TOC values in the interval are less than 0.5 percent. Vitrinite and inertinite compose at least 90 percent of the kerogen and the hydrogen index is negligible (fig. 28). Metamorphic phyllite and schist are present in samples from depths greater than approximately 14,500 feet.

The contact between the probable Eocene and the possible Paleocene occurs at about 12,200 feet in the COST No. 1 well. As shown in figure 30, this depth also corresponds to an abrupt, discontinuous increase in the R_o profile (random mean vitrinite reflectance versus depth). The increase in the age of the rocks, the sudden appearance of coal, the change in the composition of the kerogen, and the marked discontinuity in the R_o profile (fig. 30) combine to suggest the existence of a significant unconformity at this depth.

There appears to be fair agreement among the several indicators of thermal maturity in the well. On the basis of the criteria of Tissot and Welte (1984) and Hunt (1979), the current oil generative zone in the COST No. 1 well extends from approximately 9,500 feet to 12,500 feet. The random mean vitrinite reflectance varies from about 0.6 to 1.3 or 1.4 percent and T_2-max °C from Rock-Eval pyrolysis ranges between about 435 and 460 °C (fig. 30). Below 12,600 feet, however, there is no sense of accord among the various indicators of thermal maturity. Random mean vitrinite reflectance values, in particular, tend to be high and erratic. It is probable that sediments are approaching metagenic grade by 13,500 feet (an R_o of approximately 2.0 percent according to Tissot and Welte, 1984).

In the COST No. 1 well, the indicators of maturity based on kerogen analysis do not agree perfectly with those based on heavy- or light-hydrocarbon analysis. Radke and others (1980) observed that in coals, the odd-even predominance of n-alkanes from C_{15}+ extracts, as expressed by the carbon preference index (CPI), exhibits

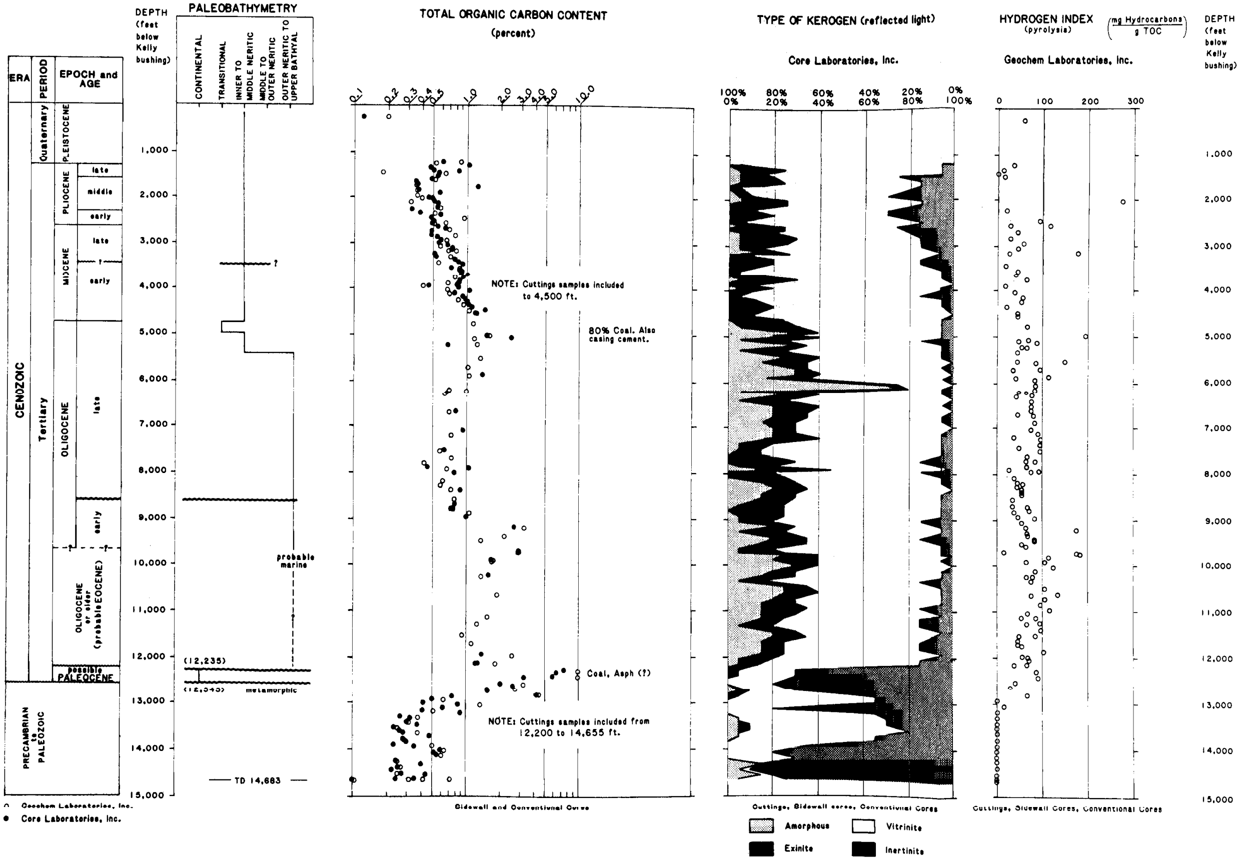

FIGURE 28. **Organic carbon and classification of organic matter COST No. 1 well, St. Lawrence subbasin.**

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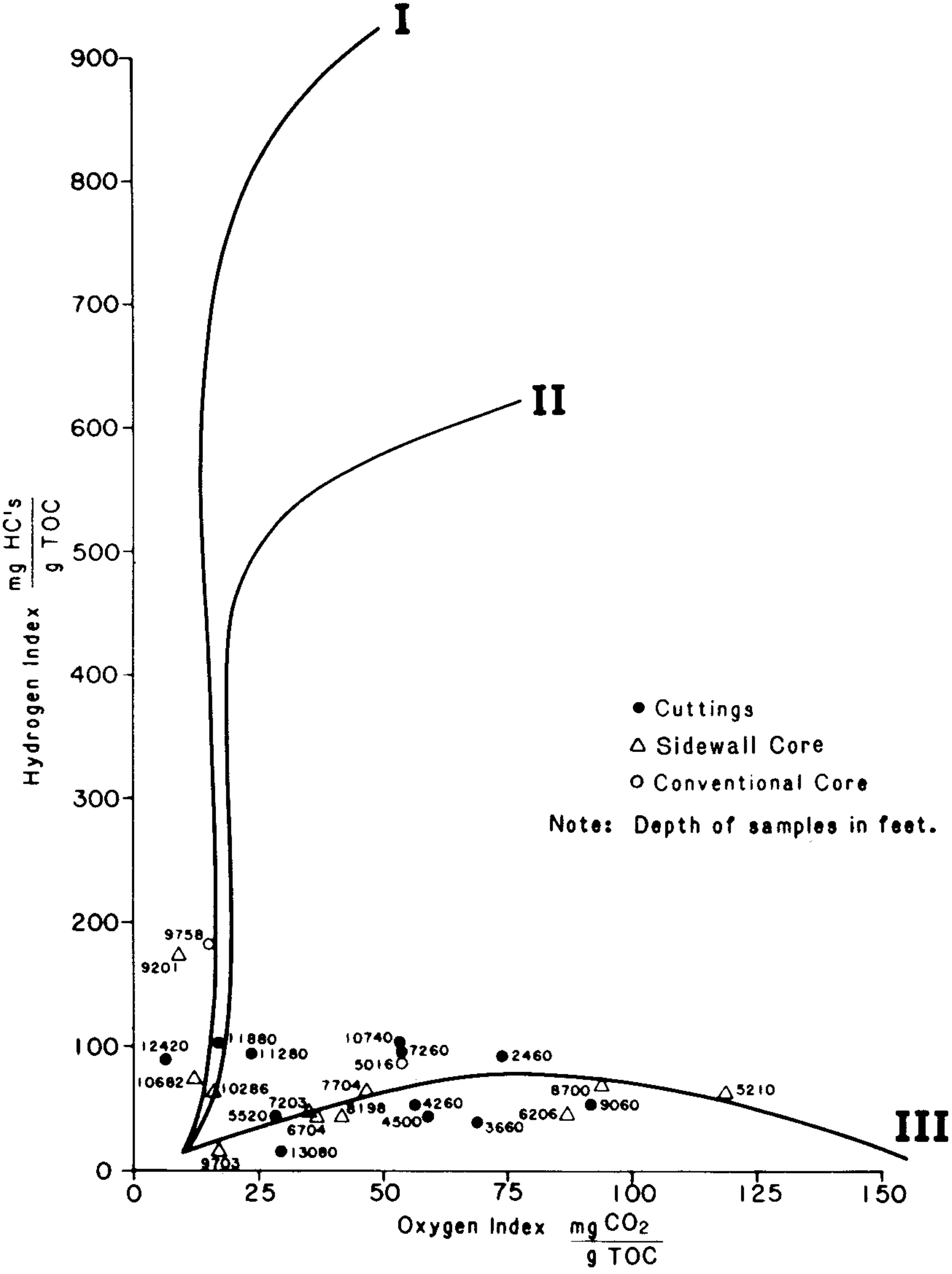

FIGURE 29. Modified Van Krevelen diagram, COST No. 1 well, St. Lawrence subbasin. (Pyrolysis analyses performed upon representative sidewall core samples by Geochem Laboratories, Inc.)

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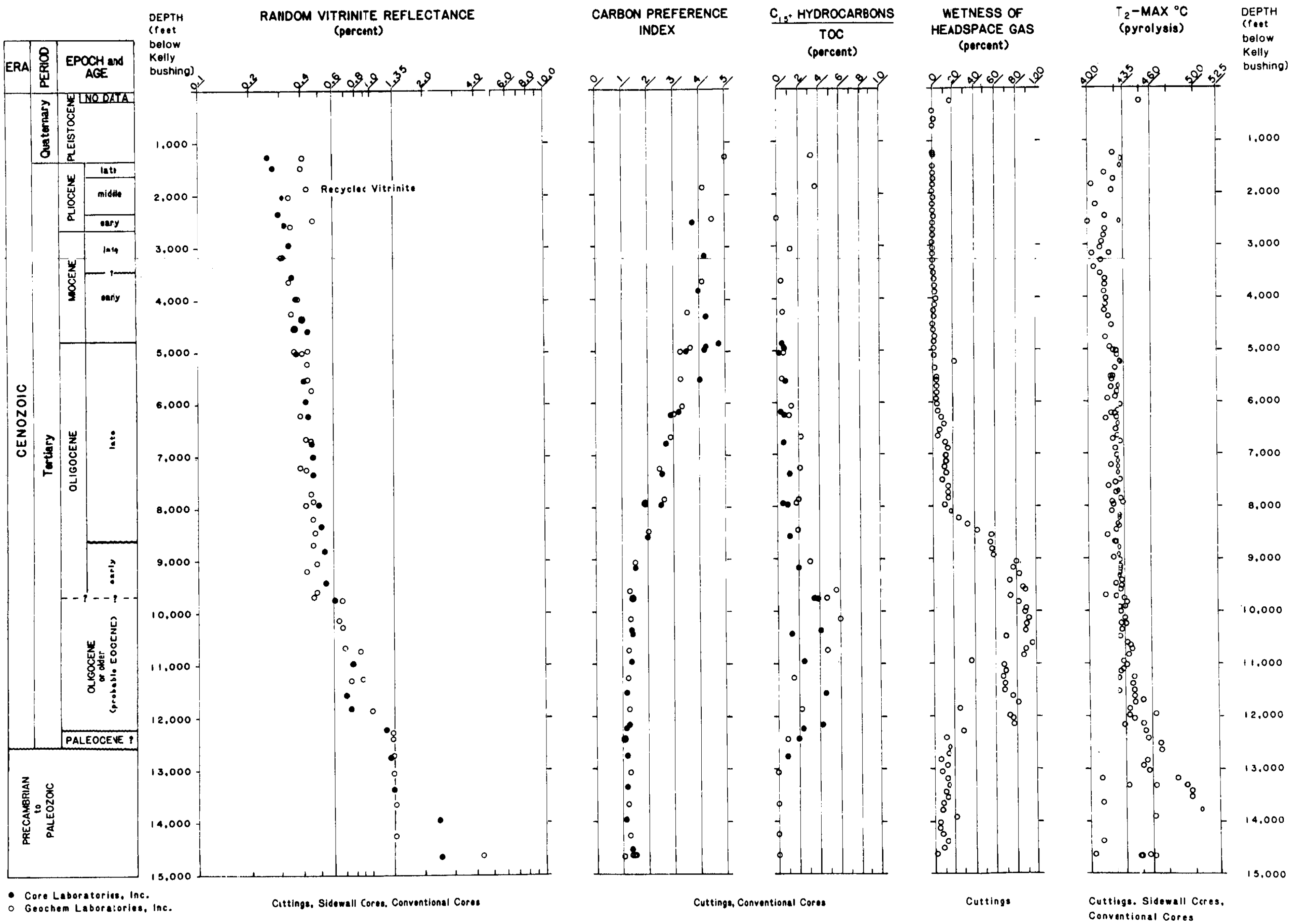

FIGURE 30. Indicators of thermal maturity COST No. 1 well, St. Lawrence subbasin.

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a gradient change between vitrinite reflectances of 0.9 and 1.0 percent. Their data actually become asymptotic at a vitrinite reflectance slightly above 1.0 percent. The peak of oil generation for a type III, humic kerogen should occur at about this R_o level (Tissot and Welte, 1984). As shown in figure 30, the CPI is becoming asymptotic at about 9,500 feet, which corresponds to an R_o of roughly 0.6 percent. The ratio of C_{15}+ extractable hydrocarbons to TOC begins to increase at a depth of around 9,000 feet and the wetness of the headspace gas begins to increase at around 8,000 feet. This suggests that these hydrocarbons may have migrated, at least from the coals within the catagenetic zone, if not from some more distant source.

Briefly, the COST No. 1 well in the St. Lawrence subbasin penetrated a sedimentary section that is dominated by humic, type III, gas-prone kerogens. The total organic carbon content is generally low. At depths greater than 13,000 feet there is no indication that sufficient hydrogen and reactive carbon have been available to generate significant quantities of hydrocarbons. The current oil window occurs between approximately 9,500 and 12,500 feet, encompassing an Oligocene to possible Paleocene stratigraphic section. Biogenic methane appears to be present above 6,000 feet and traces of thermogenic hydrocarbons are present at depth, but no significant oil shows were encountered in this deep stratigraphic test well.

COST No. 2 Well, Stuart Subbasin

Analyses were performed on samples from the COST No. 2 well by Robertson Research (U.S.), Inc. As in the section on the COST No. 1 well, all depths referred to in this chapter were measured from the kelly bushing (elevation 105 feet).

Organic carbon is generally abundant throughout most of the sedimentary section penetrated by this well, especially in the coal-bearing intervals from 3,500 to 4,600 feet, 6,400 to 8,600 feet, and 12,200 to 14,000 feet (fig. 31).

The kerogen recovered throughout the well is composed predominantly of humic, type III, gas-prone macerals probably derived from terrestrial sources (fig. 32). Examination of this kerogen in reflected light with the petrographic microscope revealed a zone between 9,500 and 12,000 feet that contained relatively higher percentages of amorphous organic material (fig. 31). However, the hydrogen index from Rock-Eval pyrolysis does not correspond to the petrographic analysis for this interval. Elemental analysis of the kerogen tends to support the pyrolysis data (Turner and others, 1983b).

There are several possible explanations for the higher petrographic estimates of amorphous organic material. Amorphous kerogen is generally assumed to be composed of sapropelic, hydrogen-rich organic material (Hunt, 1979). Such kerogen should have hydrogen indices greater than 100 milligrams per gram (mg/g) provided it has not been exposed to high temperatures for any significant period of time. Humic material can be altered mechanically or chemically to the point that it may resemble amorphous kerogen. Dow (1982) suggests that at least part of the "amorphous" fraction of the kerogen from the well is actually degraded, or finely divided, vitrinite or low-yield, oxidized amorphous material with very low oil-generating capability. Tissot and Welte (1984) point out that amorphous facies can result from severe alteration of the original constituents, which then lose their identity. Flocculated humic acids derived from the colloidal state have an amorphous appearance under the microscope. The elemental analysis of such material would fall along the type III evolution path, but its appearance under the microscope could lead it to be classified as sapropelic material with good oil potential. Finally, the transformation ratio, $S_1/(S_1+S_2)$ (Tissot and Welte, 1984), which indicates the extent to which the full genetic potential of the original kerogen has been realized, provides an additional partial explanation for the reduced hydrogen indices (fig. 31). At around 10,000 feet, some of the available hydrogen is beginning to occur in the form of light, volatile hydrocarbons as the catagenetic zone is approached. Rock-Eval pyrolysis detects this hydrogen as S_1 rather than as S_2, from which the hydrogen index is calculated (H.I. = S_2/TOC). It seems reasonable to conclude, therefore, that the organic material analyzed from this well is nearly all type III humic kerogen and coal, rather than amorphous, sapropelic material.

From 12,000 to about 14,000 feet, vitrinite group macerals become the dominant kerogen type and the hydrogen index is low (less than 100 mg/g). TOC values in this interval are erratic, and range as high as 55 percent where coal is present in a sample (fig. 31). From 14,400 to 14,889 feet (T.D.), metamorphic lithologies such as schist and marble are present in the samples. The organic carbon of the metasediments is very low. The genetic potential, that is the amount of hydrocarbons that can be generated during burial, is also very low.

The indicators of thermal maturity (fig. 33) are in better agreement with one another in the COST No. 2 well than in the No. 1 well; nevertheless, there remain inconsistencies that require explanation. Because of the large amounts of vitrinite in the No. 2 well, R_o values ought to be very reliable. They suggest that the onset of oil generation for type III kerogen should occur at about 10,700 feet and that the oil window extends to perhaps 14,000 feet. The other measures of thermal maturity imply that the threshold for oil generation may be nearer to 10,000 feet (fig. 33). When R_o values exceed 2.0 percent, dry gas becomes the most likely hydrocarbon product (Hunt, 1979; Tissot and Welte, 1984). The R_o profile projects to 2.0 percent at about 15,300 feet. It has not been precisely determined to what depths dry gas can survive, but the metamorphic basement at approximately 14,500 feet in this well clearly sets a limit at this location.

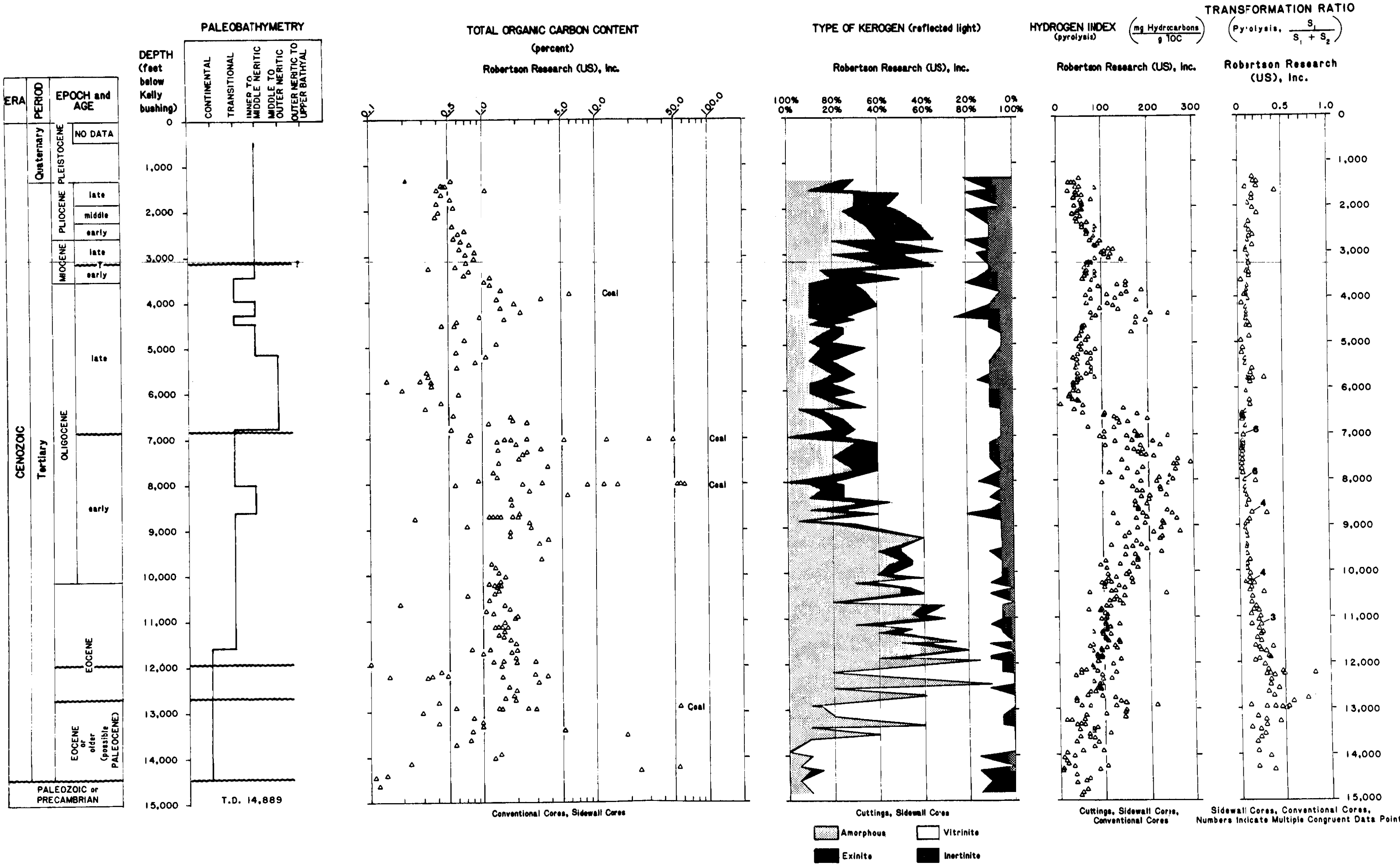

FIGURE 31. **Classification of organic matter, COST No. 2 well, Stuart subbasin.**

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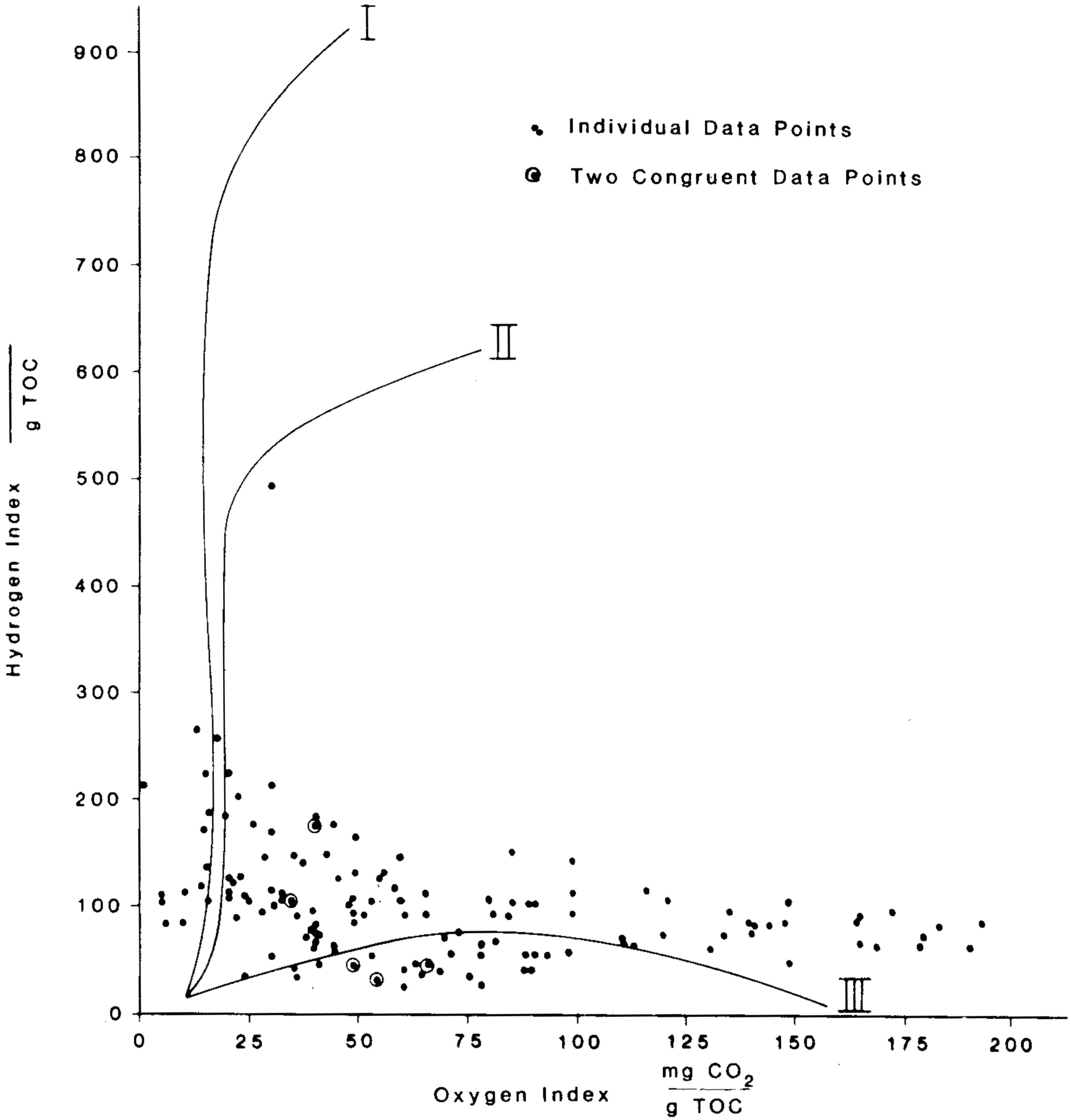

FIGURE 32. Modified Van Krevelen diagram, COST No. 2 well, Stuart subbasin. (Pyrolysis analyses performed upon selected sidewall core samples by Robertson Research (US), Inc.)

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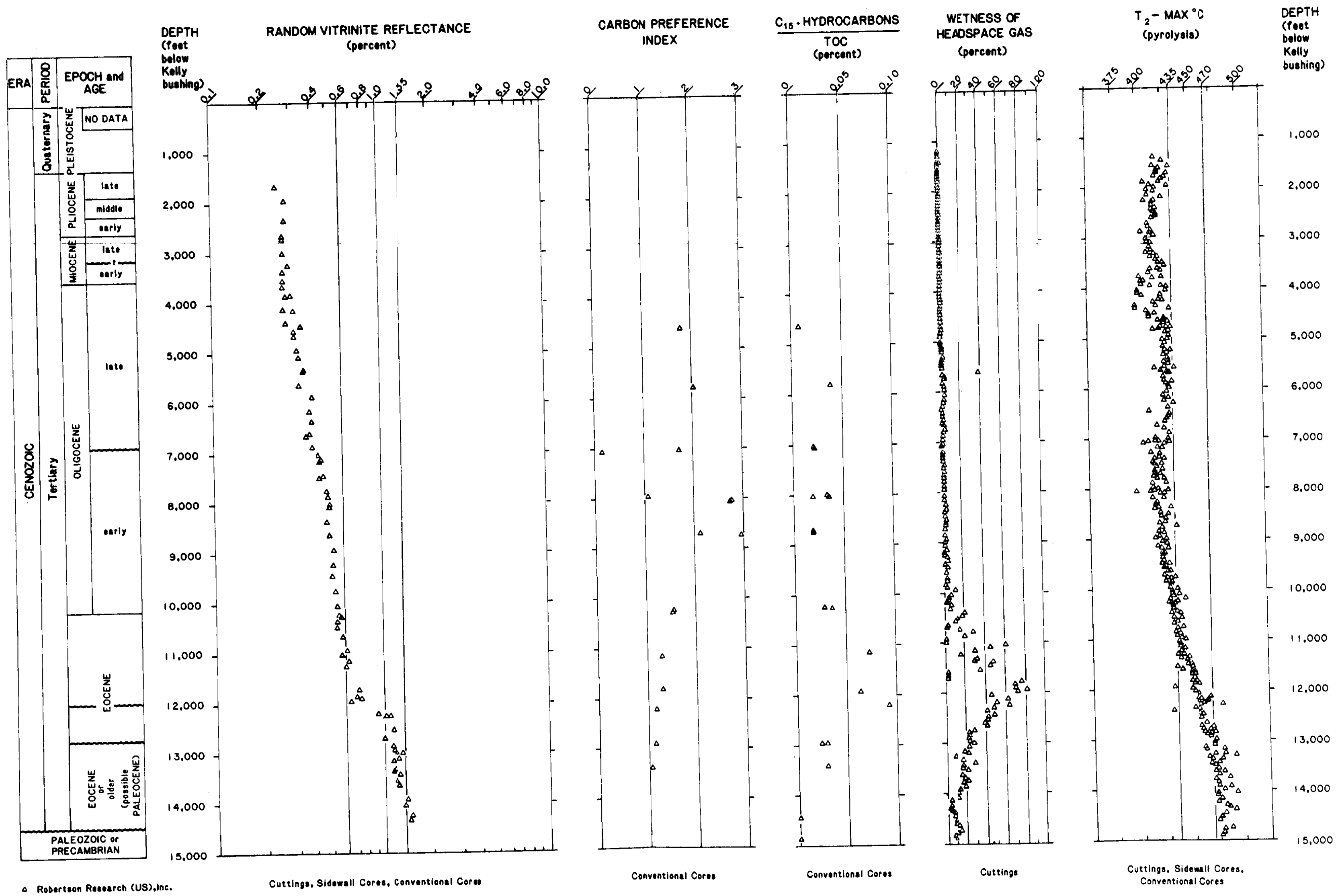

FIGURE 33. **Indicators of thermal maturity, COST No. 2 well, Stuart subbasin.**

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The R_o gradient between 8,000 and 12,100 feet appears to be anomalously shallow. That is, the R_o values do not increase with depth at the same rate at which they increase throughout the remainder of the well, except for a few samples above 3,000 feet which seem to contain reworked material. It is possible that coal, which is extremely friable, might have contaminated samples in the 8,000- to 12,100-foot interval and reduced the mean values of the vitrinite reflectance. Although this may appear unlikely in view of the fact that some of the analyses were performed on sidewall and conventional core samples, Hunt (1979) cautions that sidewall cores are generally taken after a well is drilled to total depth and the formations have been subjected to the high pressures of circulated drilling mud. Drilling mud with diesel or crude oil in it, or possibly even fine coal particles in this instance, may have introduced contaminants that were then sampled by the sidewall cores.

There is also a discontinuous increase (from around 0.7 to 1.0 percent) in the R_o profile at approximately 12,100 feet. An apparently correlative anomaly is present on a profile of the spore coloration index at about 11,900 feet (Turner and others, 1983b; Dow, 1982). Dow (1982) suggested that this anomaly may represent the Mesozoic-Cenozoic unconformity first postulated by Fisher (1982), and might entail several thousand feet of erosion. Paleontological evidence, however, indicates that Tertiary sediments occur to about 14,500 feet at this site.

The second drilling run was completed at 12,000 feet of depth and the hole was cased. This probably stopped contamination from lithologies above 12,000 feet and may explain a part of the discontinuous increase in R_o values, but it does not appear to account for the entire increase. In addition, the R_o gradient, or rate of of R_o increase with depth, is greater for the lithology below 12,100 feet than for any other part of the stratigraphic test.

The caving hypotheses can be tested in a preliminary way by constructing a Lopatin model to compare calculated levels of maturity based upon the current temperature gradient with observed R_o values from the COST No. 2 well. Lopatin (1971) suggested a method for applying the Arrhenius equation to calculate a coefficient he called the time-temperature index (TTI), which serves as a measure of thermal maturity. It corresponds to random vitrinite reflectance (R_o) or to Staplin's (1969) thermal alteration index (TAI). It can be demonstrated from the Arrhenius equation that the rate of a chemical reaction doubles for every 10 °C increase in temperature if the activation energy and the temperature of the reaction are relatively low (Tissot and Welte, 1984). Because sediments become progressively hotter upon burial, an interval maturity can be calculated by multiplying the time of residence, ΔT, in a temperature interval of 10 °C by a factor of 2^n, which changes to 2^{n+1}, $2^{n+2}...2^{n}max$ every 10 °C. Lopatin arbitrarily assigned a value of 0 to n for the temperature range from 100 to 110 °C. The total sum of the interval maturities is termed the time-temperature index, or TTI.

$$TTI = \sum_{n_{min}}^{n_{max}} 2^n \, (\Delta T_n)$$

Tissot and Welte (1984) feel that this model does not adequately take into account the consequences of higher temperatures and greater activation energies that are believed to be involved after the peak of oil generation has been reached, the point after which thermal cracking becomes the predominate mechanism. However, uncertainties regarding the correct temperature gradient, the possibility that the temperature gradient has changed through time, the absolute ages of the sediments, the timing and amount of tectonic activity, and the composition of the organic material probably present much more formidable problems than do chemical kinetics. For example, there is frequently no adequate drilling history from which a correction can be computed for raw temperature data taken from a drill hole. Waples (1984a) has pointed out that despite theoretical objections, the Lopatin model is simple to work with and that the results of many applications to exploration have demonstrated that it generally works well (Falvey and Deighton, 1982; Magoon and Claypool, 1983; Middleton and Falvey, 1983; Ibrahim, 1983; Bachman and others, 1983; Issler, 1984).

To apply the Lopatin model it is necessary to reconstruct the depositional and tectonic history for the sediments being studied. This has been done for four horizons located at 3,600, 6,900, 10,700, and 14,000 feet in the COST No. 2 well (fig. 34). The estimated absolute ages (in millions of years before present) are given in table 4.

Table 4. Depths and absolute ages of sediments in the Norton Basin COST No. 2 well used in the Lopatin computation.

Depth (feet)	Age (m.y.)
3,600	24 (late Oligocene)
6,900	30 (early Oligocene)
10,700	40 (late Eocene)
14,000	60 (late Paleocene)

Waples (1984b) considers the greatest source of error in time-temperature modeling to be poor temperature data. Because drilling fluids alter the ambient rock temperature, a correction must be made to the observed temperature measurements. Bottom hole temperatures taken at the end of each drilling run were corrected using a technique based upon the observation that the temperature rise after circulation has stopped is similar to static pressure buildup and thus may be analyzed in a similar manner (Fertl and Wichmann, 1977). In practice, this technique yields good estimates of true static formation temperature except when circulation times are in excess of 24 hours. After static bottom hole temperatures were calculated from each logging run, a plot of the temperature versus depth was constructed

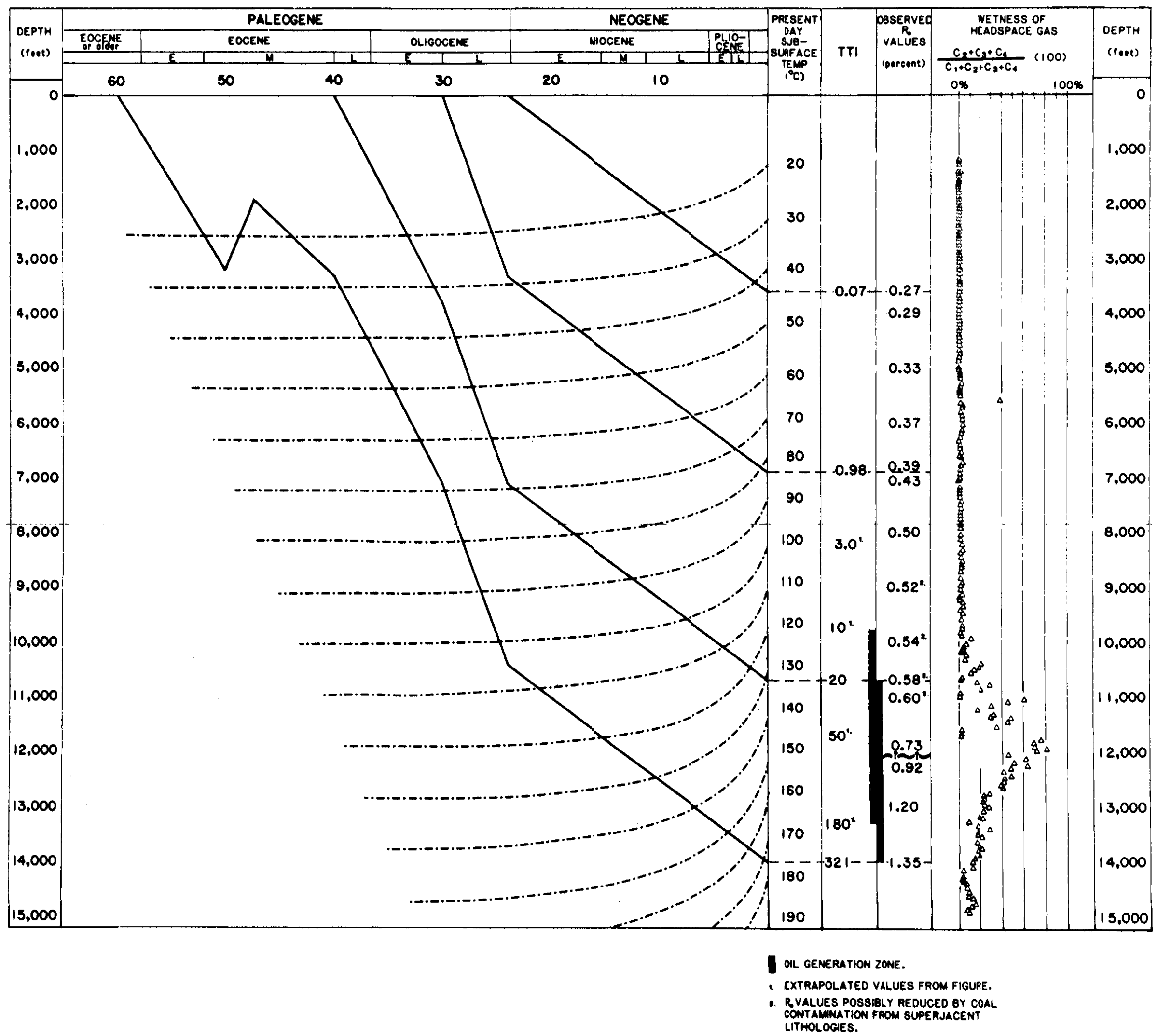

FIGURE 34. **A hypothetical depositional history, tectonic history, and temperature gradient, plus selected indications of thermal maturity, for COST No. 2 well, Stuart subbasin.**

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using both corrected static bottom hole temperatures and two fluid temperatures produced by drill stem tests. This yielded a temperature gradient of 2.38 °F per 100 feet (43 °C/km) below 5,000 feet. At depths less than 5,000 feet, temperature measurements tend to be somewhat erratic, probably due to inhomogeneities in the less-compacted sediments. Uncorrected high-resolution thermometer observations were used from the surface to 5,000 feet. The corrected temperature gradient computed for the COST No. 1 well was 2.39 °F per 100 feet (44 °C/km). Conjectures concerning the temperatures at depths less than 5,000 feet are academic with respect to this Lopatin model because the temperatures are less than 60 °C (140 °F), with the result that 2^n is less than 0.03, a value that results in TTI contributions of no more than 0.5.

Waples (1980 and 1984b) has compared calculated TTI values with measured R_o data from many worldwide samples representing a variety of ages and lithologies. Initial computations, based upon a temperature gradient of 2.38 °F per 100 feet that was assumed to have remained relatively constant for the past 60 million years of earth history, were compared with R_o values from the COST No. 2 well. These initial calculations resulted in TTI values that were much greater than Waples' correlations suggested they should be. Fisher (1982) believes that the average temperature gradient in the Norton Basin has varied between 35 and 45 °C/km since the basin formed. If it is assumed that Fisher's minimal temperature gradient, 1.93 °F per 100 feet (35 °C/km) existed after the most active period of tectonic activity, that it increased to its present value of about 2.38 °F per 100 feet (43 °C/km) rather suddenly during the last 5 or 10 million years, and that surface temperatures have not changed radically, one can then construct the depositional model illustrated in figure 34.

The main zone of oil generation, also termed the oil generation window, has been identified by various authors using random vitrinite reflectance (R_o) (table 5).

Table 5. Random mean vitrinite reflectance values (R_o) for the oil generation zone.

Author	R_o Range
Dow, 1977	0.6 to 1.35%
Hunt, 1977	0.6 to 1.35%
Tissot and Welte, 1984	0.5 to 0.77% $<R_o<$ca. 1.3%

Although the limits for the oil generation zone vary slightly, there is a general consensus that the lower threshold occurs at about 0.5 to 0.6 percent, or perhaps slightly lower if resinite is present (Snowdon and Powell, 1982). The maximum limit of the oil window is generally considered to be about 1.3 or 1.35 percent. When R_o values

Table 6. **Relationship of TTI values to hydrocarbon generation, COST No. 2 well (adapted from Waples, 1984b).**

TTI	R_0(%) Waples, 1984b	R_0(%) Norton Sound COST No. 2 Well, 1982	Stages of Hydrocarbon Generation
1	0.40	0.39 (6,900 feet)	Condensate from Resinite
3	0.50		From S-Rich Kerogen
10[1]	0.60	0.54	Oil — Early
15	0.65		
20	0.70	0.58[2] (10,700 feet)	Oil
50	0.90		Peak
75	1.00		
180[1]	1.35	1.30[1]	Late
321		1.35 (14,000 feet)	Wet Gas
900[1]	2.00	2.00[1]	Dry Gas

[1] *Extrapolated values. See figure 36.*

[2] *The observed R_o value, 0.58%, appears to reflect coal contamination from approximately 8,000 feet. The projected R_o value on figure 36 is nearer to 0.64% at a depth of 10,700 feet.*

exceed 2.0 percent, only dry gas can be anticipated. This value was not observed in the COST No. 2 well, but it can be projected to a depth of about 15,300 feet (fig. 35). This implies that even if sediments were thicker elsewhere in the basin, the thermal maturity of these sediments would probably preclude the preservation of liquid petroleum at these depths.

Lopatin (1971) originally proposed that specific TTI values correspond to various stages of hydrocarbon generation. Waples (1980, 1984b) modified these threshold values. Table 6 is a compilation of some of Waples' (1984b) R_o measurements correlated with modified TTI values based upon numerous worldwide geologic reconstructions. The TTI values from the COST No. 2 well (Stewart subbasin) are included for comparison.

The TTI values computed for the four horizons in the COST No. 2 well are 0.07 (3,600 feet), 0.98 (6,900 feet), 20 (10,700 feet) and 321 (14,000 feet). Additional extrapolated values from figure 35 appear on table 6 to aid in interpretation. Observed R_o values are generally somewhat lower than the correlative TTI values of Waples suggest they ought to be. However, R_o values taken from the interpretive projection (fig. 35) are in much better agreement though still slightly low. A TTI of 10 from the projection corresponds to an R_o value of 0.57 percent (9,700^{+} feet), and a TTI of 20 to 0.64 percent. This lends some support to the thesis that caving may have depressed the R_o values between 8,000 or 9,000 feet and 12,000 feet. If this is correct, the threshold for the oil generation zone would be nearer to 10,000 feet than 10,700 feet and the oil generation zones indicated on figure 35 by the TTI and R_o values would be in relatively good agreement with one another.

The Lopatin model does not prove that an unconformity exists at 12,100 feet, but the presence of such an unconformity would not violate the thermal constraints imposed by the model. Finally, the Lopatin model that produces TTI values which agree most satisfactorily with observed measures of thermal maturity such as vitrinite reflectance suggests that the current temperature gradient has developed in the last 5 or 10 million years and that it may have been significantly lower prior to that time.

Minor amounts of hydrocarbons were observed in Eocene siltstones and sandstones between approximately 10,000 and 13,000 feet in the COST No. 2 well. Dow (1982), reporting on analyses performed by Robertson Research (U.S.) Inc., stated that there was little direct evidence of migrated oil or gas, or of significant petroleum shows in any sample analyzed. A siltstone sample from core 9 (12,212.6 feet) produced nearly 4,000 parts per million of saturate-rich organic extract resembling normal crude oil in composition. A second sample of very fine grained sandstone suspected of containing liquid hydrocarbons from core 9 (12,213.6 feet) contained solid bituminous material identified by Robertson Research (U.S.), Inc., as epi-impsonite on the basis of its R_o and elemental analysis. Dow observed that two samples from core 10 (12,963.6 and 12,972.3 feet) and one sample from core 11 (13,404.9 feet) produced gross compositions, saturate-fraction gas chromatograms, and key ratios similar to the samples from core 9, but their lithologies were predominantly shale. Their total extract contents and extract to TOC ratios are markedly lower than the sandstone samples from core 9 (fig. 30). Sample descriptions indicate that cores 10 and 11 also contained significant amounts of coal (up to 25 percent). Dow (1982) concluded that the extractable bitumen and hydrocarbons occurring in sandstones at around 12,200 feet probably originated in the deeper (12,960 to 13,405 feet), thermally mature shales.

In the COST No. 2 well, the wetness ratio, $\frac{(C_2+C_3+C_4)}{(C_1+C_2+C_3+C_4)} \times 100$, of headspace gas begins to increase at a depth of 10,000 feet; it reaches its maximum value (75.9 percent) at about 11,750 feet (fig. 32). The C_{15}+ hydrocarbon/TOC ratio also begins to increase at about 10,000 feet and peaks (0.088) at 12,212.9 feet (core 9). Predictably, the transformation ratio, $S_1/(S_1+S_2)$, also begins to increase at 10,000 feet, and reaches its maximum value (0.882) in a sidewall core from 12,208 feet (fig. 31). Traces of "free oil" were observed in the drilling mud between 11,800 and 13,000 feet and residual oil was reported from core 9 (see Reservoir Rocks chapter). Anomalously greater amounts of gas were recorded on the mud log between 12,180 and 12,290 feet. Fluorescence of cuttings and of solvent cuts was observed between 10,200 and 11,820 feet.

Although minor amounts of gas, oil, and solid bitumen are present, the oil-generating capability of the potential source rock penetrated by COST No. 2 well does not appear to be very great. Furthermore, there is little geochemical evidence to suggest that the traces of observed hydrocarbons have migrated to this site from some unobserved source.

Snowdon (1978) and Snowdon and Powell (1982) have reported naphthenic oils and condensates they believe to have been generated from terrestrially derived organic matter at relatively low levels of thermal maturity. Specifically, they suggest that the resinite present in Tertiary coals of the Beaufort-Mackenzie Basin has produced hydrocarbons at an R_o level of between 0.4 and 0.6 percent. Snowdon and Powell (1982) state that between 5 and 15 percent resinite has been observed in samples from the Beaufort-Mackenzie Basin and they rate samples with a minimum of 10 percent resinite as excellent source rocks on the basis of the criteria of Powell (1978).

In the COST No. 2 well, R_o values increase from approximately 0.54 percent at 10,000 feet to 0.74 percent at 11,900 feet and jump discontinuously to about 1.0 percent between 11,950 and 12,200 feet. These measurements represent a range of thermal maturities that extend from roughly the threshold of oil generation to the

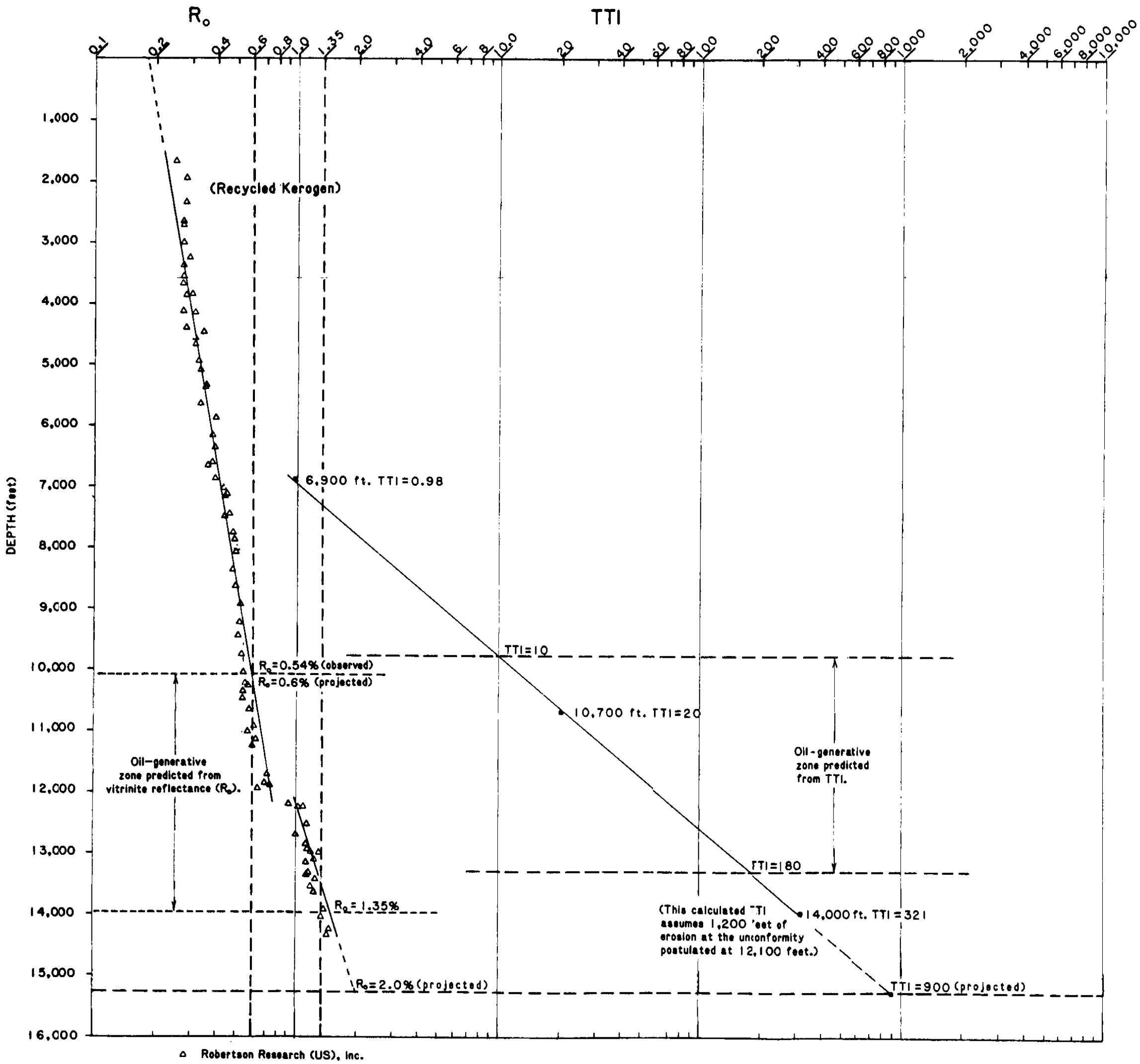

FIGURE 35. **Correlation of R_o and present-day TTI values for COST No. 2 well, Stuart subbasin.**

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maximum or peak oil-generating capability for type III kerogen (Tissot and Welte, 1984; Radke and others, 1980). Random vitrinite reflectance values, however, are predominantly low (0.5 to 0.7 percent) to a depth of 11,952 feet.

Nine cuttings samples from the COST No. 2 well that contained obvious visual coal were sent to P. Dharma Rao of the Mineral Industry Research Laboratory, University of Alaska, for petrographic analysis. With the few exceptions noted in table 7, Rao's petrological descriptions follow the International Handbook of Coal Petrology (International Committee For Coal Petrology, 1963, 1971, and 1976) and Stach's Textbook of Coal Petrology (Stach and others, 1982). The results of these point counts on a mineral-free basis are given in table 8. Five of the nine samples contain anomalously high resinite contents and a sixth contains a significant amount of sporinite.

Snowdon and Powell (1982) proposed a hydrocarbon generation model which would include resinite in addition to liptinite (waxy oils) and vitrinite (methane) group macerals from terrestrial organic matter. This model is reproduced in figure 36. Additional work is necessary to identify the source of the hydrocarbons present in the Stuart subbasin. Because type III vitrinitic kerogen and coal tend to be associated with dry gas rather than with condensate or oil, and because the liquid hydrocarbons at this site occur in sediments exhibiting a relatively low level of thermal maturity, it is possible that resinites derived from coal, either alone or in combination with subjacent thermally mature shales, may have generated the hydrocarbons observed in COST No. 2 well.

SUMMARY

The COST No. 1 well in the St. Lawrence subbasin encountered type III, humic, gas-prone kerogen and lesser amounts of coal. Biogenic methane is present in near-surface sediments, but there is little evidence to suggest that thermogenic hydrocarbons have formed in significant amounts at the well site.

The COST No. 2 well in the Stuart subbasin penetrated 14,889 feet of sediments containing predominantly type III, humic, gas-prone kerogen and coal with anomalous amounts of resinite and some other liptinitic constituents. Significant amounts of organic carbon are present but are generally associated with coal-bearing samples. Minor amounts of gaseous and liquid hydrocarbons plus bituminous material are present which are thought to be derived locally, either from mature, humic kerogen or from less mature resinite and liptinitic coal macerals. The current oil window occurs between 10,000 and 14,000 feet. Methane, probably of biogenic origin, is present in near-surface sandstones. Both COST wells penetrated significant thicknesses of thermally mature sediments.

Traces of hydrocarbons and oil shale have been reported at various localities on the margins of Norton Sound, but exploratory drilling at these sites has not resulted in any significant petroleum discoveries to date. Tertiary surface exposures are rare and tend

Table 7. **Maceral classification for northern Alaska coals (from Rao, 1983).**

Low Rank Coal Classification				Bituminous Coal Classification		
Maceral Group	Maceral Subgroup	Maceral	Maceral Class for this study	Maceral Type	Maceral	Maceral Group
huminite	humo-telinite	ulminite	vitrinite		telinite	vitrinite
					vitro-detrinite	
	humo-detrinite			telo-collinite	collinite	
	humo-collinite	gelinite	gelinite	gelo-collinite		
		corpo-huminite	phlobaphinite	corpo-collinite		
			pseudo-phlobaphinite			
	———		pseudo-vitrinite		pseudo-vitrinite	

Classification applicable to all Coals

Maceral Group	Maceral Class for this study
inertinite	fusinite
	semifusinite
	macrinite 1
	globular macrinite 2
	inertodetrinite
	sclerotinite
	micrinite

Maceral Group	Maceral Class for this study
liptinite	sporinite
	resinite
	exsudatinite 3
	cutinite
	thick cutinite 4
	alginite
	other liptinite 5
	suberinite

1 Macrinite occurs as amorphous gelified material binding such macerals as sporinite enclosed within it. Macrinite can also occur as isolated angular or rounded particles with irregular shapes and distinct boundaries.

2 Globular macrinite occurs as isolated spherical particles or as an agglomeration of particles, that are usually associated with vitrinite and frequently display oxidation rims, dessication cracks or differential compaction. They are also associated with semifusinite and can be found filling cell lumens.

3 Exsudatinite occurs as fillings of small cracks or partings within the bedding planes of the vitrinite, or as cell lumen fillings in semifusinite and fusinite. Exsudatinite in fluorescence light exhibits a variety of color from pale yellow to a bright gold or an orange gold.

4 Thick cutinite occurs as wide, banded lenses with thick cuticular ledges, and are usually strongly folded. Some thick cutinite exhibits multiple layers. In fluorescent light thick cuticles emmit a bright yellow color similar to the color of fluorescing alginite.

5 Other liptinites include liptodetrinites and other liptinitic materials such as waxes, fats and oils that cannot be identified under one of the other liptinite classes.

Table 8. Relative compositions of coal maceral groups and the liptinite macerals (mineral-free percent).

Maceral Group and Liptinite Group Macerals	Cuttings Samples (depth below kelly bushing in feet)								
	3,040-3,070	7,070-7,100	8,060-8,090	8,090-8,120	9,170-9,200	11,600-11,620	11,700-11,710	12,250-12,260	12,910-12,920
Inertinite Group	7.8	4.7	3.6	2.6	1.4	....	....	8.7	....
Vitrinite Group	76.4	78.1	79.8	78.4	61.3	62.5	69.2	75.9	83.3
Liptinite Group	15.8	17.1	16.6	19.0	37.3	37.5	30.8	15.4	16.7
Sporinite	9.5	3.0	6.5	5.0	10.7	25.0	....	....	1.5
Resinite	1.3	10.8	6.1	7.4	18.9	....	23.1	14.0	13.6
Exsudatinite	2.5	2.0	1.8	2.5	4.9	....	....	1.0	0.6
Cutinite	0.2	0.3	....	....	....	....	....	....	....
Alginite	....	0.3	....	....	0.2	....	....	....	....
Suberinite	0.6	....	....	....	....	....	....	....	....
Liptodetrinite	1.7	0.7	2.2	4.1	2.6	12.5	7.7	0.4	1.0

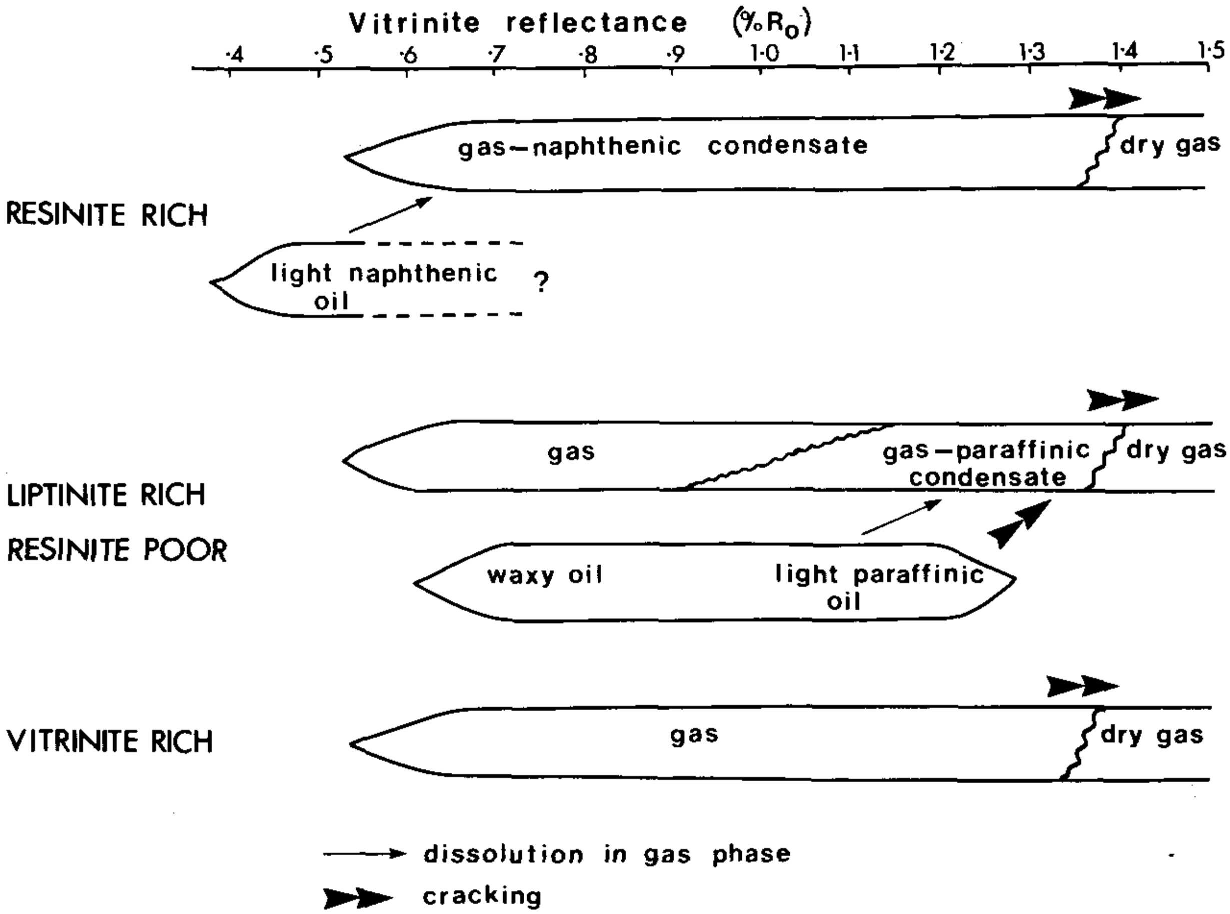

FIGURE 36. Hydrocarbon generation model for oil and condensate from source rocks containing terrestrial organic matter. Quantity and nature of ultimate product is a function of relative quantities of resinite, liptinite, vitrinite, and fusinite in source organic matter, and of level of thermal alteration (from Snowdon and Powell, 1982).

to be composed of coal when present. The Tertiary outcrops are thermally immature to mature. The Cretaceous rocks surrounding Norton Sound tend to be over-mature to metamorphic grade and are generally well indurated.

Gas seeps have produced an extensive C_2 to C_4 alkane plume along the north coast of Norton Sound. The plume originates in the vicinity of the Yukon horst and is composed largely of CO_2 with minor amounts of light hydrocarbons at its source.

Continued exploration will be necessary to evaluate the true petroleum potential of the Norton Basin area. However, the six exploratory wells drilled thus far have been disappointing.

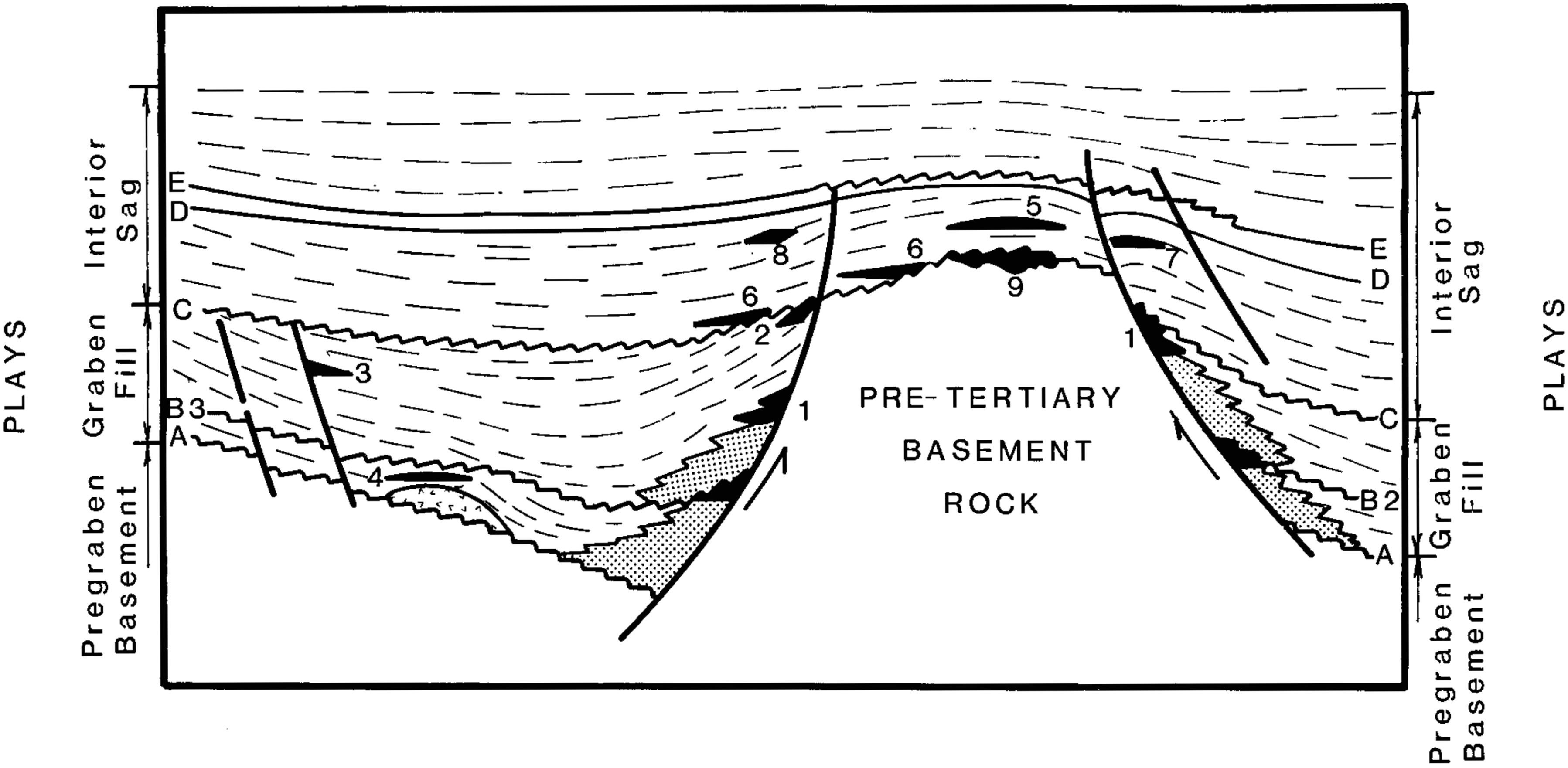

FIGURE 37. **Possible structural and stratigraphic trap configurations associated with major Tertiary sedimentary sequences and pre-Tertiary basement.** Seismic horizons A through E are depicted. Potential traps in the GRABEN FILL PLAY include (1) clastic wedges along horsts; (2) truncation of porous strata by an unconformity; (3) fault traps; and (4) compaction or drape over igneous mounds. In the INTERIOR SAG PLAY potential traps include (5) arching and drape or compaction over horsts; (6) strata lapping onto basement or unconformities; (7) roll-overs associated with normal faulting; and (8) porous strata sealed updip by impermeable silica diagenesis zone. PREGRABEN BASEMENT PLAYS include potential traps in (9) weathered carbonate or fractured quartzite or other metasedimentary or crystalline basement rock.

9

Play Concepts

Hydrocarbon accumulations known from basins geologically analogous to the Norton Basin provide a basis for the prediction of the types of plays in Norton Basin. Harding (1984) defined a conceptual framework for major hydrocarbon occurrences in extensional basins from a synthesis of the Sirte Basin of Libya, the Suez and Viking grabens of Egypt and the North Sea, and other block-faulted areas. Hydrocarbon accumulations in extensional basins can be placed in one of three major characteristic sedimentary sequences: pregraben, graben fill, and interior sag (fig. 37). Trapping mechanisms in all but the upper part of the interior sag sequence are primarily a result of structural, depositional, erosional, and compactional processes associated with the multidirectional faults that bound horst-graben fault blocks.

PREGRABEN BASEMENT PLAYS

Rocks of the miogeoclinal belt, which were penetrated in the lower parts of both Norton Basin COST wells, probably represent the lithostratigraphic sequence that would be encountered in pregraben plays. This section largely consists of schist, phyllite, slate, quartzite, and marble of Precambrian to Paleozoic age. As these rocks contain no effective intergranular porosity, any reservoir porosity would be the result of fracturing or weathering. These rocks are most likely thermally overmature; any hydrocarbons present would have to have been sourced from Tertiary sediments in deeper parts of the basin and migrated along faults or unconformities into higher basement structures.

Secondary porosity and karst features developed in carbonates during subaerial exposure prior to deposition of the graben fill constitute one potential play (fig. 37). Cataclastic marbles were encountered in both COST wells, and genetically similar carbonate rocks crop out in the York Mountains on the Seward Peninsula (Hudson, 1977) and St. Lawrence Island (Patton and Csejtey, 1980). The Renqiu oil field in the Bohai Bay Basin of eastern China represents an example of this type of trap. The reservoir consists of solution-enlarged fractures and karst features in a Precambrian carbonate fault block (Qi and Xie-Pei, 1984).

Another pregraben play involves reservoirs in fractured crystalline or metasedimentary basement rock (fig. 37). Fractured quartzite was encountered in the COST No. 2 well. The presence of granitic outcrops around Norton Sound, and magnetic anomalies offshore, suggest that weathered subcrops of granitic rock may be present in the basin. Hydrocarbons trapped in fractured quartzite and granite on the crests of fault blocks in the Sirte Basin, Libya (Conant and Goudarzi, 1967), provide an analog for this type of accumulation.

An important constraint on pregraben plays is the structural complexity of the pregraben tectonostratigraphic sequence (Harding, 1984). Complex pregraben structure tends to disrupt the reservoir continuity of fault-block structures and thus prevent large hydrocarbon accumulations. The complex geologic history of the miogeoclinal belt rocks which apparently underlie most of the Norton Basin suggests that pregraben basement plays are less prospective than plays in the graben fill or interior sag sequences.

GRABEN FILL PLAYS

The graben fill sequence in the Norton Basin is represented by the Tertiary section below seismic horizon C (figs. 13 and 14). This sedimentary sequence includes the early Oligocene, Eocene, and possible Paleocene rocks of lithologic zones To-3, Te, and Tp. The best potential reservoir rock encountered in the COST wells in this sequence consists of 230 feet of Oligocene fluviodeltaic sandstone in lithologic zone To-3 (table 3). Significant thicknesses of alluvial sandstones, as well as possible turbidites, were also encountered in the Eocene and possible Paleocene sections, but these sandstones were generally impermeable because of their mineralogical immaturity and greater burial depths. However, on basement highs and along the flanks of horsts, these sands could retain significant reservoir potential. At the COST wells, several anomalies in porosity-depth trends, as well as hydrocarbon shows, suggest that under favorable conditions these sands might form attractive potential reservoirs even where deeply buried. The two COST wells represent only a small sample of the strata in this large basin and it is likely that cleaner, quartz-rich sands occur elsewhere. Potential sources of quartz-rich detritus include basement rock composed of Cretaceous granitic intrusives and Precambrian to Paleozoic quartzites, both of which could have shed significant quantities of quartz sand into the basin.

Possible plays in the graben fill sequence include traps and structures developed in conjunction with faulting, such as tilted or dipping strata that have been sealed updip by faults (fig. 37). These types of traps are found in fields in the Gulf of Suez (Thiebaud and Robson, 1981) and in the Reconavo Basin of Brazil (Ghignone and De Andrade, 1968). Stratigraphic traps and traps associated with unconformities include clastic wedges on the flanks of horsts, submarine fans in basin depocenters, strata onlapping horsts and other positive basement structures, and truncated strata beneath unconformities (fig. 37). Examples of most of these can be found in the Sirte Basin of Libya, the Viking graben in the North Sea, and in the Egyptian Gulf of Suez (Harding, 1984).

Other possible traps include those associated with igneous features present within the graben fill sequence. Several features that appear to be igneous intrusive bodies have been seismically identified, as have several mound-shaped features of probable volcanic origin that rest on basement (fig. 37). Arching, draping, and differential compaction of strata over these igneous mounds, or lapouts on their flanks, represent potential traps. Similar domal features containing oil have been discovered in the Sado Basin in the Sea of Japan (Suzuki, 1983).

Clastic wedges that appear to be alluvial to submarine fan-delta complexes that onlap basement horsts (or are truncated by unconformities along horst flanks) are probably the most prospective exploration targets in the Norton Basin. Analogous plays are found in the southern Brae area of the North Sea, where a field with an oil column of about 1,500 feet is contained in alluvial fan conglomerates and sandstones that were shed from an uplifted fault block (Harms and others, 1980).

INTERIOR SAG PLAYS

The stratigraphic section involved in the interior sag play includes the late Oligocene, Miocene, Pliocene, and early Pleistocene strata above seismic horizon C (lithologic zones To-2, To-1, and Tmp) (figs. 13 and 14). Potential reservoir rocks encountered in this interval include the fluviodeltaic and marginal marine shelf sands of the upper Oligocene section. In the COST No. 2 well, 685 feet of sandstone displaying potential reservoir quality was encountered in lithologic zones To-1 and To-2 (table 3). These sands probably represent marginal marine equivalents of the alluvial sands that are inferred to represent the bulk of the late Oligocene section in the basin.

Potential interior sag plays include arched strata formed by draping or compaction over horsts, and to a lesser extent, fault, stratigraphic, and unconformity traps (fig. 37). Strata arched over igneous bodies (laccoliths?) also occur in this section and constitute another potential play. A more speculative play involves potential reservoir sands that are sealed updip by the subregional Miocene silica diagenetic zone (fig. 37).

Probably the most prospective interior sag plays involve arch or drape features over horsts and horst shoulders. Examples of these types of traps are present in the Sirte Basin, Libya (Parsons and others, 1980; Harding, 1984), and in the Viking graben of the North Sea (Blair, 1975; Harding, 1984).

TIMING OF OIL GENERATION AND TRAP FORMATION

Potential source rocks occur within the oil window in the Norton Basin graben fill sequence below burial depths of about 9,500 to 10,700 feet. The pregraben Paleozoic metasediments are overmature; the late Oligocene through early Pleistocene interior sag sequence is thermally immature.

The relative timing of thermal maturity derived from Lopatin modeling of the COST No. 2 well suggests that the basal Tertiary sequence (now at about 13,500 feet) entered the oil generation window about 20 million years ago (early Miocene). Because most of the prospective traps in the Norton Basin are associated with major normal faulting that was mainly active prior to mid-Oligocene time (seismic horizon C), most of the potential hydrocarbon traps should have formed prior to oil generation. Some exceptions may be the drape or compaction features present in the section above seismic horizon C, most of which formed in the Neogene during, and perhaps after, the main phase of hydrocarbon generation.

Potential migration conduits for hydrocarbons generated at depth include regional and local unconformities, faults, and the porous facies of clastic wedges which interfinger at their distal ends with thermally mature potential source rocks. Minor reactivation of faults extending upward into the thermally immature interior sag sequence might provide migration routes into the shallower arched-drape or compaction structures.

Because the dominant type of organic matter present in the potential source rocks is humic, gas-prone kerogen derived from terrestrial sources, the most likely hydrocarbons to be found in the basin are gas and gas condensate. However, oil shows in the COST No. 2 well between 11,800 and 13,000 feet, and oil-saturated zones in a conglomeratic sandstone between 12,180 and 12,290 feet, indicate that the sediments in the Norton Basin are capable of generating oil. The oil in these shows is thought to have been derived chiefly from resinite and lignitic coal macerals (Turner and others, 1983a,b).

There are numerous examples of oil accumulations, some very large, that were generated from continental sediments. In the Gippsland Basin of Australia, for instance, 3 billion barrels of recoverable oil have been discovered in a humic coal-bearing fluviodeltaic sequence that is both the reservoir and the source for the oil (Shanmugam, 1985). The oil there is thought to be derived from coal and resin. The giant Daqing oil field in northeastern China is another example of oil generated in a basin containing only nonmarine sediments. The oil was derived from freshwater algae and higher terrestrial plant debris deposited in a large lake basin (Wanli, 1985). The Mahakam Delta of Indonesia contains oil and gas that were derived from coal and associated shale (Durand and Oudin, 1979). Snowdon and Powell (1982) describe oils in the Tertiary of the Beaufort-Mackenzie Basin thought to have been generated from terrestrially derived organic matter. Gibling and others (1985) describe many small Cenozoic intermontane basins in northern Thailand that contain distinctive nonmarine sequences of oil shale and coal that have the potential for oil generation.

SUMMARY

The volume and distribution of reservoir rock, seals, and trapping configurations do not appear to pose significant problems to hydrocarbon accumulation in the Norton Basin. The timing of thermal maturity and trap formation also generally appears favorable. However, Fisher (1982) suggested that thermally mature sediment in the basin composes, at most, 11 percent of the total basin volume, and that these sediments are restricted to isolated structural lows or grabens. He also suggested that the numerous faults and fault blocks may have disrupted lateral migration paths from these lows. These constraints, and the predominance of humic, gas-prone kerogen, are probably the most important limiting factors for commercial hydrocarbon accumulations in the basin. Despite the poor exploration results thus far and the high probability of gas or gas condensate being the type of hydrocarbons most likely to be found, oil shows in the COST No. 2 well, taken with the cited instances of large accumulations of oil sourced from similar nonmarine sediments in other basins, indicate that the potential for significant petroleum accumulations in the Norton Basin cannot be ruled out without further exploration.

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Part 3

Shallow Geology, Geohazards, and Environmental Conditions

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10

Shallow Geology

Investigations of the shallow geology of the northern Bering Sea have been ongoing since the late 1940's. Academic studies on various aspects of the Bering Land Bridge, investigations concerning placer gold mining, and detailed studies of potential geohazards related to petroleum exploration and development have all contributed to the knowledge of this area. As a result of these relatively comprehensive studies, the physical attributes of the seafloor and the Quaternary history of the Bering Sea area are relatively well understood. This section includes an assessment of the petroleum-related environmental geology of the Norton Basin area and a brief synopsis of the Quaternary history of the Bering Sea area.

DATA BASE

The surface and near-surface geology of the northern Bering Sea has been elucidated by integrating high-resolution seismic reflection surveys with data obtained from bottom samples, box cores, and vibracores. Much of the data base for this assessment is from USGS investigations, which include the Conservation Division's (now Minerals Management Service) high-density seismic survey of the Sale 57 area of Norton Sound. Also included is the 1979 Tetra Tech, Inc., survey of the shallow geologic characteristics of the COST No. 1 well site. This survey, a part of the application for permission to drill (APD), included a geotechnical study of the upper 25 feet of sediment and a high-resolution seismic-reflection survey of the seafloor and its near-surface features. A similar study, also utilized, was conducted in 1980 by Nekton, Inc., at the COST No. 2 well site.

PHYSIOGRAPHY

The northern Bering Sea (fig. 38) includes the Norton Basin planning area, which is bounded by the Norton Sound coastline on the east and southeast, the Seward Peninsula on the north, the 63 degree north latitude on the southern border, and the US-USSR convention line of 1867 on the west.

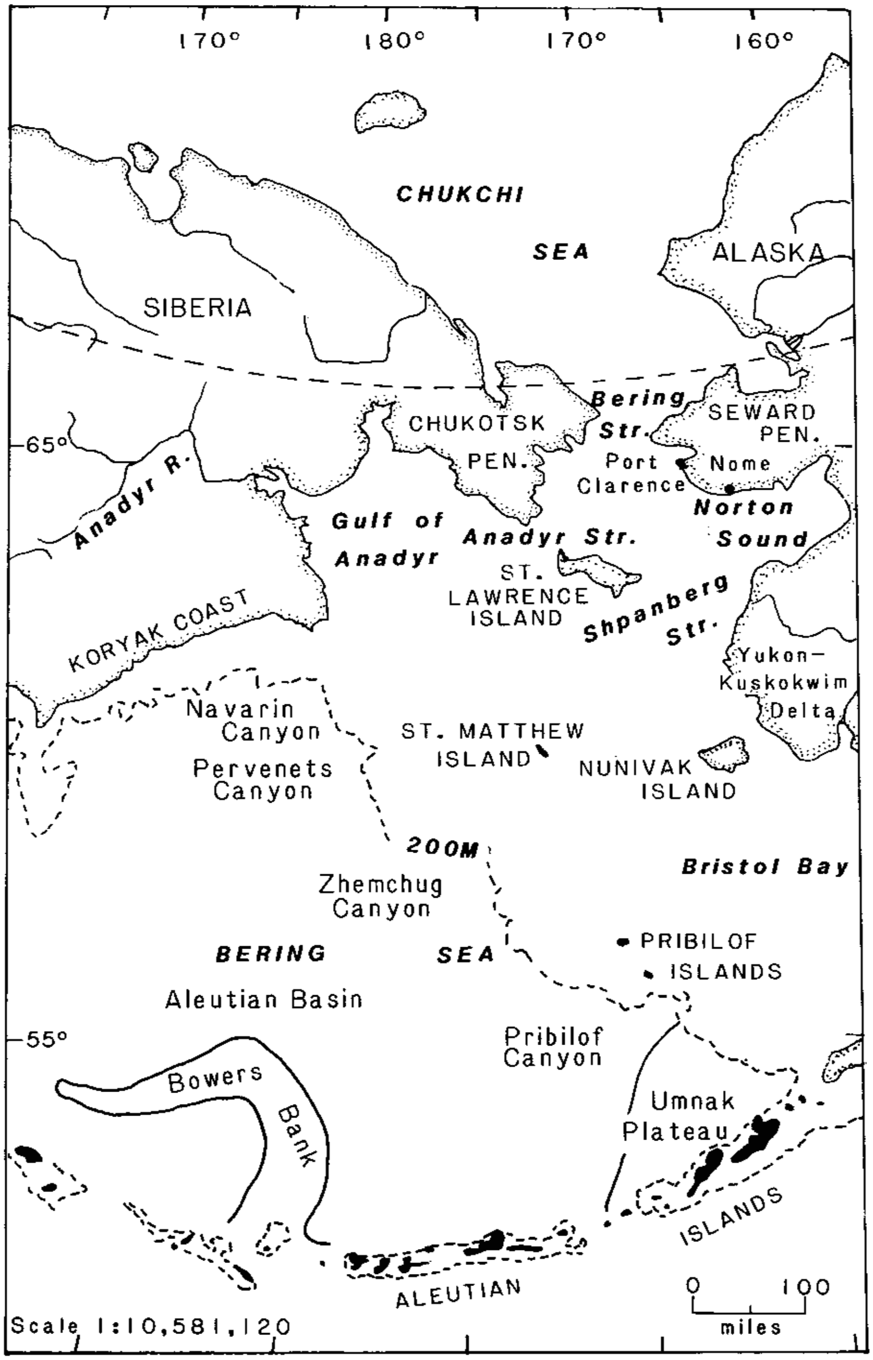

FIGURE 38. **Physiographic map of the Bering Sea region. Adapted from Nelson, Hopkins and Scholl (1974).**

The northern Bering Sea occupies a relatively flat epicontinental shelf area that covers more than 77,200 square miles. The present bathymetry and geomorphological configuration are the result of glacial, fluvial, and littoral sedimentological processes which occurred primarily during Pleistocene low stands of sea level (fig. 39). These generally regressive features have been subsequently modified by transgressive (erosional and sedimentological) processes.

Federal waters in the Norton Sound area range in depth from 19 to over 164 feet (fig. 39). The seafloor slopes generally westward toward the international boundary with the Soviet Union. Superimposed on this westward slope are subtle but distinct topographic features that have been grouped into over 20 physiographic provinces by Hopkins and others (1976). Larsen and others (1980) list four morphologic provinces, each the result of different geological processes: (1) a western area of hummocky relief composed of glacial gravel and a transgressive-marine substrate, (2) a southeastern area characterized by a featureless plain composed of a transgressive-marine substrate, (3) a northeastern province of sand ridges and shoals with a transgressive-marine substrate, and (4) an eastern province characterized by a flat, marine reentrant (the present Norton Sound) floored by the silt and silty sand of the present Yukon River prodelta.

A portion of the Yukon River delta-front is also present in the southern part of Norton Sound. The delta-front is a seaward extension of nearshore Holocene sand deposits and is characterized by a 1 to 2 degree seaward sloping seafloor. Seaward, the delta-front grades into the prodelta, which represents the present limit of deltaic sedimentation. The prodelta slopes less than 1 degree and is present under marine water 52 to 89 feet deep. The portion of the Yukon River Delta and delta-front located in Federal waters is separated from the presently prograding shoreline by a sub-ice platform (Larsen and others, 1980). This platform is 3 to 12 miles wide along the southern boundary of Norton Sound and occurs in water depths of less than 32 feet.

The character and distribution of modern sediments in the Norton Sound are affected to a great extent by ice gouging, storm surging, tidal and bottom currents, and the release of biogenic gas. These dynamic processes are responsible for the formation of transient bedforms such as scour marks, longitudinal current lineations, megaripples, ice gouges, and biogenic gas craters (Hoose and others, 1981; Steffy and Hoose, 1981; Steffy and Lybeck, 1981; Steffy, Turner, Lybeck, and Roe, 1981; Steffy, Turner, and Lybeck, 1981).

QUATERNARY GEOLOGY

Three early to middle Pleistocene glaciations encroached upon the northern Bering Sea shelf from the eastern Siberia-Chukotsk Peninsula area and from the western Alaska-Seward Peninsula area (Grim and McManus, 1970; Nelson and others, 1974; Hopkins, 1979 and

1982). Siberian glaciers extended over 90 miles beyond the Chukotsk Peninsula and into the western Chirikov Basin and western St. Lawrence Island areas. These glacial advances are recorded by morainal ridges (expressed as gravel bars) that extend northward from the island. Local valley glaciations on the Seward Peninsula extended somewhat more than a mile offshore. Moraines and outwash deposits were encountered by drillholes just offshore of Nome (Nelson and Hopkins, 1972).

Between 20,000 and 14,000 years ago, the last worldwide glaciation (Wisconsin) lowered sea level by nearly 280 feet, exposing the northern Bering Sea and the Bering Strait to both subaerial erosion and deposition (Hopkins, 1982). Three major continental glaciers covered western North America, northeastern Siberia, and the Brooks Range in Alaska. The Bering Sea shelf, however, remained largely unglaciated. Hopkins (1982) envisions the unglaciated shelf area as a low-lying periglacial plain covered by arctic steppe type vegetation.

During the Wisconsin low stand of sea level, the ancestral Yukon, Kuskokwim, and Anadyr Rivers drained southward over the subaerially exposed Bering Sea continental shelf and deposited sediment on the continental slope and into the abyssal Aleutian Basin (Nelson and others, 1974). Grim and McManus (1970) recognized the buried channels of streams that once drained southwestward from the Seward Peninsula into the Chirikov Basin. Knebel and Creager (1973) recognized similar channel features between St. Lawrence and St. Matthew Islands on the central continental shelf. The ancestral Anadyr River flowed southward from the Chukotsk Peninsula via the Gulf of Anadyr and through the submarine Pervenets Canyon (Nelson and others, 1974). The ancestral Kuskokwim River flowed southward into Bristol Bay. Between 20,000 and 2,500 years ago, the Yukon River migrated a distance of over 185 miles from a debouchment south of Nunivak Island to its present position in the Norton Sound (Knebel and Creager, 1973; Dupré, 1978). Both the distribution and accumulation of late Pleistocene and Holocene sediment in the Norton Sound were greatly influenced by migration of the Yukon River Delta and its channels.

The migration of the Yukon River, the last deglaciation, and the latest marine transgression over the Bering Sea shelf occurred essentially synchronously. A sea level curve for the Bering Sea region given by Hopkins (1982) (fig. 40) depicts a rising sea level that followed the measured maximum sea level low (-280 feet) that occurred approximately 20,000 years ago. This sea level rise commenced about 16,000 years ago, but was interrupted by several stillstands. These stillstands resulted in the development of a series of shorelines, the remnants of which are present as submerged sand ridges in the western Chirikov Basin (Nelson, Dupré, Field, and Howard, 1980). In many areas, a generally thin veneer of Holocene sediments has allowed the surface expression of relict gravel deposits, stream valleys, outwash fans, and hummocky topography (Grim and McManus, 1970).

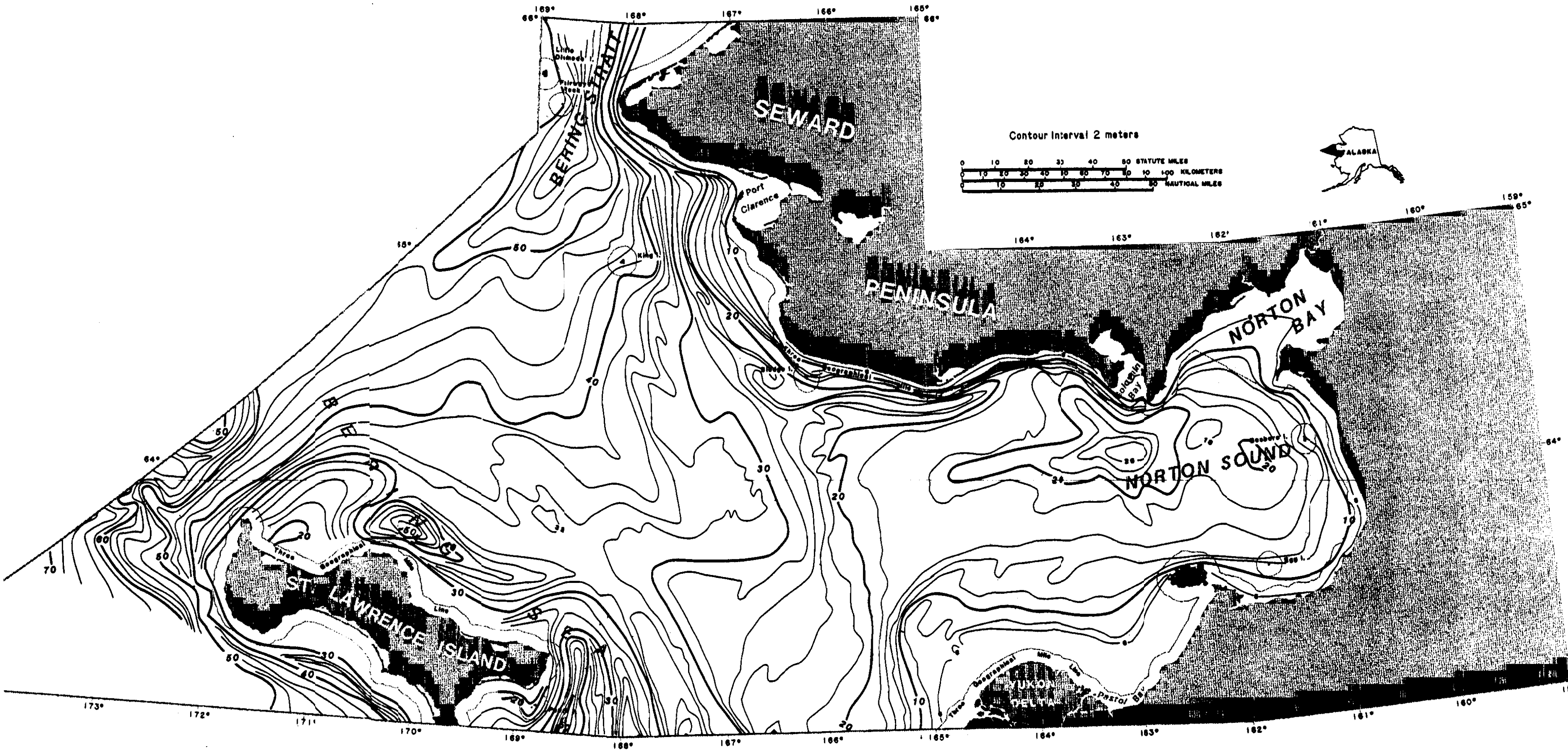

FIGURE 39. Bathymetric map of the Norton Sound Planning Area. Adapted from Hopkins and others (1976) and Steffy, Turner and Lybeck (1981).

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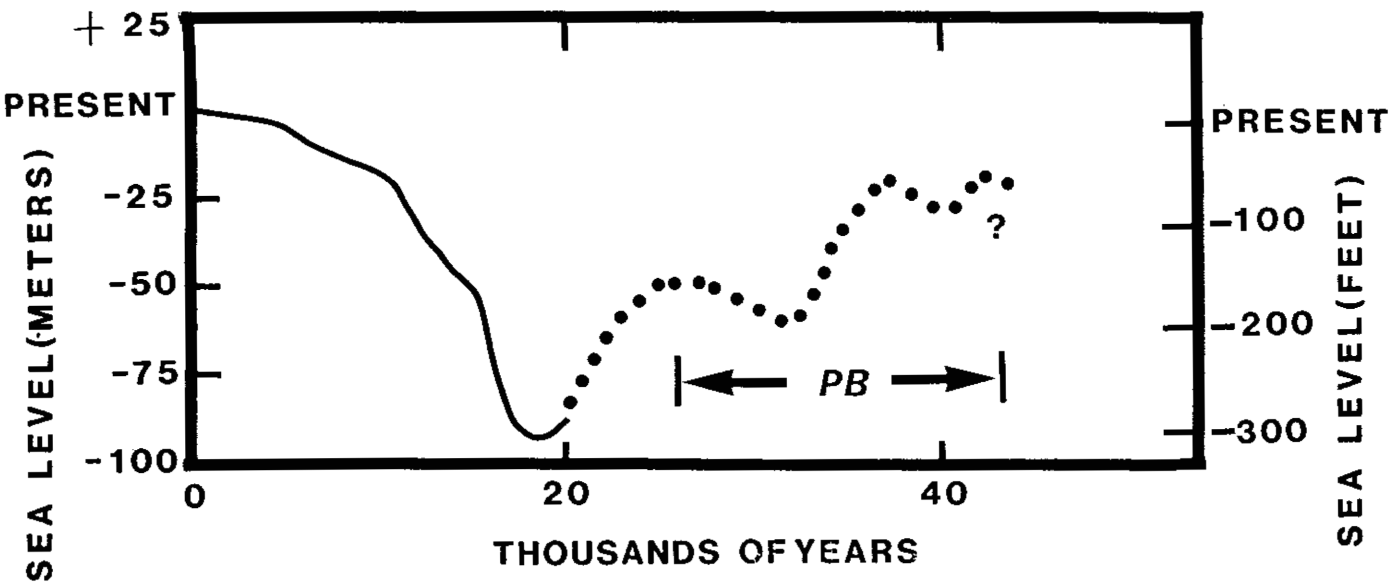

FIGURE 40 Sea level history for the Bering Sea. PB indicates where the sea level curve is based on data extrapolated from Prudhoe Bay. Adapted from Hopkins(1982).

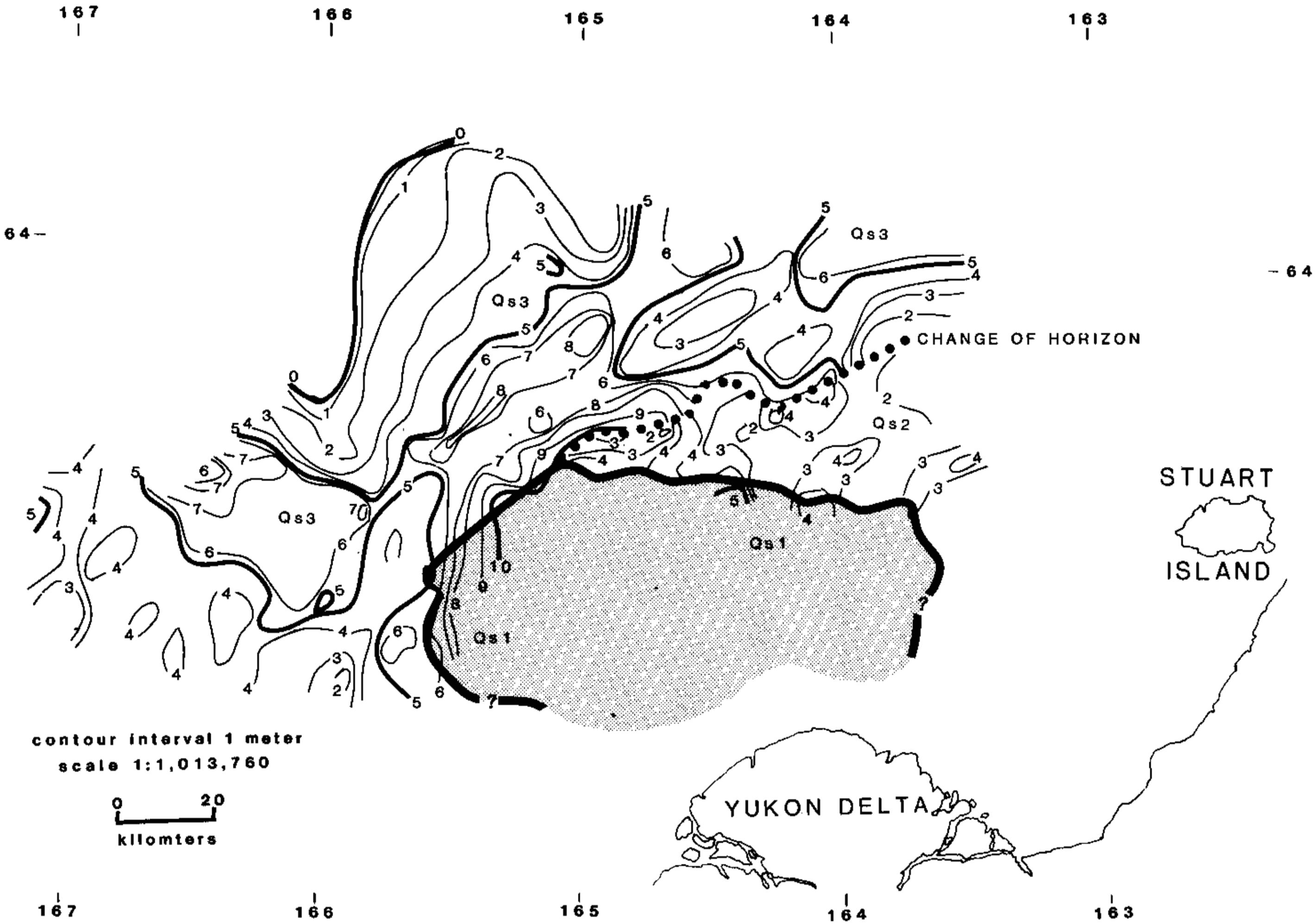

FIGURE 41. Isopach map of three Holocene sedimentary units in Norton Sound. QS1, the youngest unit, averages 5 meters thick and only its distribution is shown by the shaded area. QS1 obscures the distribution of the underlying QS2 and QS3 units. Adapted from Steffy, Turner, Lybeck, and Roe (1981).

Several glacioeustatic stillstands were in phase with the oscillatory advances and retreats of the glaciers. A rising sea level as early as 15,500 years ago breached the Bering Land Bridge at -125 feet elevation and connected the Bering and Chukchi Seas via the Bering Strait (Hopkins, 1982). Deglaciation accelerated about 14,000 years ago (Hopkins, 1982). Approximately 12,000 years ago, sea level rose to -98 feet, flooding the Shpanberg Strait and isolating St. Lawrence Island from mainland Alaska (Hopkins, 1979). From 10,000 to 9,500 years ago, a rapid transgression in eastern Norton Sound buried tundra peat deposits (Nelson, 1980; Steffy, Turner, Lybeck, and Roe, 1981). Two subsurface peat layers in Norton Sound were mapped using high-resolution seismic reflection data. Figure 41 is an isopach map of three Quaternary sedimentary units (Qs1, Qs2, and Qs3) which are bounded by the two peat layers and the seafloor. These organic-rich horizons may represent the remains of two subaerially exposed surfaces that developed peat-rich covers during stillstands 10,000 and 9,000 years ago, at elevations of -82 and -52 feet, respectively. Nearshore, Qs2 overlaps Qs3, which indicates an oscillating shoreline. Qs3 is a progradational wedge (up to 35 feet thick) of Holocene marine silt containing interbedded storm-sand layers. Subsequent to the stillstand represented by the youngest peat layer, up to 18 feet of additional marine silt and sand (Qs2) were deposited. This wedge rapidly thins seaward and pinchs out 50 miles northwest of the Yukon River Delta (fig. 41). A layer of Holocene silt less than 6 feet thick is present in the northern and eastern parts of Norton Sound.

In the Chirikov Basin, these same transgressions deposited several tens of feet of coarse-grained sand as well as a lag gravel derived from bedrock and older glacial sediments (Nelson, 1980). In some areas, a veneer of coarse- to medium-grained sand was deposited over late Pleistocene freshwater silt and tundra deposits.

The Yukon River Delta reached its present position about 2,500 years ago (McDougall, 1980). Over the past 2,500 years, a 5-foot-thick wedge of fine sand (Qs1) has prograded seaward from the delta (fig. 41). The bathymetric trough in the northern half of Norton Sound (fig. 39) is essentially a site of non-deposition.

Relict beach ridges, outwash fans, stream valleys, and glacial deposits are common in the northern Bering Sea area. Although the Yukon River supplies 90 percent of the sediment entering the Bering Sea (an estimated 70 to 90 million metric tons per year according to McManus and others, 1977), the presence of relict topographical features and the absence of thick deposits of Holocene sediment suggest that bottom currents in the Norton Sound and the Bering Strait are strong enough to prevent significant sediment accumulations. Since the opening of the Shpanberg Strait 12,000 years ago, sediment from the Yukon River has been carried northward through the Bering Strait into the southern Chukchi Sea (Knebel and Creager, 1973).

Before the opening of the Shpanberg Strait, the northward flow of the Bering Sea was through the Anadyr Strait seaway and into the southern Chukchi Sea via the Bering Strait. The strong bottom currents associated with this flow not only prohibited the deposition of Holocene sediments, but winnowed the fines from the existing glacial deposits as well, leaving lag gravel deposits behind. A north-trending bathymetric trough and the linear sand bodies found in the western Chirikov Basin area off Point Clarence may reflect this northward paleo-flow (fig. 39).

SUMMARY

The seafloor geomorphology of the northern Bering Sea is the result of three Pleistocene glaciations and associated low stands of sea level. The migration of the Yukon River, the last major deglaciation, and the latest marine transgression over the Bering Sea shelf occurred almost synchronously about 20,000 years ago. Limited Holocene sedimentation, partially due to strong bottom currents, has allowed relict glacial features to remain exposed in the Chirikov Basin and the western Norton Basin. A progradational wedge (up to 58 feet thick) of Holocene muds, silts, sands, and organic-rich interbeds extends seaward from the Yukon River Delta into the central and eastern parts of the Norton Basin. Active sediment transport mechanisms continually rework the upper several feet of sediment.

11

Geohazards

Seafloor instability, storm surging, and floating ice are potential hazards to oil and gas exploration and development in the Norton Basin planning area. A geological process or environmental condition is considered a potential hazard if it could threaten the structural integrity of a drill rig, pipeline foundation, or the safety of men and equipment working in the area. High-resolution seismic reflection data, geotechnical borehole information, and seafloor sample analyses were used in the identification of types and characteristics of potentially hazardous conditions. The Conservation Division's high-resolution seismic reflection survey of the Sale 57 area identified and located areas and conditions that could be hazardous to petroleum exploration and development. Outside of the Sale 57 area, the limited amount of public data prohibits lease-block-specific identification of geohazard locations.

SEAFLOOR INSTABILITY

Hazards related to seafloor instability that may affect bottom-founded structures include faulting, gas-charged sediments, seismicity, substrate liquefaction, and erosion. Foundation support failure results from a reduction in shear strength of the supporting substrate or by removal of the surrounding sediment by erosion. Seismicity and near-surface faulting can cause a loss of foundation support by differential displacement, shaking, and substrate liquefaction induced by vibration. Substrate liquefaction may also be induced by storm-wave cyclic loading (Clukey and others, 1980).

Seismicity

Seismicity studies of west-central Alaska are essential for the safe planning and design of structures involved in petroleum exploration and development in the Norton Sound area. A 5-year study by Biswas and others (1983) utilized a local seismographic network in the Seward Peninsula region to monitor and record seismic activity. This investigation revealed a significantly higher level of seismicity, both onshore and offshore, than had been previously recognized for the area.

Earthquakes located by the local seismographic network were found widely distributed across the Seward Peninsula and Norton Sound region. In many instances, however, the epicenters were found to cluster along or parallel to mapped faults or linear structural trends (fig. 42). On the Seward Peninsula, concentrations of epicenters were noted along the Kuzitrin and Darby Mountain fault systems, the Penny River-Engstrom-Anvil Creek fault set, and along the Kigluaik fault, which marks the abrupt northern boundary of the Kigluaik Mountains. The Bendeleben fault, recognized by Hudson and Plafker (1978) as having major Holocene displacements along its surface trace, appears to be relatively inactive at present. Although the distribution of earthquake epicenters in Norton Sound exhibits a wide scatter, there is a weak concentration along the basement fault system (fig. 42). Little seismic activity was detected along the western section of the Kaltag fault or along its projected trace in Norton Sound. The maximum magnitude of any earthquake recorded by the local seismographic network in Norton Sound measured 4.2 on the Richter Scale. This particular earthquake occurred north of St. Lawrence Island in the western part of the planning area.

Attempts have been made to deduce the regional stress pattern of the Norton Sound and Seward Peninsula areas from focal mechanisms of earthquakes located in those areas (Biswas and others, 1980; Biswas and others, 1983). Studies of fault plane solutions for selected earthquakes and clusters of small earthquakes show normal faulting as the principal mode of strain-energy release in this region. The dominance of normal faults, as evidenced by seismic reflection data from Norton Sound as well as by regional mapping on the Seward Peninsula (Hudson, 1977), also indicates that tension is the primary stress operative in this area. A study of stress trajectories for the Alaska-Aleutian region based on the distribution of post-Miocene volcanos, dike swarm patterns, and Quaternary faults (Nakamura and others, 1980) reveals a westerly orientation for the Norton Sound area; the stress orientation calculated from fault plane solutions is northwesterly.

From the results of regional stress pattern studies, Biswas and others (1983) postulated that the area in and around Norton Sound and the Seward Peninsula represents the active back-arc region of the Aleutian subduction complex. Earthquakes located in this back-arc region are then considered to be a direct result of southward spreading of the rigid back-arc lithosphere plate.

Faults

High-resolution seismic reflection surveys have located surface and near-surface faults in the northern Bering Sea area (Johnson and Holmes, 1981; Steffy and Hoose, 1981). The majority of these shallow faults parallel, and may be controlled by, the structure of the underlying rock. Faults in the western part of Norton Sound and in the Chirikov Basin trend northwest; in the eastern Norton Sound, faults trend nearly east-west (fig. 43).

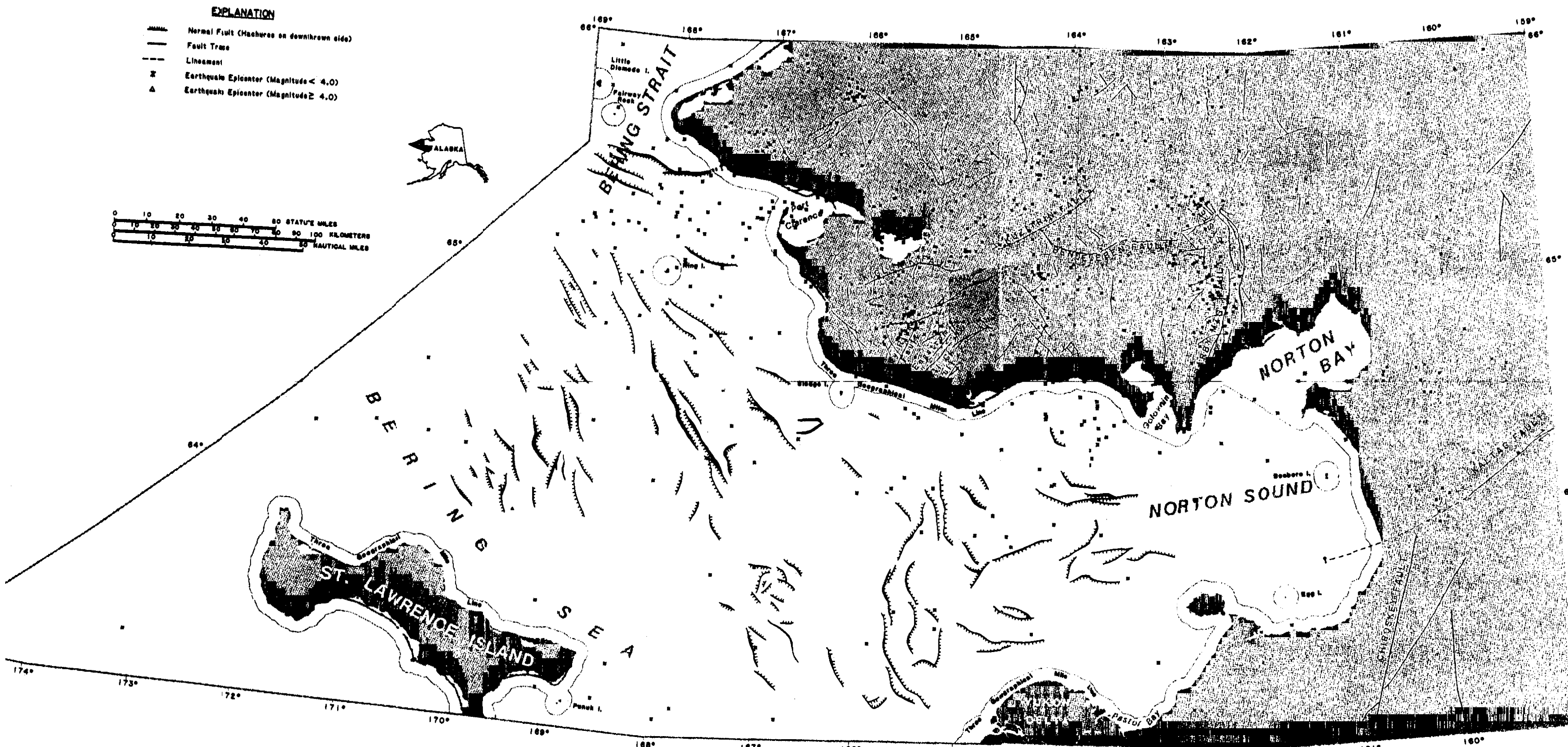

FIGURE 42. Locations of epicenters of earthquakes recorded by the local seismographic network (Biswas and others, 1983) from 1977 through mid-1982 in the Norton Basin region, in relation to structural and geographic features.

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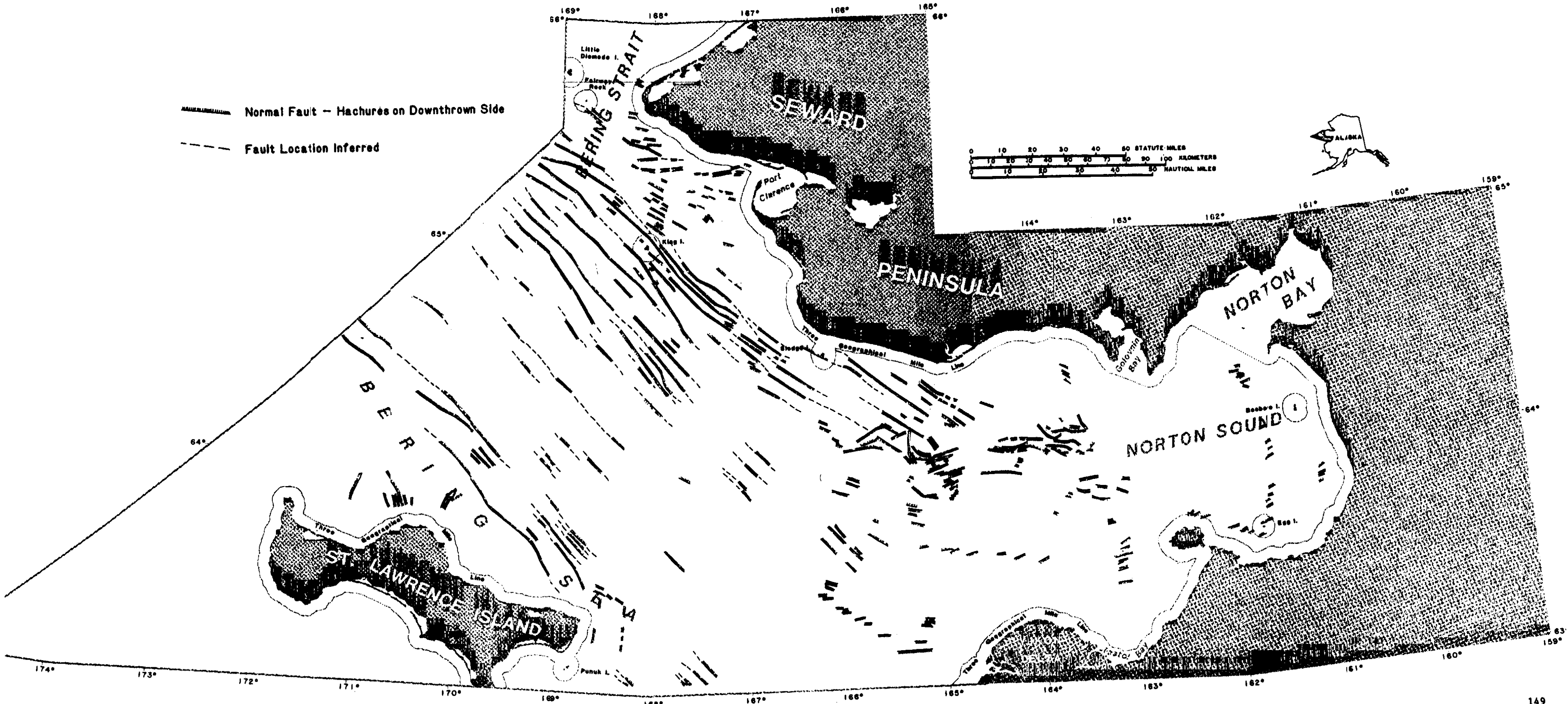

FIGURE 43. Surface and near-surface faults in the Norton Basin Planning Area. Adapted from Johnson and Holmes (1981) and Steffy and Hoose (1981).

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Surface fault density is highest and most complex in the area west of Port Clarence (Johnson and Holmes, 1981). Several younger, west-trending faults intersect and offset the dominant northwest-trending faults. West-trending faults bound the Bering Strait depression (BSD) and its eastward extension, the Port Clarence rift. These faults have measured seafloor scarps of 15 and 27 feet. Other west-trending faults have scarps of up to 57 feet. Seafloor fault scarps may indicate either recent movement or a lack of erosion by bottom currents.

A bathymetric trough paralleling the northern coast of St. Lawrence Island is the seafloor expression of a significant fault zone. Johnson and Holmes (1981) state that movement along this fault zone is related to the transcurrent, right-lateral Kaltag fault, which is known to displace Pleistocene sediments in western Alaska. An irregular sea bottom apparently obscures scarps associated with this fault zone.

Numerous surface and near-surface faults were mapped in the Sale 57 area by Steffy and Hoose (1981). Shallow growth faults continued to move through the Pleistocene, but apparently do not displace Holocene sediments. Only a few faults could be mapped in the southern half of the Sale 57 area because widespread shallow, gas-charged sediments mask the underlying structure on seismic reflection data. It can be assumed, however, that shallow faulting is present.

Shallow faulting represents a potential hazard in the Norton Sound planning area. The seismicity of the area indicates active fault movement, which could result in seafloor displacements that could endanger bottom-founded structures.

Sediment Transport Processes

The seafloor topography of the northern Bering Sea is the result of the interaction of wind, water, ice, and various sedimentological processes. Unconsolidated surface sediments are continually reworked by ice gouging, bottom currents, storm surging, and the release of biogenic gas. Active erosion and redistribution of sediment could reduce the support of bottom-founded structures. Such processes are expressed in the northern Bering Sea as sand waves, longitudinal current lineations, megaripples, current scour, ice gouges, and gas craters. Figure 44 shows the location of these bedform features in the Norton Sound area, except for the sand waves, which are found west of the Port Clarence area.

Active sand waves are found on the crests and flanks of large, linear sand ridges lying west of Port Clarence. These asymmetric bedforms are oriented transverse to the dominant northward current directions and have amplitudes of 3 to 6 feet and wavelengths of 30 to 650 feet (Cacchione and Drake, 1979).

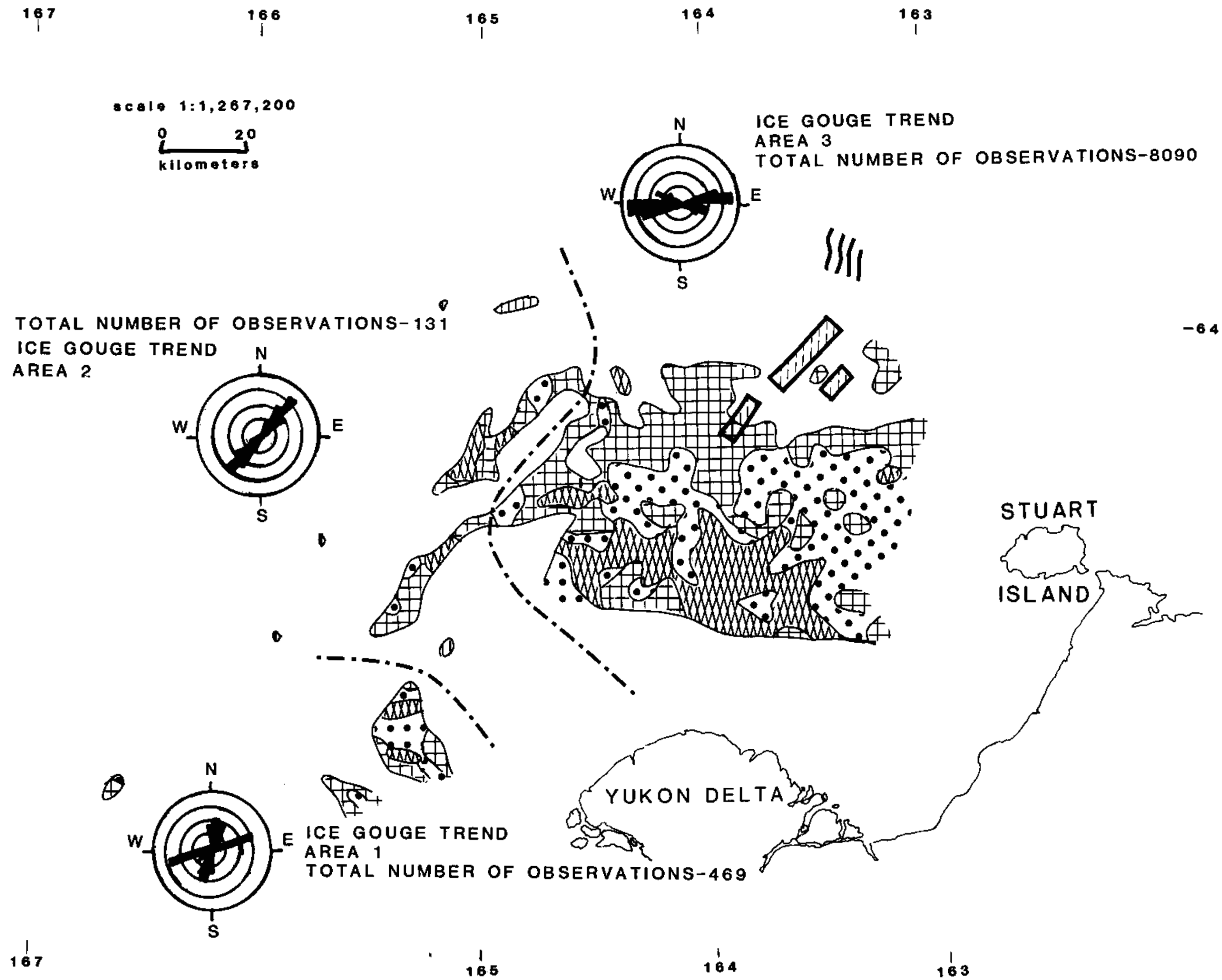

FIGURE 44. **Map showing seafloor features in Norton Sound. Adapted from Steffy and Lybeck (1981).**

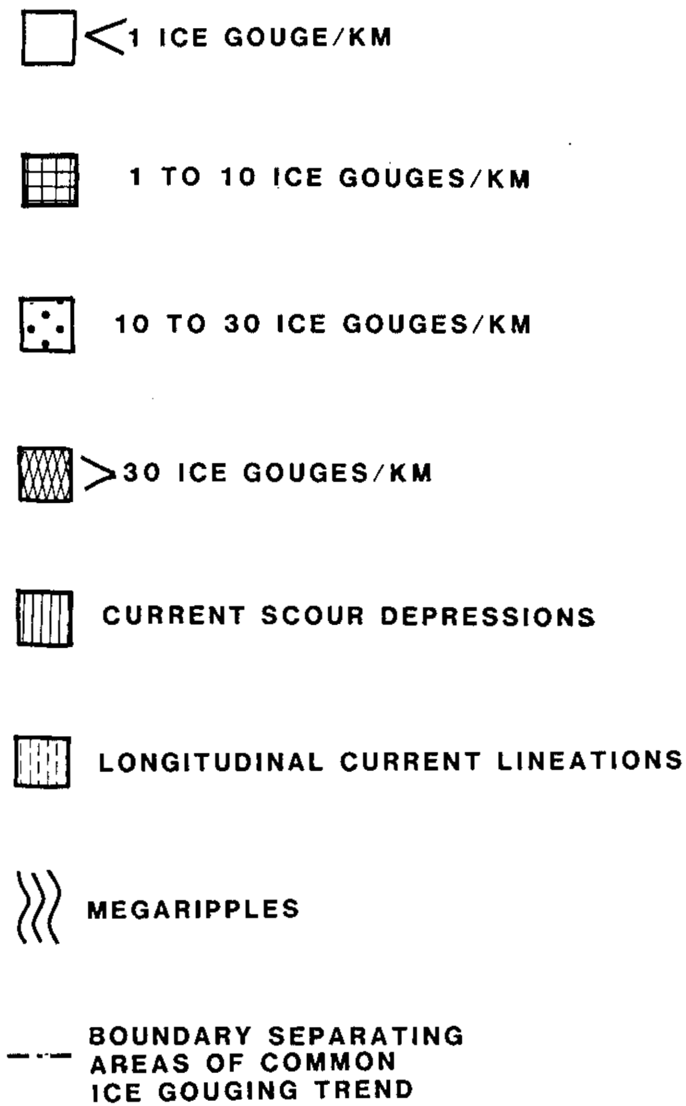

FIGURE 44 (continued)

Megaripples are present in the northern part of Norton Sound in a bathymetric trough characterized by water depths greater than 68 feet (fig. 44). The strike of the megaripple crests is northerly, which is normal to the prevailing current direction (Nelson, Dupré, Field, and Howard, 1980). Megaripples generally have amplitudes of less than 2 feet and wavelengths between 65 and 165 feet. Bottom samples collected by the USGS indicate that the local surface sediment consists of a silty, fine sand (Larsen, Nelson, and Thor, 1981).

Longitudinal current lineations are present as a series of furrows along the southern flank of a bathymetric trough in the northern part of Norton Sound (fig. 44). The strike of the lineation crests parallels the prevailing westerly current direction. These lineations have amplitudes of less than 2 feet and wavelengths of 32 to 98 feet. The local sediment consists of silty, fine sand (Larsen, Nelson, and Thor, 1981).

Current scour causes many of the broad, flat-bottomed, elongated depressions that are present throughout Norton Sound (fig. 44). The two most extensive areas of scour are located just west of the Yukon River Delta and in the flat prodelta area 50 miles north of the delta. The area north of the delta is characterized by elongated depressions 330 to 500 feet long, 115 to 260 feet wide, that are less than 3 feet deep. These depressions trend N. 100° W. and are located on the southern flank of a bathymetric trough in 62 feet of water. The trend is parallel to the prevailing westerly current direction. The local surface sediment is a silty, fine sand. The area west of the delta is characterized by elongated depressions 460 to 520 feet long, 260 to 320 feet wide, and less than 6 feet deep. These depressions trend N. 15° W. and occur in 18 feet of water on the flat, shallow sub-ice platform. This trend is oblique to the prevailing northeasterly current direction but is aligned with the dominant bottom-current flow. The local bottom sediment is a silty, fine sand (Larsen, Nelson, and Thor, 1981).

Gas-Charged Sediments

The distribution of acoustic anomalies in Norton Sound suggests that gas-charged sediments are probably ubiquitous in the planning area. Shallow occurrences of gas-charged sediments can cause increases in pore pressure which causes a decrease in the shear strength of the sediment. Such conditions could lead to unstable foundation conditions. Gas-charged sediments can often be identified on analog high-resolution seismic reflection data as anomalous acoustic events characterized by polarity reversal, amplitude increase, reflection "wipe out," and reflection "pull down." Gas-charged sediments are distributed throughout Norton Sound but are absent in the Chirikov Basin area. Steffy and Hoose (1981) mapped extensive areas of gas-charged sediments in Norton Sound by using high-resolution seismic reflection data. Nelson and others (1979) state that most of the shallow gas in Norton Sound is probably biogenically generated from buried Quaternary peat layers, then trapped in overlying cohesive silts and silty, fine sands. These thin peaty layers commonly have measured organic carbon contents of 2 to 8 percent and contain abundant biogenic methane.

The degassing of sediments may be either continuous or episodic. Storm-induced cyclic loading of unconsolidated surface sediments can cause rapid changes in pore pressure that reduce shear strength and permit gas to escape (Fisher and others, 1979). Degassing is often evidenced by seafloor cratering, which is prevalent in the central and eastern parts of Norton Sound (Holmes, 1979). These craters are typically associated with near-surface acoustic anomalies, shallow deposits of organic-rich mud, and gas-charged sediments. Biogenic gas-generated craters range from 3 to 30 feet in diameter and are usually less than 1.5 feet deep. The absence of gas-charged sediments and cratering in the non-cohesive, coarse-grained seafloor material of the Chirikov Basin is attributable to the gradual diffusion of biogenic gas through these permeable sediments (Larsen, Nelson, and Thor, 1981).

A well-documented near-surface gas accumulation that is seeping into the water column is located approximately 25 miles south of Nome (Holmes and others, 1978; Nelson and others, 1978). This gas accumulation, which covers an area of about 19 square miles, is identified by a shallow acoustic anomaly on high-resolution seismic data. The gas consists primarily of CO_2 with a minor component of hydrocarbon gases and gasoline-range hydrocarbons; the CO_2 is present in the free state in sediment interstices (Kvenvolden and Claypool, 1980). Specific characteristics of the gasoline-range hydrocarbons suggest that the mixture may be an immature condensate of lower temperature origin than normal crude oil. It is possible that these gases are migrating up faults that offset Tertiary strata. If so, this suggests the presence of thermogenic gas accumulations in the Norton Basin. Because of the volatile nature of such gases, specific safety preparations are necessary when drilling in the Norton Basin.

Substrate Liquefaction

Substrate liquefaction is the fluidization of granular, non-cohesive sediments. This fluidization results in a reduction of sediment shear strength and its ability to support bottom-founded structures. Cyclic loading caused by vibrating machinery, earthquake shaking, and storm waves can induce substrate liquefaction. The build-up of pore pressure by cyclic loading in cohesionless, fine-grained material temporarily or permanently reduces shear strength (Sowers, 1979). This happens if the permeability of the material is insufficient to dissipate increasing pore pressures. Increased pore pressure enables the substrate to withstand large strains up to the time that failure ensues. Whether or not substrate liquefaction will occur depends upon a number of interrelated factors such as the ability of the fine-grained material to dissipate pore pressure, the initial density of the material, and the amount of applied stress.

The upper 6 feet of silt and fine-grained sand cover in the prodelta area north and west of the Yukon River is considered to have the greatest potential for substrate liquefaction (Clukey and others, 1980). In the late fall, this area is subjected to large storms with large-amplitude, low-frequency waves that travel into Norton Sound from the southern Bering Sea. The shallow water depths (commonly less than 60 feet) render this region particularly susceptible to wave-induced stresses.

FLOATING ICE

Ice gouges are furrows in the seafloor caused by single- or multi-keeled ice floes driven by wind and water currents. Single-keeled ice gouges in the Norton Sound area range from 15 to 165 feet wide and appear to be infilled to varying degrees by sediment. Ice gouges were mapped and grouped into 3 areas on the basis of gouge-density and gouge-trend (Steffy and Lybeck, 1981) (fig. 44). The maximum ice gouge density occurs in the shallow-water areas of Norton Sound, especially around the Yukon River Delta. The gouges occur in water depths of 21 to 79 feet and are most common in depths of 32 to 56 feet. Most of the gouges are found in area 3, the delta-front north of the Yukon River Delta (fig. 44). Thor and Nelson (1981) attribute this concentration to the westward-moving ice pack of Norton Sound shearing against the shorefast ice offshore from the delta. This shearing causes the normally thin (less than 6 feet) annual ice to form composite ice ridges thick enough to gouge the seafloor. These pressure ridges produce multi-keeled ice gouges. Smaller amounts of ice gouging occur in areas 1 and 2 (fig. 44). Ice gouging in area 1 may be caused by the Bering Sea pack ice shearing against shorefast ice that extends westward from the delta (Dupré, 1978). Ice gouging in area 2 results from an interaction of shorefast ice with both Norton Sound and Bering Sea pack ice (Thor and Nelson, 1981). In all three areas, the major trends parallel the bathymetric contours.

STORM SURGING

Shoreline areas of the northern Bering Sea are vulnerable to storm surging, a process that causes drastic changes in seafloor sedimentation (Larsen and others, 1980). Bottom-founded structures used in the Norton Basin will require careful design to limit the potential effects of storm surges. Storm surges are most likely to occur in Norton Sound during the late summer or early fall. Strong winds from the southwest drive water into the shallow embayments of the sound and sea level rises as high as 10 feet above the mean water level may occur. Storm sand layers up to 8 inches thick have been deposited in the Yukon River Delta area (Larson and others, 1980).

A well-documented storm in Norton Sound occurred from November 10 to 17, 1974. The storm, a once-in-30-years event, generated a surge that was 20 feet above the normal tidal range of 4 feet. Maximum sustained winds of 38 knots with gusts of 70 knots were recorded (Sharma, 1979).

SUMMARY

A broad spectrum of potential geohazards that could result in seafloor instability, such as substrate liquefaction, surface or near-surface faulting, the presence of gas-charged sediments, and various effects of seismicity, impose engineering constraints on oil and gas exploration and development in the northern Bering Sea area. Additional constraints are dictated by the presence of floating ice and the likelihood of storm surging.

12

Environmental Conditions

METEOROLOGY AND OCEANOGRAPHY

Most of the meteorologic and oceanographic information on the northern Bering Sea area summarized here is contained in the Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska (Brower and others, 1977) and The Alaska Marine Ice Atlas (Labelle and others, 1983). Data compiled by the National Weather Service and other Federal agencies and data compiled by the Arctic Environmental Information and Data Center of the State of Alaska were also used.

The Norton Sound region is climatically characterized by a subarctic, semi-arid weather regime. Cyclonic atmospheric circulation patterns dominate in the region. Annual weather patterns are controlled by the Honolulu, Arctic, and Siberian highs, and the Aleutian lows. The Norton Sound region is affected by both a moderating marine climate to the west and an extreme onshore climate to the east. Cloudy skies and strong surface winds characterize the sound's marine weather. Storms are more frequent in the fall and winter (Sharma, 1979). Temperatures vary from a January mean of 5 °F to a July mean of 55 °F. Recorded temperatures have dropped as low as -55 °F.

Maximum recorded winds in the region have reached 75 miles per hour. In winter, maximum winds accompany the storms that approach Norton Sound from the southwest, although the predominant winter wind direction is from the northeast and averages 12 to 17 miles per hour. Summer winds blow from a southerly direction and average 8 to 12 miles per hour.

There are two dominant marine surface current patterns in the Norton Sound area: a northward flow that passes east of St. Lawrence Island and a counterclockwise system in Norton Sound.

Tidal variations in Norton Sound are relatively small, but exert an important influence on the surface current circulation pattern. Tides move northward through the northern Bering Sea and proceed through the sound in a counterclockwise direction. Within the sound, tidal heights range from 1.6 to 6.8 feet.

Wave heights greater than 8 feet are common less than 10 percent of the time in August and September and less than 20 percent of the time in October.

SEA ICE

The freeze-up period in Norton Sound extends from November through early December. At Nome, the mean dates of sea ice break-up and freeze-over are May 29 and November 12, respectively. Ice spreads south from the Chukchi Sea to the western portion of Norton Sound and around St. Lawrence Island. Ice also forms in Norton Bay and spreads southwestward. Pack ice generally begins to form in Norton Sound in mid- to late October. Some areas in and around the sound are completely ice covered by mid-November. After mid-December, pack ice generally completely covers the sound. By mid-March the ice pack at the head of the sound begins to thin, but does not show appreciable melting until mid-May. By mid-June the sound is completely ice-free.

Sea ice conditions vary throughout Norton Sound. Ice movement is controlled by a combination of geography and the prevailing northeast winter winds. The prevailing winds cause a generally east-northeast to west-southwest evacuation of ice throughout the winter. Except for the shorefast ice, sea ice in this area is entirely replaced by this process several times during a season. First-year ice usually moves out by the time it is about 18 inches thick. Areas of convergence and divergence exist within the zone of floating pack ice. In convergent zones, overriding ice can form ridges up to 110 feet thick. These submerged ridges often cause seafloor gouging. Divergent zones are characterized by abundant small openings in the pack ice.

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REFERENCES

AGAT Consultants, Inc., 1982, Reservoir quality study, ARCO Norton Basin COST Well No. 2, 5 vols.: Denver, CO (report prepared for ARCO Exploration Company).

AGAT Consultants, Inc., 1980, Lithological analysis of core and sidewall samples, Norton Sound, Alaska, 2 vols.: Denver, CO (report prepared for ARCO Exploration Company).

Albrecht, P., Vandenbroucke, M., and Mandengue, M., 1976, Geochemical studies on the organic matter from the Doula Basin (Cameroon), Part 1, Evolution of the extractable organic matter and the formation of petroleum: Geochimica et Cosmochimica Acta, vol. 40, p. 791-799.

Alger, R. P., Raymer, L. L., Hoyle, W. R., and Tixier, M. P., 1963, Formation density log applications in liquid-filled holes: Journal of Petroleum Technology, March 1963.

Anderson, Warren, and Associates, Inc., 1980, Norton Basin COST No. 1 Well, Paleontology Report: 32 p., 3 figs. (report prepared for ARCO Exploration Company).

Anstey, N. A., 1977, Seismic Interpretation: The physical aspects: Boston, International Human Resource Development Corporation, 625 p.

ARCO Oil and Gas Company, undated, Environmental Analysis for Norton Sound COST No. 1, Anchorage, Alaska.

Asquith, G. B., 1982, Basic well log analysis for geologists: Tulsa, American Association of Petroleum Geologists, 216 p.

Bachman, S. B., Lewis, S. D., and Schweller, W. J., 1983, Evolution of a forearc basin, Luzon Central Valley, Philippines: A.A.P.G. Bulletin, v. 67, p. 1143-1162.

Balsley, J. K., and Parker, L. R., 1983, Cretaceous wave-dominated delta, barrier island, and submarine fan depositional systems, Book cliffs, east central Utah: Tulsa, American Association of Petroleum Geologists Field Guide, 283 p.

Barker, C., 1974, Pyrolysis techniques for source-rock evaluation: A.A.P.G. Bulletin, v. 58, p. 2349-2361.

Barnes, D. F., 1977, Bouguer Gravity Map of Alaska: U.S. Geological Survey Geophysical Inv. Map, GP 913, 1 sheet.

Barron, John, 1980, Lower Miocene to Quaternary diatom biostratigraphy of leg 57, off northeastern Japan, in Initial Reports of the Deep Sea Drilling Project, vol. 56, 57, Pt. 2: Washington (U.S. Govt. Printing Office), p. 641-686.

Barron, J. A., and Keller, G., 1982, Widespread Miocene deep-sea hiatuses: coincidence with periods of global cooling: Geology, vol. 10, p. 577-581.

Bayliss, G. S., 1980, Hydrocarbon source facies analysis, COST Norton Basin Well, Norton Sound, Alaska: Houston, Texas, Geochem Laboratories, Inc., 96 p.

Bayliss, G. S., and Smith, M. R., 1980, Source Rock evaluation reference manual: Houston, GeoChem Laboratories, Inc., p. 80.

Beikman, H. M., 1980, Geologic map of Alaska: U.S. Geological Survey, 2 sheets, scale 1:2,500,000.

Bernard, B. B., Brooks, J. M., and Sackett, W. M., 1976, Natural gas seepage in the Gulf of Mexico. Earth and Planetary Science Letters, v. 31, p. 48-54.

Bernard, B. B., Brooks, J. M., and Sackett, W. M., 1977, A geochemical model for characterization of hydrocarbon gas sources in marine sediments: 9th Offshore Technology Conference Proceedings, v. 1, p. 435-438.

Biostratigraphics Consulting Micropaleontology, 1982, ARCO Norton Basin COST No. 2 well Paleontology reports: 5 parts, 91 p. (report prepared for ARCO Exploration Company).

Biswas, N. N., Pujol, J., Tytgat, G., and Dean, K., 1983, Synthesis of Seismicity Studies for Western Alaska: Environmental Assessment of the Alaskan Continental Shelf, Final Report, Hazards and Data Management, U.S. Department of Commerce, NOAA, 69 p.

Biswas, N. N., Gedney, L., and Agnew, J., 1980, Seismicity of Western Alaska: Bulletin of the Seismological Society of America, v. 70, no. 3, p. 873-883.

Blair, D. G., 1975, Structural styles in North Sea oil and gas fields, in Woodland, A. W., ed., Petroleum and the Continental Shelf of north-west Europe. Vol. 1, Geology: London, Applied Science Publishers, p. 327-335.

Bott, M. H. P., 1976, Formation of sedimentary basins of graben type by extension of the continental crust: Tectonophysics, v. 36, no. 1, p. 77-86.

Bouma, A. H., 1962, Sedimentology of some flysch deposits, a graphic approach to facies interpretation: Amsterdam, Elsevier Publishing Company, 168 p.

Bray, E. E., and Evans, E. D., 1961, Distribution of n-paraffins as a clue to recognition of source beds: Geochimica et Cosmochimica Acta, v. 22, p. 2-15.

Brouwers, Elisabeth, (in press) Ostracode assemblages from boreholes HLA 17 and 18, western Beaufort Sea, northern Alaska, appendix G: Environmental Assessment of the Alaska Continental Shelf, U.S. Bureau of Land Management/National Oceanic and Atmospheric Administration.

Brower, W. H., Diaz, H. F., Prechtel, H. S., Searby, H. W., and Wise, J. L., 1977, Climatic Atlas of the outer continental shelf waters and coastal regions of Alaska, vol. 2, Bering Sea. AEIDC Publication B-77, Alaska Environmental Information and Data Center, University of Alaska, Anchorage.

Bujak, J. P., 1984, Cenozoic Dinoflagellate cyst and Acritarchs from the Bering Sea and Northern north Pacific, DSDP Leg 19: Micropaleontology, v. 30, no. 2, p. 180-212.

Bureau of Land Management, 1982, Final environmental impact statement for Norton Sound OCS Proposed Oil and Gas Lease Sale No. 57: U.S. Department of the Interior, BLM OCS Office, Anchorage, Alaska.

Cacchione, D. A., and Drake, D. E., 1979, Sediment transport in Norton Sound Alaska: Regional patterns and GEOPROBE system measurements: U.S. Geological Survey open-file report [79-1555], 88 p.

Claypool, G. E., and Reed, P. R., 1976, Thermal-analysis technique for source rock evaluation: Quantitative estimates of organic richness and effects of lithologic variation: A.A.P.G. Bulletin, v. 60, no. 4. p. 608-626.

Cline, J. D., and Holmes, M. L., 1977, Submarine seepage of natural gas in Norton Sound, Alaska: Science, v. 198, p. 1149-1153.

Clukey, E. C., Cacchione, D. A., and Nelson, C. H., 1980. Liquefaction potential of the Yukon prodelta, Bering Sea, in Larsen, M. C., Nelson, C. H., and Thor, D. R., eds., Geological, geochemical, and geotechnical observations on the Bering Shelf, Alaska: U.S. Geological Survey open-file report [80-979], 476 p.

Conant, L. C., and Goudarzi, G. H., 1967, Stratigraphic and tectonic framework of Libya. A.A.P.G. Bulletin, v. 51, no. 5, p. 719-730.

Conservation Division, U.S. Dept. of Interior, 1980, High-resolution seismic survey of Norton Sound, Bering Sea, Alaska (available from U.S. National Oceanic and Atmospheric Administration (E.D.S.), Mail Code D 621, Boulder, CO 80303).

Cooke, C. W., 1985, Estimates of Undiscovered, Economically Recoverable Oil and Gas Resources for the Outer Continental Shelf as of July 1984. OCS Report MMS 85-0012, 45 p. U.S. Department of Interior, Minerals Management Service, Reston, VA.

Core Laboratories, Inc., Geochemical Services, 1980, Hydrocarbon source-bed evaluation, Norton Basin COST No. 1, Norton Sound, Alaska: Dallas, Texas, 129 p.

Crimes, T. P., 1970, The significance of trace fossils in sedimentology, stratigraphy, and paleoecology with examples from lower Paleozoic strata: in Crimes, T. P., and Harper, J. C., eds., Trace Fossils, Geological Journal Special Issue No. 3, Liverpool, Seel House Press, p. 101-126.

Csejtey, Bela, and Patton, W. W., 1974, Petrology of the nepheline syenite of St. Lawrence Island, Alaska: Journal of Research U.S. Geological Survey, v. 2, no. 1, January-February 1974, p. 41-47.

Davey, R. J., Downie, Charles, Sarjeant, W. A. S., and Williams, G. L., 1966, Studies on Mesozoic and Cainozoic dinoflagellate cysts: Bulletin British Museum (Natural History), Geology Supplement 3, 248 p., 26 pl., 64 text-figs.

Decker, J., and Karl, S., 1977, Preliminary aero-magnetic map of Seward Peninsula, Alaska: U.S. Geological Survey open-file report [77-796-E].

Demaison, G., 1981, Stratigraphic aspects of source bed occurrence, The organic facies concept: in Geochemistry for Geologists, AAPG Geochemistry for Geologists (short course notes), Dallas, Texas, 1981, 101 p.

Demshur, D. M., and Swetland, P. J., 1980, Hydrocarbon source-bed evaluation, Norton Basin COST No. 1, Norton Sound, Alaska: Dallas, Texas, Core Laboratories, Inc., 129 p.

Department of Commerce, 1969, Coast and Geodetic Survey PBM-1m (magnetic map of St. Lawrence Island to Port Clarence): U.S. Department of Commerce, Washington D.C., 1 sheet, scale 1:250,000.

Donovan, T. J., Gorgy, R. L., and Roberts, A. A., 1979, Aeromagnetic detection of diagenetic magnetite over oil fields: A.A.P.G. Bulletin, v. 63, no. 2, p. 245-248.

Dow, W. G., 1977, Kerogen studies and geological interpretations: Journal of Geochemical Exploration, v. 7, no. 2, p. 79-99.

Dow, W. G., 1982, Geochemical Analysis of Norton Sound COST No. 2 well, Alaska: Houston, Texas, Robertson Research (U.S.), Inc., 33 p.

Dow, W. G., and O'Connor, D. J., 1981, Kerogen maturity and type by reflected light microscopy applied to petroleum exploration, _in_ Geochemistry for Geologists, AAPG Geochemistry for Geologists (short course notes): Dallas, Texas, 27 p.

Dow, W. D., and O'Connor, D. J., 1982, Kerogen maturity and type by reflected light microscopy applied to petroleum exploration, _in_ How to Assess Maturation and Paleotemperatures, SEPM Short Course No. 7, Tulsa: Society of Economic Paleontologists and Mineralogists, p. 133-157.

Dresser Atlas, Dresser Industries, Inc., 1979, Log Interpretation Charts: Houston, 108 p.

Dupré, W. R., 1978, Yukon delta coastal processes study: NOAA, U. S. Department of Commerce, Environmental Assessment of the Alaskan Continental Shelf, Annual Report of Principal Investigators for the Year Ending March 1978, v. 11, p. 384-446.

Durand, B., and Oudin, J. L., 1979, Example de migration des hydrocarbures dans une serie deltaique: le delta de la mahakam, Kalimantan, Indonesie, _in_ Exploration, Supply and Demand: Bucharest, 10th World Petroleum Congress Proceedings, vol. 2, p. 3-11.

Dutro, J. T., Jr., 1981, Geology of Alaska bordering the Arctic Ocean, _in_ Nairn, A. E. M., Churkin, M., Jr., and Stehi, F. G., eds., The Ocean Basins and margins: New York, Plenum Press, p. 21-36.

Espitalie, J., Laporte, J. L., Madec, M., Marquis, F., Leplat, P., Paulet, J., and Boutefeu, A., 1977, Methode rapide de caracterisation des roches meres, de leur potentiel petrolier et de leur degre d'evolution: Rev. J l'Institute Francais Petroleum, v. 32, no. 1, p. 23-42.

Falvey, D. A., and Deighton, I., 1982, Recent advances in burial and thermal geohistory analysis: Australian Petroleum Exploration Association Journal, v. 22, pt. 1, p. 65-81.

Fertl, W. H., and Wichmann, P. A., 1977, How to determine static BHT from well log data: World Oil, v. 184, p. 105-106.

Fisher, M. A., Patton, W. W., Jr., Thor, D. R., Holmes, M. L., Scott, E. W., Nelson, C. H., and Wilson, C. L., 1979, Resource report for proposed OCS Lease Sale 57: Norton Basin, Alaska: U.S. Geological Survey open-file report [79-720], 23 p.

Fisher, M. A., McClellan, P. H., Holmes, M. L., and Childs, J. R., 1980, Preliminary free-air gravity map, Norton Basin, Alaska: U.S. Geological Survey open-file report [80-1068], 1 sheet, scale 1:250,000.

Fisher, M. A., Patton, W. W., and Holmes, M. L., 1981, Geology and Petroleum Potential of the Norton Basin Area, Alaska: U.S. Geological Survey open-file report [81-1316].

Fisher, M. A., Patton, W. W., and Holmes, M. L., 1982, Geology of Norton Basin and continental shelf beneath northwestern Bering Sea, Alaska: A.A.P.G. Bulletin, v. 66, no. 3, p. 255-285.

Fisher, M. A., 1982, Petroleum geology of Norton Basin, Alaska: A.A.P.G. Bulletin, v. 66, no. 3, p. 286-301.

Fisher, W. L., Brown, L. F., Scott, A. J., and McGowen, J. H., 1974, Delta systems in the exploration for oil and gas: Bureau of Economic Geology, University of Texas, Austin, Texas, 155 p.

Folk, R. L., 1974, Petrology of sedimentary rocks, Hemphill Publishing Company, Austin, Texas, 182 p.

Forbes, R. B., Evans, B. W., and Pollock, S., 1981, The Nome Group blueschist terrane: a possible extension of the Brooks Range Schist Belt: Geological Society of America, 77 Annual Meeting, Senora, Mexico, Abstracts with Program, Cordilleran Section, v. 13, no. 2, p. 56.

Fuex, A. N., 1977, The use of stable isotopes in hydrocarbon exploration: Journal of Geochemical Exploration, v. 7, no. 2, p. 155-188.

Geochem Laboratories, Inc., see Bayliss, 1980.

Ghignone, J. I., and De Andrade, G., 1968, General geology and Major Oil Fields of Reconcavo Basin, Brazil: in Geology of giant petroleum fields; a symposium of papers on giant fields of the world including those presented at the 53rd annual meeting of the AAPG in Oklahoma City, Oklahoma, April 23-25, 1968, p. 337-358.

Gibling, M. R., Ukakimaphan, Y., and Srisuk, S., 1985, Oil shale and coal in intermontane basins of Thailand: A.A.P.G. Bulletin, v. 69, no. 5, p. 760-766.

Gladenkov, Y. B., 1977, Stages in the evolution of mollusks and subdivisions of the North Pacific Neogene, in Saito, Tsunemasa, and Ujiié, Hiroshi, eds., Proceedings of the First International Congress on Pacific Neogene Stratigraphy, Tokyo, 1976: Tokyo, Science Council of Japan, Geological Society of Japan, and International Union of Geological Sciences, p. 89-91.

Grim, M. S., and McManus, D. A., 1970, A shallow seismic-profiling survey of the northern Bering Sea: Marine Geology, v. 8, p. 293-320.

Hammond, R. D., and Gaither, J. R., 1983, Anomalous seismic character, Bering Sea shelf: Geophysics, v. 48, p. 590-605.

Harding, T. P., 1984, Graben hydrocarbon occurrences and structural style: A.A.P.G. Bulletin, v. 68, no. 3, p. 333-362.

Harms, J. C., Southard, J. B., Spearing, D. R., and Walker, R. G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: Society of Economic Paleontologists and Mineralogists Short Course No. 2, 161 p.

Harms, J. C., Tackenberg, T., and Pickles, E., 1980, Brae Field Area, North Sea: (abstract), A.A.P.G. Bulletin, v. 64, p. 178.

Harms, J. C., Tackenberry, T., Pickles, E., and Pollock, R. E., 1981, The Brae Oil field area, in Illing, L. V., and Hobson, G. D., eds., Petroleum geology of northwest Europe: London, Hayden and Son, p. 352-357.

Hart, J. L., 1973, Pacific fishes of Canada: Bulletin of the Fisheries Research Board of Canada, No. 180, 740 p.

Hayes, J. B., 1984, Sandstone porosity evolution, in Sandstone Diagenesis Course Notes: Tulsa, American Association of Petroleum Geologists, p. 1-36.

Hein, J. R., Scholl, D. W., Barron, J. A., Jones, M. G., and Miller, Jacquelyn, 1978, Diagenesis of late Cenozoic diatomaceous deposits and formation of the bottom simulating reflector in the southern Bering Sea: Sedimentology, v. 25, p. 155-181.

Helander, 1983, Fundamentals of formation evaluation: Tulsa, Oil and Gas Consultants International, Inc. 332 p.

Helwig, J., Chang, Y. M., Smith, M. T., and Chong, G. G., 1984, Tectonics of Norton Basin: Abstracts with Programs, 80th Annual Meeting Cordilleran Section, The Geological Society of America, v. 16, no. 5, April 1984.

Herman, Yvone, and Hopkins, D. M., 1980, Arctic ocean climate in late Cenozoic time: Science, v. 209, August 1, p. 557-562.

Hingle, A. T., 1959, The use of logs in exploration problems: Soc. Exploration Geophysicists, 29th Mtg., Los Angeles.

Hoare, J. M., and Coonrad, 1980, The Togiak basalt, a new formation in southwestern Alaska: U.S. Geological Survey Bulletin, 1482-C, p. cl-cll.

Holmes, M. L., 1979, Distribution of gas-charged sediment in Norton Sound and Chirikov Basin. NOAA, U.S. Department of Commerce. Environmental Assessment of the Alaskan Continental Shelf, Annual report of Principal Investigators for the year ending March 1979. Part 10, p. 75-94.

Holmes, M. L., Cline, J. D., and Johnson, J. L., 1978, Geological Setting of the Norton Basin gas seep: 1978 Offshore Technology Conference, Houston, Proceedings: May 8-11, 1978, OTC 3051, p. 73-80.

Holmes, M. L., and Creager, J. S., 1981, The role of the Kaltag and Kobuk faults in the tectonic evolution of the Bering Strait region: in Hood, D. W. and Calder, J. A., eds., The eastern Bering Sea Shelf Oceanography and Resources: U.S. Department of Commerce, NOAA, Office of Marine Pollution Assessment, p. 293-302.

Hoose, P. J., Steffy, D. A., and Lybeck, L. D., 1981, Isopach map of Quaternary and upper Tertiary strata, Norton Sound, Alaska: U.S. Geological Survey open-file report [81-723], 1 oversized sheet, scale 1:250,000.

Hopkins, D. M., Nelson, C. H., Perry, T. N., and Alpha, R. R., 1976, Physiographic Subdivisions of the Chirikov Basin, northern Bering Sea. U.S. Geological Survey professional paper 759-B, 7 p.

Hopkins, D. M., 1979, Landscape and Climate of Beringia during late Pleistocene and Holocene time, in Laughlin, W. S., and Harper, A. B., eds., The First Americans: Origins, Affinities, and Adaptations, New York, G. Fischer Publishing, 340 p.

Hopkins, D. M., 1982, Aspects of the paleogeography of Beringia during the late Pleistocene, in Hopkins, D. M., Matthews, J. V., Jr., Schweger, C. E., and S. B. Young, eds., Paleoecology of Beringia, New York, Academic Press, p. 3-28.

Hudson, T., and Plafker, G., 1978, Kigluaik and Bendeleben Faults, Seward Peninsula: U.S. Geological Survey Circular 772-B, p. B47-B50.

Hudson, Travis, 1977, Preliminary geologic map of Seward Peninsula, Alaska: U.S. Geological Survey open-file report [OF-77-796A].

Hudson, Travis, 1979, Igneous and metamorphic rocks of the Serpentine Hot Springs area, Seward Peninsula, Alaska: U.S. Geological Survey professional paper 1079, 27 p.

Hunt, J. M., 1979, Petroleum Geochemistry and Geology: San Francisco, W. H. Freeman and Company, 617 p.

Hyndman, 1972, Petrology of igneous and metamorphic rocks: New York, McGraw-Hill Company, 533 p.

Ibrahim, M. W., 1983, Petroleum geology of southern Iraq: A.A.P.G. Bulletin, v. 67, no. 1, p. 97-130.

International Committee for Coal Petrology, 1963, 1971, and 1976, International Handbook of Coal Petrology: second edition, 1963, Supplements 1971 and 1976. Centre National De La Recherche Scientifique, Paris, France.

Isaacs, C. M., Pisciotto, K. A., and Garrison, R. E., 1983, Facies and diagenesis of the Miocene Monterey Formation, California: A summary: in Iijima, A., Hein, J. R., eds., Siliceous deposits in the Pacific region: Sedimentology No. 36, Amsterdam, Elsevier, p. 247-282.

Issler, D. R., 1984, Calculation of organic maturation levels for offshore eastern Canada - implications for general application of Lopatin's method: Canadian Journal of Earth Sciences, v. 21, p. 247-282.

Johnson, J. L., and Holmes, M. L., 1980, Surface and subsurface faulting in Norton Sound and Chirikov Basin, Alaska: U.S. Geological Survey open-file report [80-979], 25 p.

Johnson, J. L., and Holmes, M. L., 1981, Report on surface and subsurface faulting in Norton Sound and Chirikov Basin, Alaska: No. AA, U.S. Department of Commerce, Environmental Assessment of the Alaskan Continental Shelf, Annual Reports of the Principal Investigators for the year ending March 1980, v. 5, p. 420-444.

Knebel, H. J., and J. S. Creager, 1973, Yukon River: evidence for extensive migration during the Holocene transgression: Science, v. 179, p. 1230-1231.

Koizumi, Itaru, 1973, The Late Cenozoic diatoms of sites 183-193, Leg 19 Deep Sea Drilling Project, in Creager, J. S., Scholl, D. W., and others, eds., Initial Reports of the Deep Sea Drilling Project, Volume 19, Washington (U.S. Government Printing Office), p. 505-856.

Kvenvolden, K. A., and Claypool, G. E., 1980, Origin of gasoline-range hydrocarbons and their migration by solution in carbon dioxide in Norton Basin, Alaska: A.A.P.G. Bulletin, v. 64, no. 7, p. 1078-1085.

Kvenvolden, K. A., Nelson, C. H., Thor, D. R., Larson, M. C., Redden, G. D., Rapp, J. B., and Des Marais, D. J., 1979, Biogenic and thermogenic gas in gas-charged sediment of Norton Sound, Alaska: 11th Offshore Technology Conference Proceedings, v. 1, p. 479-486.

Labelle, J. C., Wise, J. L., Voelker, R. P., Schulze, R. H., and Wohl, G. M., 1983, Alaska Marine Ice Atlas: Anchorage, Alaska Environmental Information and Data Center, University of Alaska.

Larsen, B. R., Nelson, C. H., Heropoules, C., and J. J. Patry, 1981, Distribution of trace elements in bottom sediment of northern Bering Sea: NOAA, U.S. Department of Commerce, Environmental Assessment of the Alaskan Continental Shelf Annual Reports of Principal Investigators for the year ending March 1980, v. 5, p. 445-567.

Larsen, M. C., Nelson, C. H., and D. R. Thor, 1981, Sedimentary processes and potential geologic hazards on the sea floor of the northern Bering Sea: in Hood, D. W., and Calder, J. A., eds., The Eastern Bering Sea Shelf: Oceanography and resources, NOAA, U.S. Department of Commerce, p. 247-261.

Larsen, M. C., Nelson, C. H., and Thor, D. R., 1980, Sedimentary processes and potential geologic hazards on the sea floor of northern Bering Sea, in Larsen, M. C., Nelson, C. H., and Thor, D. R., eds., Geological, geochemical, and geotechnical observations on the Bering Shelf, Alaska: U.S. Geological Survey open-file report [80-979], 32 p.

Larskaya, Ye S., and Zhabrev, D. H., 1964, Effects of stratal temperatures and pressures on the composition of dispersed organic matter from the example of the Mesozoic-Cenozoic deposits of the western Ciscaspian region: Dokl. Akad. Nauk SSSR, v. 157, no. 4, p. 135-139.

Lentin, J. K., and Williams, G. L., 1977, Fossil dinoflagellates: Index to genera and species: Bedford Institute of Oceanography Rept. Serv. BI-R-77-8, Halifax, 209 p.

Link, T. A., Downing, J.A., Raasch, G. O., Byrne, A. W., Wilson, D. W. R., Reece, A., 1960, Geological map of Arctic: Prepared by First International Symposium on Arctic Geology, Alberta Society of Petroleum Geology, 1 oversized map, Scale 1:1,750,000.

Lopatin, N. V., 1971. Temperature and geologic time as factors in coalification (in Russian): Izv. Akad. Nauk SSSR, Seriya geologicheskaya, no. 3, p. 95-106 (cited in Waples, 1981).

Lyle, W. M., Palmer, I. F., Bolm, J. G., and Flett, T. O., 1982, Hydrocarbon reservoir and source-rock characteristics from selected areas of Southwestern Alaska: Alaska Division of Geological and Geophysical Surveys Professional Report 77, p. 1-35.

Magoon, L. B., and Claypool, G. E., 1983, Petroleum geochemistry of the North Slope of Alaska: time and degree of thermal maturity, in Malvin Bijorov, ed., Advances in Organic Geochemistry, New York , N.Y., John Wiley, p. 28-38.

Marlow, M.S., Cooper, A. K., and Childs, J. R., 1983, Tectonic evolution of Gulf of Anadyr and formation of Anadyr and Navarin Basins: AAPG Bulletin, v. 67, p. 646-665.

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

Martini, E., 1971, Standard Tertiary and Quaternary calcareous nannoplankton zonation, in Farinacci, A., ed., Proceedings of the Second Planktonic Conference, 1970: Rome, Edizioni Tecno-Scienza, p. 739-785.

McDougall, K., 1980, Microfaunal analysis of late Quaternary deposits of the northern Bering Sea, 34 p., in Larsen, M. C., Nelson, C. H., and Thor, D. R., eds., Geological, Geochemical, and Geotechnical Observations on the Bering Shelf, Alaska: U.S. Geological Survey open-file report [80-979], 476 p.

McKenzie, Dan, 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25-32.

McManus, D. A., Kolla, A. V., Hopkins, B. M., and Nelson, C. H., 1977, Distribution of bottom sediments on the continental shelf, northern Bering Sea. U.S. Geological Survey professional paper 759-C.

Menner, V. V., Baranova, Y. P., and Zhidkova, L. S., 1977, Neogene of the Northeastern U.S.S.R. (Kolyma Region, Kamchatka, and Sakhalin), in Saito, Tsunemasa, and Ujiié, Hiroshi, eds., Proceedings of the First International Congress on Pacific Neogene Stratigraphy, Tokyo, 1976: Tokyo, Science Council of Japan, Geological Society of Japan, and International Union of Geological Sciences, p. 83-88.

Middleton, M. F., and Falvey, D. A., 1983, Maturation modeling in Otway Basin, Australia: A.A.P.G. Bulletin, v. 67, no. 2 p. 271-279.

Miller, D. J., Payne, T. G., and Gryc, G., 1959, Geology of possible petroleum provinces in Alaska: U.S.G.S. Bulletin 1094, p. 131.

Miller, T. P., Patton, W. W., Jr., and Lanphere, M. A., 1966, Preliminary report on a plutonic belt in west-central Alaska: U.S. Geological Survey Professional Paper 550-D, p. D158-D162.

Miller, T. P., and Bunker, C. M., 1976, A Reconnaissance study of the Uranium and Thorium contents of plutonic rocks of the Southeastern Seward Peninsula, Alaska: U.S. Geological Survey Journal of Research, v. 4, p. 367-377.

Minerals Management Service, 1980, Offshore Field Operations, Deputy Minerals Manager, OCS Environmental Assessment No. AK-80-1: U.S. Minerals Management Service, Anchorage, Alaska.

Minerals Management Service, 1981, OCS Environmental Assessment no. AK-81-5: Deputy Minerals Manager, Offshore Field Operations, U.S. Minerals Management Service, Anchorage, Alaska.

Minerals Management Service, 1982, Guidelines for collection of meteorological, oceanographic, and performance data: Offshore Field Operations, U.S. Minerals Management Service, Anchorage, Alaska.

Miyashiro, Akiho, 1974, Volcanic rock series in island arcs and active continental margins: American Journal of Science, v. 274, p. 321-355.

Mobil Exploration and Producing Services, Inc., 1980, Report on the Benedum and Associates Unit No. 1 test well. Available from State of Alaska Oil and Gas Commission.

Mutti, E., and Ricci Lucchi, F., 1972, Le torbiditi dell' Appennino settentrionale: introduzione all' analisi di facies: Memorie della Societa' Geologica Italiana, v. 11, p. 161-199. English translation in International Geology Review, 1978, v. 20, no. 2, p. 125-166.

Nakamura, K., Plafker, G., Jacob, K. H., and Davies, J. N., 1980, A tectonic stress trajectory map of Alaska using information from volcanoes and faults: Bulletin of the Earthquake Research Institute, University of Tokyo, v. 55, p. 89-100.

Nekton, Inc., 1980a, Biological Survey: Proposed Continental Offshore Stratigraphic Test No. 2, Norton Sound, Alaska, report to ARCO Oil and Gas Company, Anchorage, Alaska.

Nekton, Inc., 1980b, Shallow Drilling Hazards Survey: Proposed Continental Offshore Stratigraphic Test No. 2, Norton Sound, Alaska, report to ARCO Oil and Gas Company, Anchorage, Alaska.

Nelson, C. H., 1980, Late Pleistocene-Holocene transgressive sedimentation in deltaic and non-deltaic areas of the Bering epicontinental shelf, 30 p., in Larsen, M. C., Nelson, C. H., and Thor, D. R., eds., Geological, geochemical, and geotechnical observations on the Bering Shelf, Alaska: U.S. Geological Survey open-file report [80-979], 467 p.

Nelson, C. H., Dupré, W. R., Field, M. E., and Howard, J. D., 1980, Linear sand bodies in the Bering Sea epicontinental shelf, in Larsen, M. C., Nelson, C. H., and Thor, D. R., eds., Geological, geochemical, and geotechnical observations on the Bering Shelf, Bering Shelf, Alaska: U.S. Geological Survey open-file report [80-979], 467 p.

Nelson, C. H., and Hopkins, D. M., 1972, Sedimentary processes and distribution of particulate gold in northern Bering Sea: U.S. Geological Survey professional paper 689, 27 p.

Nelson, C. H., Hopkins, D. M., and Scholl, D. W., 1974, Tectonic setting and Cenozoic sedimentary history of the Bering Sea, in Herman, Yvonne, ed., Arctic geology and oceanography, Springer-Verlag, New York, p. 119-140.

Nelson, C. H., Kvenvolden, K. A., and E. C. Clukey, 1978, Thermogenic gases in near-surface sediments of Norton Sound, Alaska: 1978 Offshore Technology Conference, Houston, Proceedings: May 8-11, 1978, OTC 3354, p. 2623-2633.

Nelson, C. H., Rowland, R. W., Stoker, S. W., and Larsen, B. R., 1980, Interplay of physical and biological sedimentary structures of the Bering epicontinental shelf, in Larsen, M. C., Nelson, C. H., and Thor, D. R., eds., Geological, geochemical, and geotechnical observations on the Bering Shelf, Alaska: U.S. Geological Survey open-file report [80-979], 467 p.

Nelson, C. H., Thor, D. R., Sandstrom, M. W., and Kvenvolden, K. A., 1979, Modern biogenic gas-generated waters (sea-floor "pock marks") on the Bering Shelf, Alaska: Geological Society of America Bulletin, pt. 1, v. 90, p. 1144-1152.

Nelson, H. C., and Nilsen, T. H., 1984, Modern and ancient deep-sea fan sedimentation: Tulsa, Society of Economic Paleontologists and Mineralogists, SEPM short course no. 14, 404 p.

Nilsen, T. H., 1984, Sedimentation of turbidites with application to Alaskan basins, a short course [unpub. syllabus]: Anchorage, Alaska, Alaska Geological Society, 81 p.

Park, R., and Epstein, S., 1960, ^{13}C in lake waters and its possible bearing on paleolimnology: American Journal of Science, v. 258, p. 253-272.

Parsons, M. G., Zaggar, A. M., and Curry, J. J., 1980, Hydrocarbon occurrences in the Sirte basin, Libya: in Maill, A.D., ed., Facts and principles of world petroleum occurrence: Canadian Society of Petroleum Geologists Memoir no. 6, p. 723-732.

Patton, W. W., 1973, Reconnaissance geology of the northern Yukon-Koyukuk Province, Alaska: U.S. Geological Survey professional paper 774-A, p. A1-A17.

Patton, W. W., and Csejtey, Bela, Jr., 1971, preliminary geologic investigations of western St. Lawrence Island, Alaska: U.S. Geological Survey professional paper 684-C, 15 p.

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.

Patton, W. W., Jr., and Dutro, J. T., Jr., 1969, Preliminary report on the Paleozoic and Mesozoic sedimentary sequence on St. Lawrence Island, Alaska: U.S. Geological Survey professional paper 650-D, p. 138-143.

Patton, W. W., and Csejtey B., 1980, Geologic map of St. Lawrence Island, Alaska: U.S. Geological Survey Miscellaneous Inv. Map I-1203, 1 sheet, scale 1:250,000.

Payne, T. G., 1955, Mesozoic and Cenozoic tectonic elements of Alaska: U.S. Geological Survey Miscellaneous Inv. Map I-84, Scale 1:500,000.

Phillippi, G. T., 1957, Identification of oil-source beds by chemical means: 20th International Geological Congress, Proceedings, Mexico City, 1956, Sec. 3, pp. 25-28.

Poupoun, A., Clavier, C., Dumanoir, J., Gaymard, R., and Misk, A., 1970, Log analysis of sand-shale sequences, a systematic approach: Journal of Petroleum Technology, v. 22, p. 867-881.

Powell, T. G., and McKirdy, D. M., 1975, Geologic factors controlling crude oil composition in Australia and Papua, New Guinea: A.A.P.G. Bulletin, v. 59, no. 7, p. 1176-1197.

Powell, T. G., 1978, An assessment of the hydrocarbon source rock potential of the Canadian Arctic Islands: Canadian Geological Survey Paper 78-12, 82 p.

Prothero, D. K., 1985, Mid-Oligocene extinction event in North American land mammals, Science, v. 229, p. 550-551.

Qi, Fei, and Xie-Pei, Wang, 1984, Significant role of structural fractures in Renqiu buried-hill oil field in eastern China: A.A.P.G. Bulletin, v. 68, no. 8, p. 971-982.

Radke, M., Schaefer, R. G., Leythaeuser, D., and Teichmuller, M., 1980, Composition of soluble organic matter in coals: Relation to rank and liptinite fluorescence: Geochemica et Cosmochemica Acta, v. 44, p. 1787-1800.

Rao, P. D., 1983, Petrology of Cretaceous coals from Northern Alaska, final technical report: Mineral Industry Research Laboratory Report, no. 64, University of Alaska, 141 p.

Robertson Research (U.S.), Inc., see Dow, 1982.

Roeder, D. and Mull, C. G., 1978, Tectonics of Brooks Range Ophiolites Alaska: A.A.P.G. Bulletin, v. 62, no. 9, p. 1696-1713.

Rouse, G. E., 1977, Paleogene palynomorph ranges in western and northern Canada: Contributions of Stratigraphic Palynology, Cenozoic palynology, vol.1, Contribution Series No. 5A: American Association of Stratigraphic Palynologists Foundation, p. 49-65, 2 pl.

Sachs, V. N., and Strelkov, S. A., 1961, Mesozoic and Cenozoic of the Soviet Arctic; in Raasch, G. O., ed., Geology of the Arctic, University Toronto Press, Toronto, Canada, p. 48-67.

Sainsbury, C. L., 1969, Geology and ore deposits of the central York Mountains, western Seward Peninsula, Alaska: U.S. Geological Survey Bulletin 1287, p. 1-10.

Sainsbury, C. L., Coleman, R. G., and Kachadoorian, R., 1970, Blueschist and related greenschist facies rocks of the Seward Peninsula, Alaska: U.S. Geological Survey professional paper 700B, p. B33-B42.

Schlumberger Well Services, Inc., 1972a, Log Interpretation Charts: Houston, Texas, 92 p.

Schlumberger Well Services, Inc., 1972b, Log Interpretation: vol. 1, Principles: Houston, Texas, 113 p.

Schlumberger Well Services, Inc., 1974, Log Interpretation Charts: vol. 2, Applications: Houston, Texas, 116 p.

Schlumberger Well Services, Inc., 1981. Dipmeter interpretation: vol. 1, Fundamentals, Houston, 61 p.

Scholl, D. W., and Hopkins, D. M., 1969, Newly discovered Cenozoic basins, Bering Sea shelf, Alaska: AAPG Bulletin, v. 53, p. 2067-2078.

Scholl, D. W., Buffington, S. C., Hopkins, D. M., and Alpha, T. R., 1970, The structure and origin of the large submarine canyons of the Bering Sea. Marine Geology, v. 8., p. 187-210.

Schrader, Hans, 1973, Cenozoic diatoms from the northeast Pacific, in leg 18, Initial reports of the Deep Sea Drilling Project: National Science Foundation, p. 673-798.

Selley, R. C., 1978, Concepts and methods of subsurface facies analysis: American Association of Petroleum Geologists, Education Course Notes Series no. 9, Tulsa, Oklahoma, 86 p.

Serova, M. Y., 1976, The Caucasina eocaenica kamchatica zone and the Eocene-Oligocene boundary in the northwestern Pacific, in Takayanagi, Yokichi, and Saito, Tsunemasa, eds., Progress in micropaleontology, selected papers in honor of Prof. Kiyoshi Asano: New York, American Museum of Natural History, Micropaleontology Press, Special Publication, p. 314-328.

Shanmugam, G., 1985, Significance of coniferous rain forests and related organic matter in generating commercial quantities of oil, Gippsland Basin, Australia. A.A.P.G. Bulletin, v. 69, no. 8, p. 1241-1254.

Sharma, G. D., 1979, The Alaskan shelf: Hydrographic, sedimentary, and geotechnical environment: New York, Springer-Verlag, 498 p.

Sheriff, R. E., 1980, Seismic Stratigraphy: Boston, International Human Resources Development Corporation, 227 p.

Sheriff, R. E., 1978, A first course in geophysical examination and interpretation: Boston, International Human Resource Development Corporation, 313 p.

Silverman, S. R., 1964, Investigations of petroleum origin and mechanisms by carbon isotope studies, in Miller, S. L. and Wasserburg, G. J., eds., Isotope and Cosmic Chemistry: Amsterdam, North-Holland Publishing Company, p. 92-102.

Silverman, S. R., and Epstein, S., 1958, Carbon isotopic composition of petroleums and other sedimentary organic materials: A.A.P.G. Bulletin, v. 42, no. 5, p. 998-1012.

Smith, P. S., 1910, Geology and mineral resources of the Solomon and Casadepage quadrangles, Seward Peninsula, Alaska: U.S. Geological Survey Bulletin, v. 433, 234 p.

Snowdon, L. R., 1978, Organic geochemistry of the Upper Cretaceous Tertiary delta complexes of the Beaufort-MacKenzie sedimentary basin, Northern Canada. Phd. Thesis, Rice University, Houston, Texas, 130 p.

Snowdon, L. R. and Powell, T. G., 1982, Immature oil and condensate: modification of hydrocarbon generation model for terrestrial organic matter: A.A.P.G. Bulletin, v. 66, no. 6, p. 775-788.

Sowers, G. F., 1979, Introductory soil mechanics and foundations: Geotechnical Engineering (Fourth edition). New York, MacMillan, 621 p.

Stach, E., Mackowsky, M.-Th., Teichmuller, M., Taylor, G. H., Chandra, D., and Teichmuller, R., 1982, Stach's textbook of coal petrology: Berlin, Gebruder Borntraeger, 535 p.

Staplin, F. L., 1969, Sedimentary organic matter, organic metamorphism, and oil and gas occurrence: Bulletin of Canadian Petroleum Geology, v. 17, no. 1, p. 47-66.

Steffy, D. A., Turner, B. W., and Lybeck, L. D., 1981, Bathymetric map of Norton Sound, Alaska: U.S. Geological Survey open-file report [81-719], 1 oversized sheet, scale 1:250,000.

Steffy, D. A., Turner, B. W., Lybeck, L. D., and Roe, J. T., 1981, Isopach map of Holocene sedimentary units, Norton Sound, Alaska: U.S. Geological Survey open-file report [81-720], 1 oversized sheet, scale 1:250,000.

Steffy, D. A., and Hoose, P. J., 1981, Map showing acoustic anomalies and near-surface faulting, Norton Sound, Alaska: U.S. Geological Survey open-file report [81-722], 1 oversized sheet, scale 1:250,000.

Steffy, D. A. and Lybeck, L. D., 1981, Map showing selected geologic features, Norton Sound, Alaska: U.S. Geological Survey open-file report [81-721], 1 oversized sheet, scale 1:250,000.

Stover, L. E., and Evitt, W. R., 1978, Analyses of pre-Pleistocene organic walled dinoflagellates: Palo Alto, Stanford University Publications, 300 p.

Surdam, R. C., Boesc, S. W., Crossey, L. J., 1984, The chemistry of secondary porosity: in Sandstone Diagenesis Course Notes, A.A.P.G., Tulsa, 1984.

Suzuki, V., 1983, The volcanic mound, in Bally, A. W., ed., Seismic expression of structural styles, AAPG studies in Geology series 15, Tulsa: 1.3-16 - 1.3-18.

Tetra Tech, Inc., 1979a, Interpretative Report on COST Site No. 1 and 2 Site-Specific Hazard Survey, Norton Sound, Alaska, Report to ARCO Oil and Gas Company: Anchorage, Alaska.

Tetra Tech, Inc., 1979b, Marine Biological Survey at Proposed Continental Offshore Stratigraphic Test No. 1 - Norton Sound, Alaska. Report to ARCO Oil and Gas Company: Anchorage, Alaska.

Thiebaud, C. E., and Robson, D. A., 1981, The geology of the Asl oil field, Western Sinai, Egypt. Journal of Petroleum Geology, v. 4, p. 77-87.

Thor, D. R., and C. H. Nelson, 1981, Ice gouging on the subarctic Bering Shelf: NOAA, U.S. Department of Commerce, Environmental assessment of the Alaskan Continental Shelf, annual reports of principal investigators for the year ending March 1980, v. 5, p. 289-314.

Till, A. B., 1982, Granulite, peridotite, and blueschist - early tectonic history of the Seward Peninsula, Alaska [abs]: Alaska Geological Society Symposium, Anchorage, Alaska, 1982, Proceedings, Alaska Geological Society, p. 33-35.

Tipsword, H. L., Setzer, F. M., and Smith, F. L., Jr., 1966, Interpretation of depositional environments in Gulf Coast petroleum exploration from paleoecology and related stratigraphy: Gulf Coast Association of Geological Societies Transactions, vol. XVI, p. 119-130.

Tissot, B. P., and Welte, D. H., 1984, Petroleum Formation and Occurrence (2nd ed.) rev.: New York, Springer-Verlag, 699 p.

Tixier, M. P., Morris, R. L., and Connell, J. G., 1968, Log evaluation of low-resistivity pay sands in the Gulf Coast: The Log Analyst, November-December 1968.

Turner, R. F., Bolm, J. G., McCarthy, C. M., Steffy, D. A., Lowry, Paul, and Flett, T. O., 1983a, Geological and operational summary, Norton Sound COST No. 1 well, Norton Sound, Alaska: U.S. Geological Survey open-file report [83-124], 164 p.

Turner, R. F., Bolm, J. G., McCarthy, C. M., Steffy, D. A., Lowry, Paul, Flett, T. O., and Blunt, David, 1983b, Geological and operational summary, Norton Sound Cost No. 2 well, Norton Sound, Alaska: U.S. Geological Survey open-file report [83-557], 154 p.

Turner, R. F., McCarthy, C. M., Steffy, D. A., Lynch, M. B., Martin, G. C., Sherwood, K. W., Flett, T. O., and Adams, A. J., 1984, Geological and operational summary, Navarin Basin COST No. 1 well, Bering Sea, Alaska: U.S. Minerals Management Service, OCS Report MMS 84-0031, 245 p.

Turner, D. L., and Swanson, S., 1981, Continental rifting - a new tectonic model for the Seward Peninsula: Geothermal Reconnaissance Survey of the Central Seward Peninsula, Alaska Geophys. Inst. Rept. UAGR - 284 p.

Vail, P. R., Mitchum, R. M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, part 4: Global cycles of relative changes of sea level: in C. E. Payton, ed., Seismic Stratigraphy: Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir 26: Tulsa, OK, p. 83-97.

Van Krevelen, D. W., 1961, Coal: New York, Elsevier, 514 p.

Vixo, D. L., and Prucha, R. G., 1983, Interpretation Report of Airborne Magnetometer Survey, Norton Basin: Aero Service Division, Western Geophysical Company of America (Proprietary report cited with permission of Western Geophysical Company), 36 p.

Voloshinova, N. A., Kuznetsova, V. N., and Leonenko, L. S., 1970, Neogene Foraminifera of Kakhalin: Proceedings of the All Union Petroleum Scientific Research, Geological Exploration Institute: Washington, D. C., Smithsonian Institution and National Science Foundation (translated from Russian by the National Translations Center, TT 76-53241), 608 p.

Walker, R. G., 1965, The origin and significance of the internal sedimentary structures of turbidites: Yorkshire Geological Society Proc., v. 35, p. 1-21.

Wanli, Yang, 1985, Daging oil field, Peoples Republic of China: A giant field with oil of nonmarine origin: A.A.P.G. Bulletin, v. 69, no. 7, p. 1101-1111.

Waples, D. W., 1980, Time and temperature in petroleum formation: application of Lopatin's method to petroleum exploration: A.A.P.G. Bulletin, v. 64, no. 7, p. 916-926.

Waples, D. W., 1981, Organic geochemistry for exploration geologists: Minneapolis, Burgess Publishing Company, 151 p.

Waples, D. W., 1984a, Modern approaches in source-rock evaluation: in Woodward, J., Meissner, F. F., and Clayton, J. L., eds., Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Denver, Colorado, Rocky Mountain Association of Geologists, p. 35-49.

Waples, D. W., 1984b, Organic geochemistry for petroleum explorationists (course notes): Houston, International Human Resources Development Corporation.

Williams, G. L., and Brideaux, W. W., 1975, Palynological analyses of upper Mesozoic and Cenozoic rocks of the Grand Banks, Atlantic continental margin: Geological Survey of Canada Bulletin 236, p. 26, pl. 17, fig. 10.

Williams, G. L., and Bujak, J. P., 1977, Cenozoic palynostratigraphy of offshore Eastern Canada: American Association of Stratigraphic Palynologists, Contribution Series No. 5A, p. 14-48.

Wolfe, J. A., 1977, Paleogene floras from the Gulf of Alaska: U.S. Geological Survey professional paper 997, 108 p.

Woodward-Clyde Consultants, February 6, 1981, Environmental Report for Norton Basin COST No. 2, Report to ARCO Oil and Gas Company: Anchorage, Alaska.

Woodward-Clyde Consultants, 1979, Geotechnical Investigation Program and Siting Study for Jack-Up Rig Footing Behavior in Norton Sound Offshore Alaska, Report to Tetra Tech, Inc.: Anchorage, Alaska.

Worsley, T. R., 1973, Calcareous nannofossils, Leg 19 of the Deep Sea Drilling Project, in: Creager, J. S., Scholl, D. W., and others, Initial Reports of the Deep Sea Drilling Project, Volume 19: Washington, D. C. (U.S. Government Printing Office), p. 741-750.

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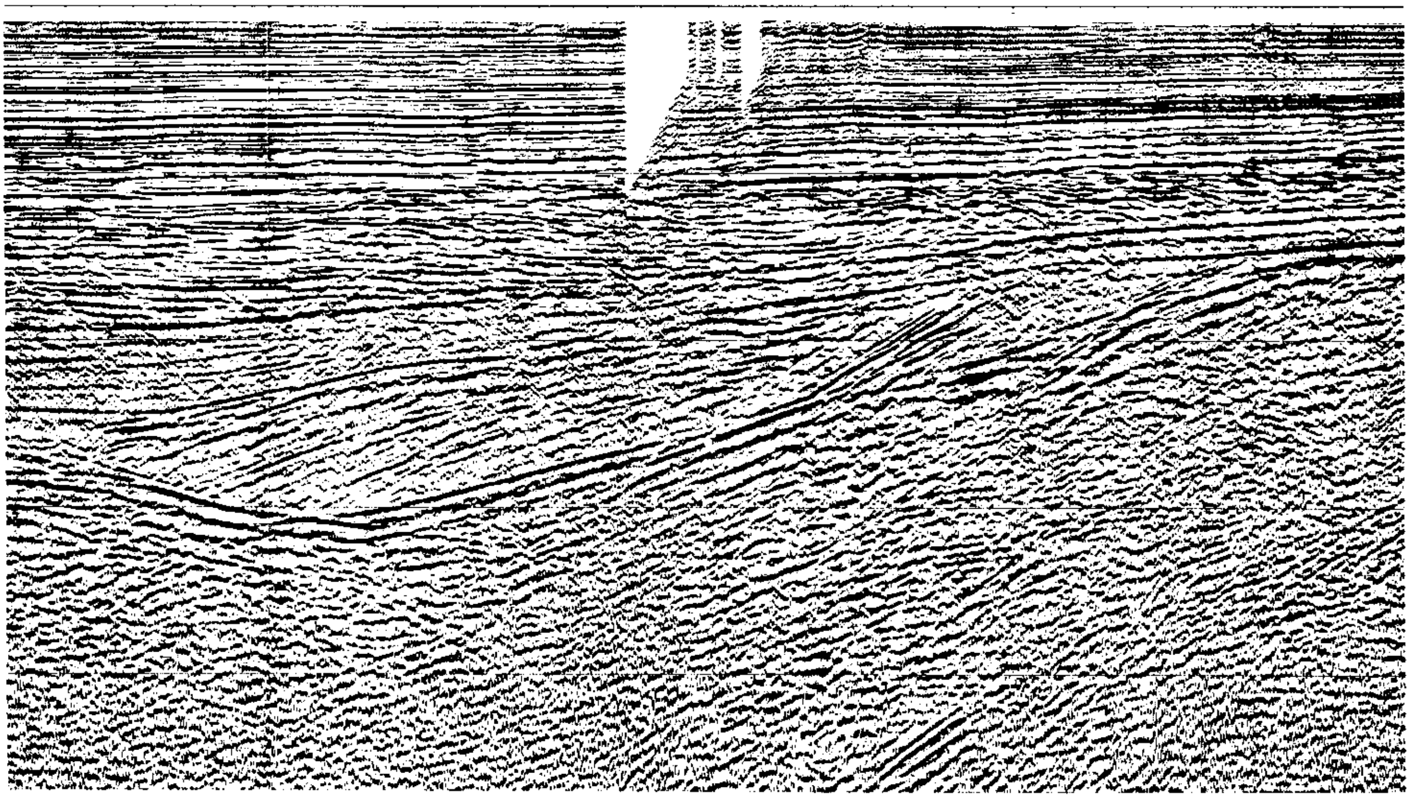

Seismic profile along the western flank of the Yukon horst, St. Lawrence subbasin. Seismic profile courtesy of Western Geophysical Company of America.