GEOLOGIC AND OPERATIONAL SUMMARY, NORTON SOUND COST NO. 2 WELL NORTON SOUND ALASKA

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
MINERALS MANAGEMENT SERVICE

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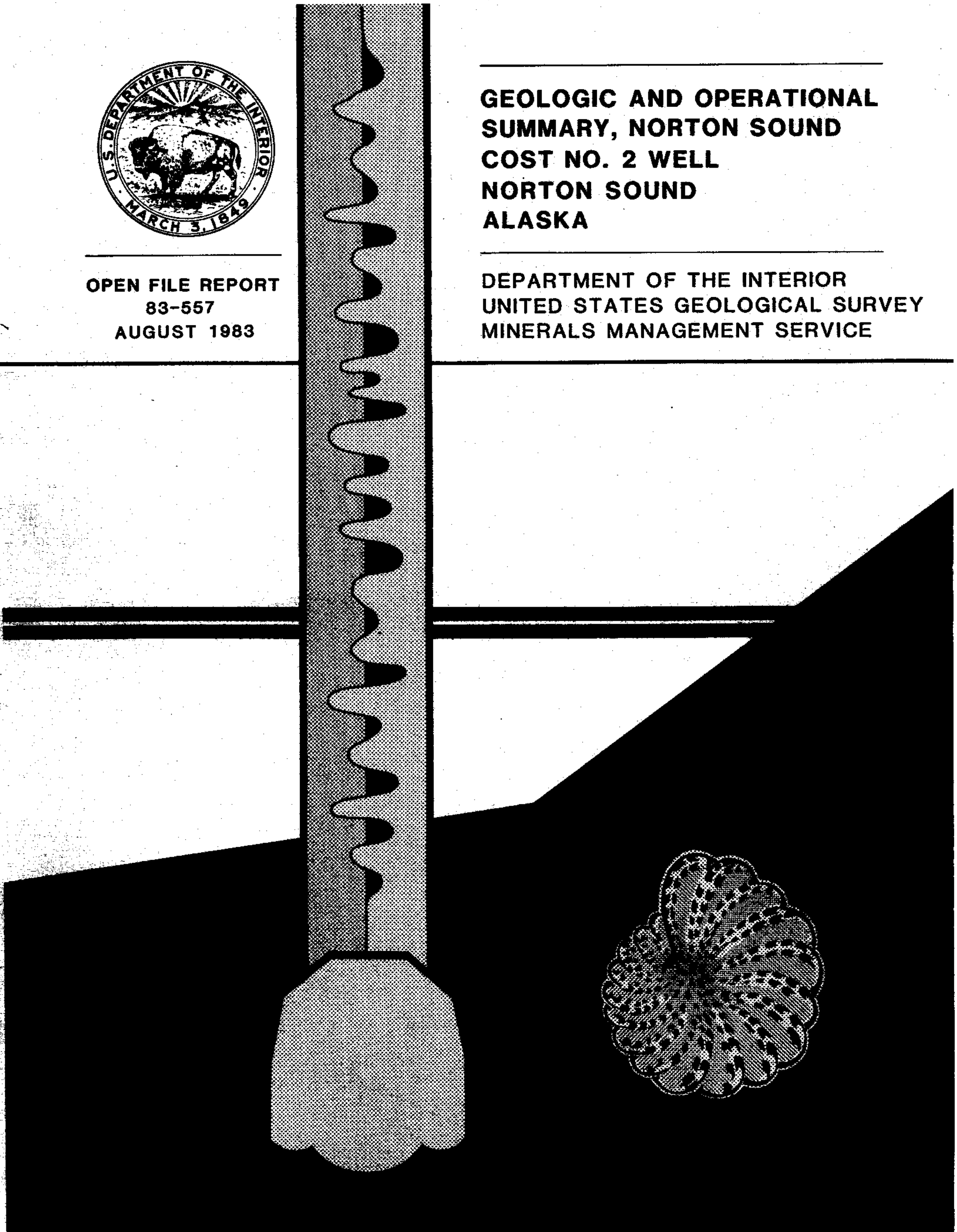
AUGUST 1983



UNITED STATES DEPARTMENT OF THE INTERIOR
MINERALS MANAGEMENT SERVICE

Geological and Operational Summary
Norton Sound COST No. 2 Well
Norton Sound, Alaska

R. F. Turner (ed), J. G. Bolm, C. M. McCarthy,
D. A. Steffy, Paul Lowry, T. O. Flett, and David Blunt

U.S. GEOLOGICAL SURVEY
OPEN-FILE REPORT 83-557

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Bering Sea Area, Alaska

Ronald F. Turner, Editor

INTRODUCTION

Title 30, Code of Federal Regulations (CFR), paragraph 251.14 stipulates that geological data and processed geological information obtained from Deep Stratigraphic Test wells drilled on the Outer Continental Shelf (OCS) be made available for public inspection 60 calendar days after the issuance of the first Federal lease within 50 nautical miles of the wellsite or 10 years after completion of the well if no leases are issued. Tracts within this distance of the first Norton Sound Deep Stratigraphic Test well (designated the ARCO Norton Sound COST No. 2 Well by the operator and hereafter referred to as the well or the No. 2 well) were offered for lease in Sale 57 on March 15, 1983. Ninety-eight bids on 64 tracts were received with the total high bids amounting to $325 million. Fifty-nine bids were accepted and five rejected. The effective issuance date of the leases is June 1, 1983.

This open-file report is presented in accordance with the requirements of 30 CFR 251.14. The interpretations contained herein are chiefly the work of Minerals Management Service personnel, although substantial contributions were made by geoscience consulting companies.

The ARCO Norton Sound No. 2 well was completed on August 27, 1982, on OCS Lease Block 273, located approximately 68 miles south of Nome, Alaska (fig. 1). The well data is available for public inspection at the Minerals Management Service, Offshore Field Operations office, located at 800 "A" Street, Anchorage, Alaska, 99501.

All measurements are given as measured depths in feet from the Kelly Bushing (KB), which was 105 feet above sea level. For the most part, measurements are given in U.S. Customary Units except where scientific convention dictates metric usage. A conversion chart is provided.

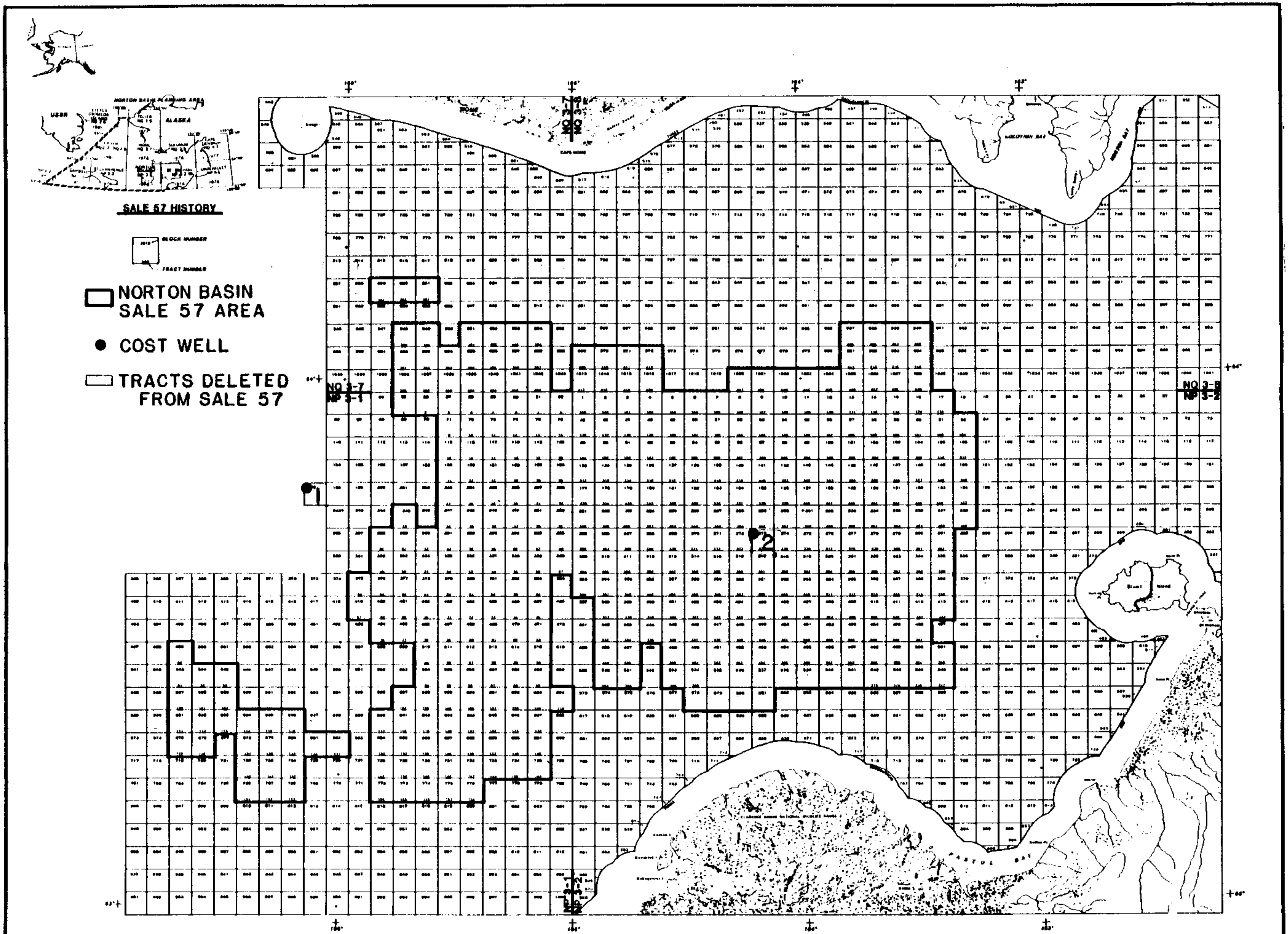


Figure 1. Location Map showing Norton Basin Sale 57 Area and COST Wells 1 and 2.

December, 1982

EQUIVALENT MEASUREMENT UNITS

U.S. Customary to SI Metric Units:

1 inch = 2.54 centimeters

1 foot = 0.3048 meter

1 statute mile = 1.61 kilometers

1 nautical mile = 1.85 kilometers

1 pound = 0.45 kilogram

1 pound/gallon = 119.83 kilograms/cubic meter

1 pound/square inch = 0.07 kilograms/square centimeters

1 gallon = 3.78 liters (cubic decimeters)

1 barrel = (42 U.S. gals.) = 0.16 cubic meters

Temperature in degrees Fahrenheit = °F less 32, divided by 1.8 for degrees Celsius.

Other Conversions: 1 knot = 1 nautical mile/hour

1 nautical mile = 1.15 statute miles or 6,080 feet

OPERATIONAL SUMMARY

by

Colleen McCarthy

The jackup drilling rig, Key Singapore, arrived on location in Norton Sound on June 3, 1982, 1630 hours A.S.T. and the Norton Sound Continental Offshore Stratigraphic Test No. 2 well was spudded June 7, 1982. Drilling was completed 81 days later on August 27, 1982 at a true vertical depth of 14,889 feet. After wireline logging, running velocity and temperature surveys, sidewall coring, and drill-stem testing were accomplished, the well was plugged and abandoned, and the rig was under tow by September 20, 1982.

The construction of the Key Singapore, owned by Keydril Company, was completed in March of 1982 and the rig was given the classification ABS 1-A. Minerals Management Service representatives inspected the rig March 15, 1982.

The Key Singapore is a Le Tourneau 116-C design and is a self-elevating drilling unit. It was designed to withstand 35-foot waves and 115-knot winds in 300 feet of water. The rig was rated at an air temperature of -10° and for a drilling depth of 30,000 feet in 300 feet water depth. The Key Singapore was properly winterized for arctic use, and there were no major accidents or incidents during the drilling of the well. While the rig was being towed out of Alaskan waters, however, it collided with rocks off the Aleutian Chain and all personnel were evacuated. The Key Singapore was recovered with no major damage to the rig.

A study was made by Woodward-Clyde Consultants to obtain information on the subsurface conditions at the drilling location in order to develop criteria and recommendations for jackup rig siting, design, and installation of the platform piles and conductors. This was accomplished by drilling three borings; one 300-foot penetration and two 50-foot penetrations. The samples recovered were then tested, both on board the research vessel and in the laboratory, to determine the design strength properties of the foundation soils.

Nome, which is approximately 68 miles NW of the location, was the shore base for sea and air support operations. Kenai and Dutch Harbor were occasional sources of nonroutine equipment and materials supply. All major materials needed for the entire well were stored on a large supply barge anchored approximately one mile from the drilling location. Two sea-going supply boats shuttled material between the barge and the rig. These supply boats also supplied fuel, water, and miscellaneous cargo via lighterage barge from Nome. Helicopters certified for instrument flight transported personnel, groceries, and lightweight equipment between the rig and the primary shore base at Nome. Personnel, equipment, and supplied were transported to and from the shore base by both chartered and commercial air carriers.

ARCO Alaska acted as the operator for itself and the following nineteen companies that shared expenses for the well.

AMOCO Production Co.

Chevron, U.S.A., Inc.

Cities Service Co.

CONOCO, Inc.

Elf-Aquitane Co.

Exxon Company, U.S.A.

Getty Oil Co.

Gulf Oil Corp.

Marathon Oil Co.

Mobil Exploration and Production Service

Murphy Oil Corp.

Pennzoil Oil and Gas, Inc.

Phillips Petroleum Co.

Shell Oil Co.

Sohio Alaska Petroleum Co.

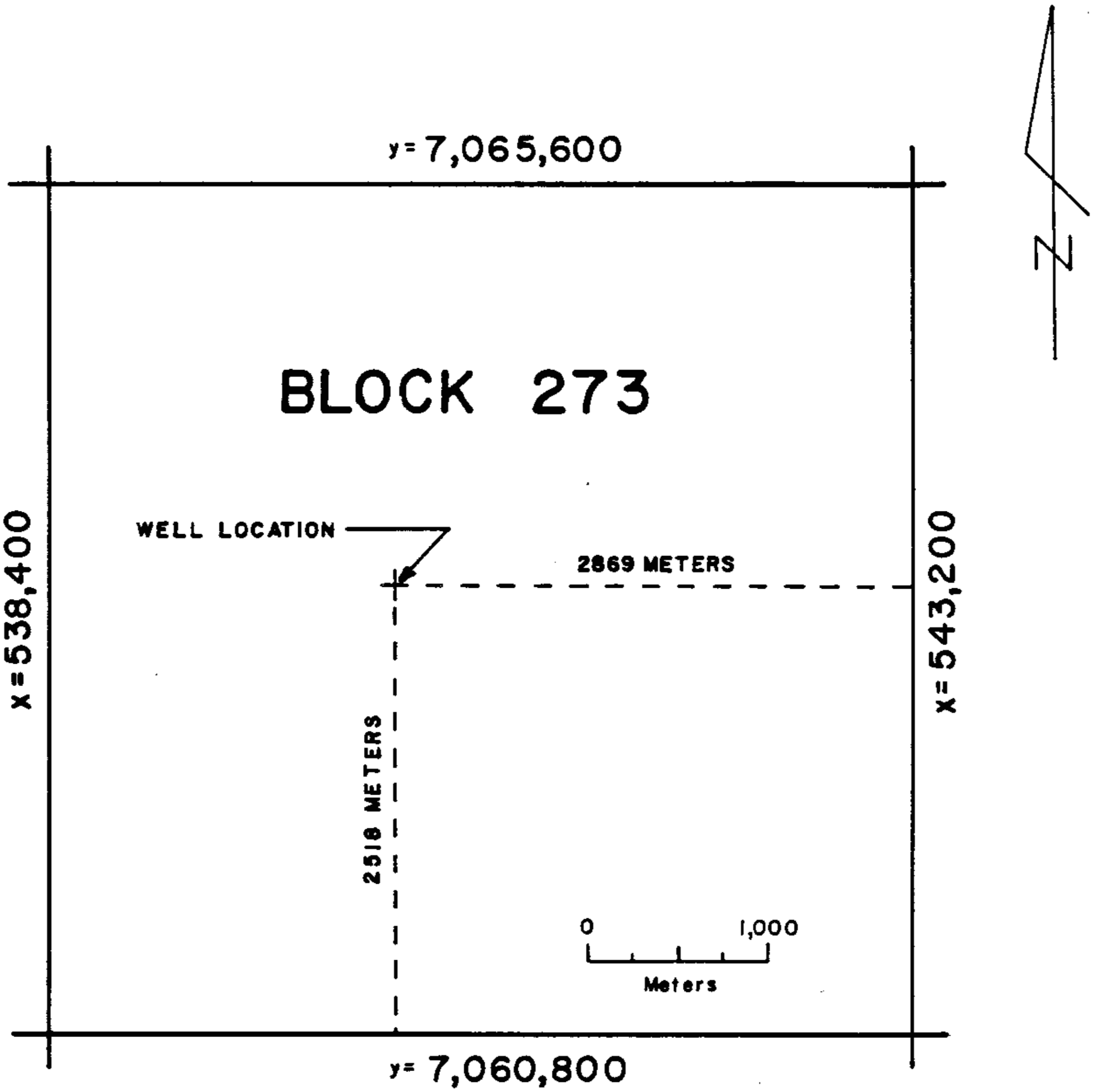
Sun Oil Co.

Tenneco Oil Co.

Texaco, Inc.

Union Oil Company of California

Norton Sound COST No. 2 well was located at lat 63° 41' 49.43" N; long 164° 11' 03.38" W, or UTM coordinates (zone 3) X = 540,331.3 m and Y = 7,063,318.2 m. The survey plat for the final well site location is shown in Figure 2. Water depth at the location is 49 feet. All measurements were made from the Kelly Bushing (KB) which was 105 feet above sea level and 154 feet above the seafloor.



GEODETIC POSITION	UNIVERSAL TRANSVERSE MERCATOR COORDINATES, ZONE 3, in METERS.
LAT. 63° 41' 49.43" N.	y= 7,063,318.2
LONG. 164°11' 03.38" W.	x= 540,331.3

Figure 2. Final location plat showing the position of Norton Sound COST No. 2 well in OCS Protraction Diagram "St. Michael, NP 3-2."

The well was drilled to a depth of 10,254 feet with less than 4° deviation from vertical; the angle increased to 6° by 12,020 feet; and at total true vertical depth, 14,889 feet, deviation was 10°.

Drilling stipulations required the operator to provide the Minerals Management Service with all well logs, samples, core slabs, operational and technical reports, and geologic information.

Owing to the ice season in Norton Sound the drilling window is from June to October.

Drilling Program

The No. 2 well was drilled using sixteen 12 1/4-inch drill bits to a depth of 11,555 feet and deepened with fourteen 3 1/2-inch bits to 14,889 feet. Additional bits were used to open the hole before setting the larger casing strings, to drill through cement, for clean-out trips, and for the conventional coring program. Drilling rates ranged from 3 to 250 feet/hour, and averaged 100 feet/hour down to 3900 feet, 75 feet/hour to 7400 feet, 35 feet/hour to 11,400 feet, and 14 feet/hour for the remainder of the well. The daily drilling progress for the well is shown on Figure 3.

Four strings of casing were cemented in the well, as shown in Figure 4. The 30-inch conductor casing was set at 416 feet, with 950 sacks of Class G cement. At 1181 feet, 2200 sacks of Class G cement were used to cement the 20-

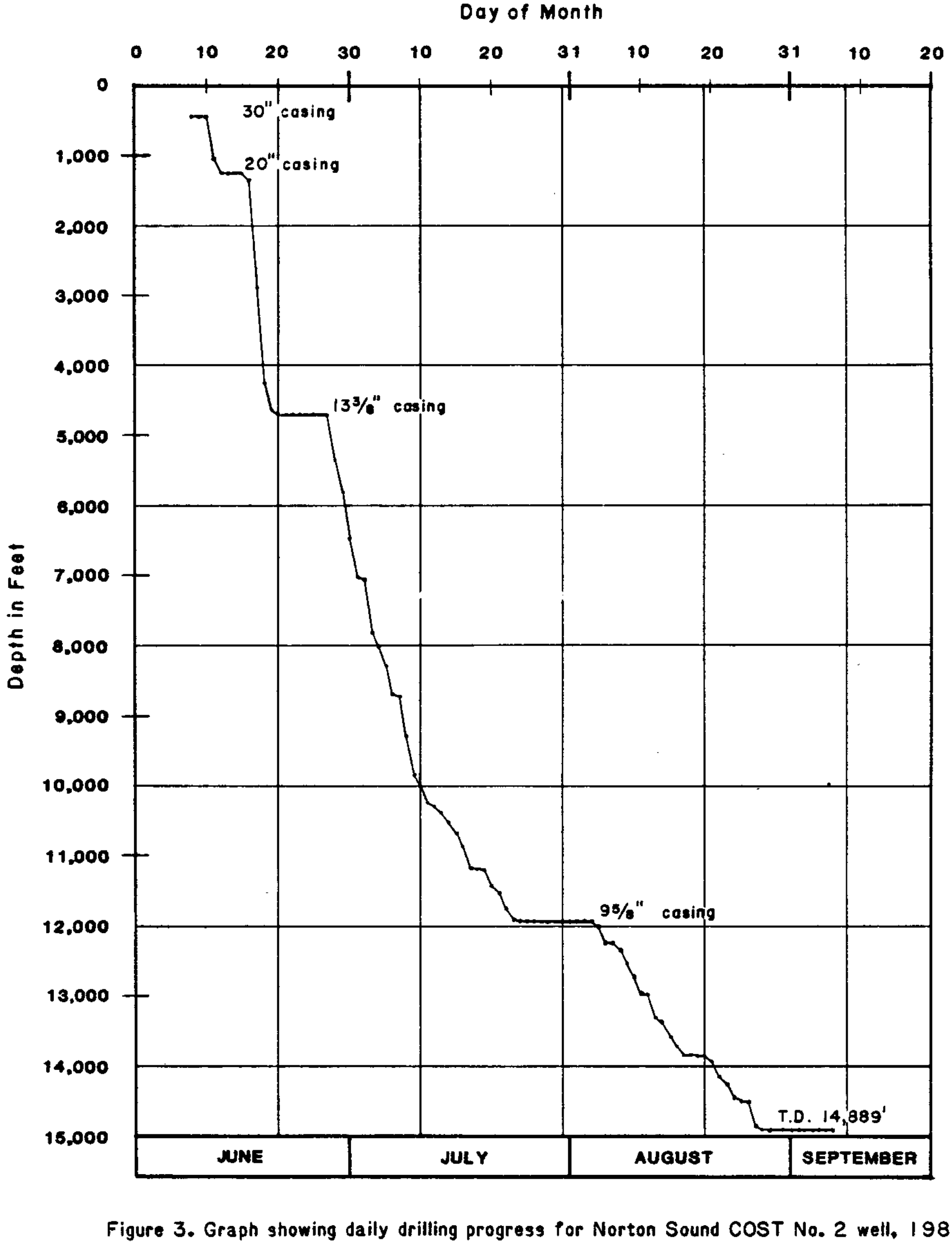


Figure 3. Graph showing daily drilling progress for Norton Sound COST No. 2 well, 1982.

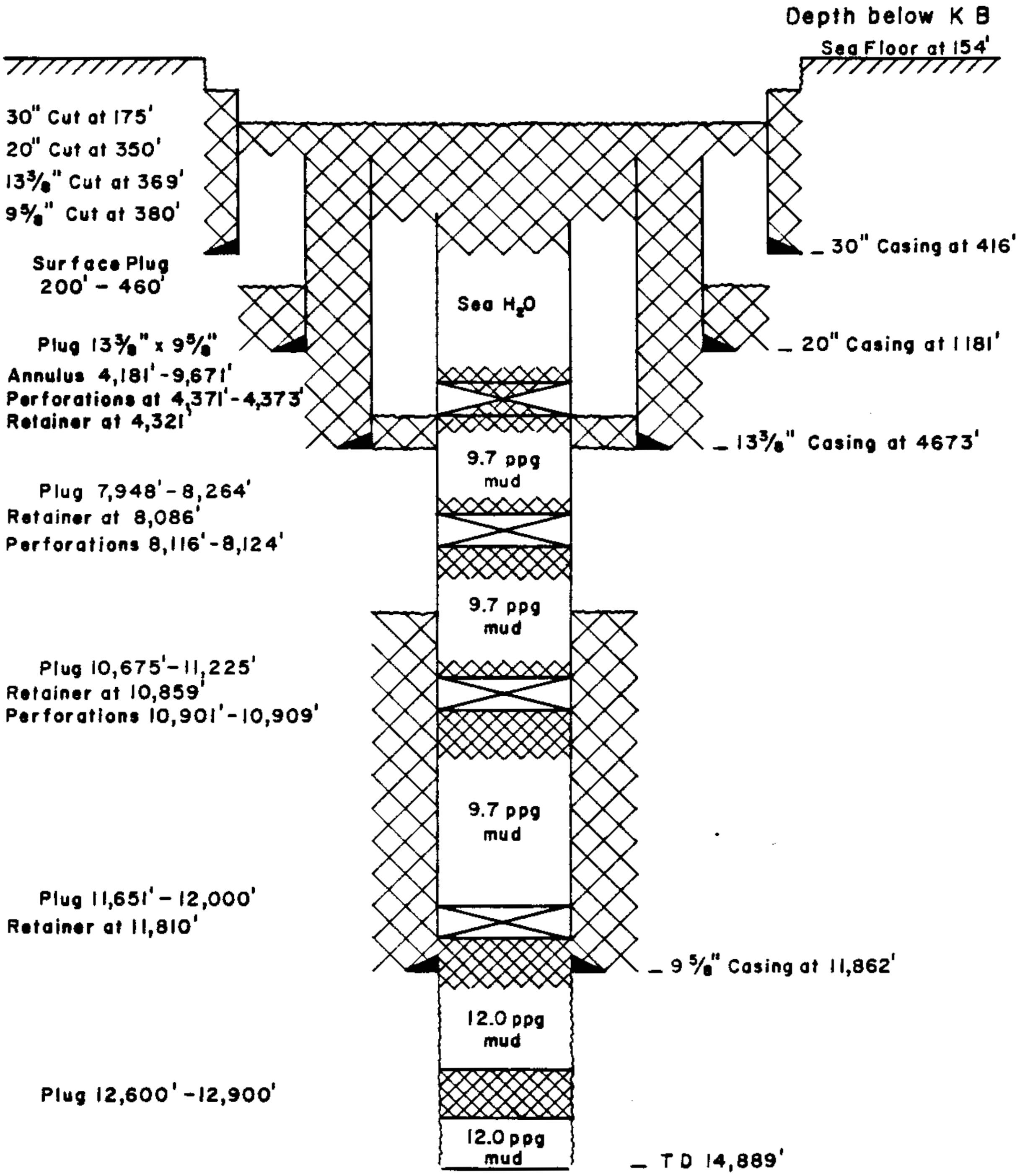


Figure 4. Schematic diagram showing casing strings, plugging, and abandonment program, Norton Sound COST No. 2 well.

inch casing. While cementing the 20-inch casing, lost circulation problems were encountered and there were no returns to the surface. Twenty-four hundred sacks of Class G cement were used to cement the 13 3/8-inch casing, at 4673 feet. The 9 5/8-inch casing was set at 11,862 feet with 255 sacks of Class G cement and below this casing point the well was open hole.

Drilling Mud

Selected drilling mud properties and their changes with depth are shown in Figure 5. Drilling fluid for the well was sea water to 1,231 feet, and lignosulfanate mud for the remainder of the hole. Mud weight was kept at about 9.0 pounds/gallon to 5100 feet, 10 pounds/gallon at 11,100 feet and increasing to 12 pounds/gallon at total depth. Viscosity varied between 35 to 46 seconds throughout the well, averaging around 38 seconds. Chloride concentrations ranged from 600 ppm to 5700 ppm, generally decreasing with depth. Calcium concentrations were generally limited to concentrations near zero, although values were as high as 500 ppm at 14,750 feet. Mud pH ranged from 8.0 to 12.0, staying at about 10.0 throughout most of the well. Between 12,212 and 13,717 feet, gas associated with coal beds was encountered. Mud weight was increased from 10.0 ppg to 11.5 ppg throughout this interval and well control was maintained at all times. Mud-logging services were provided by Exploration Logging from 154 feet to total depth.

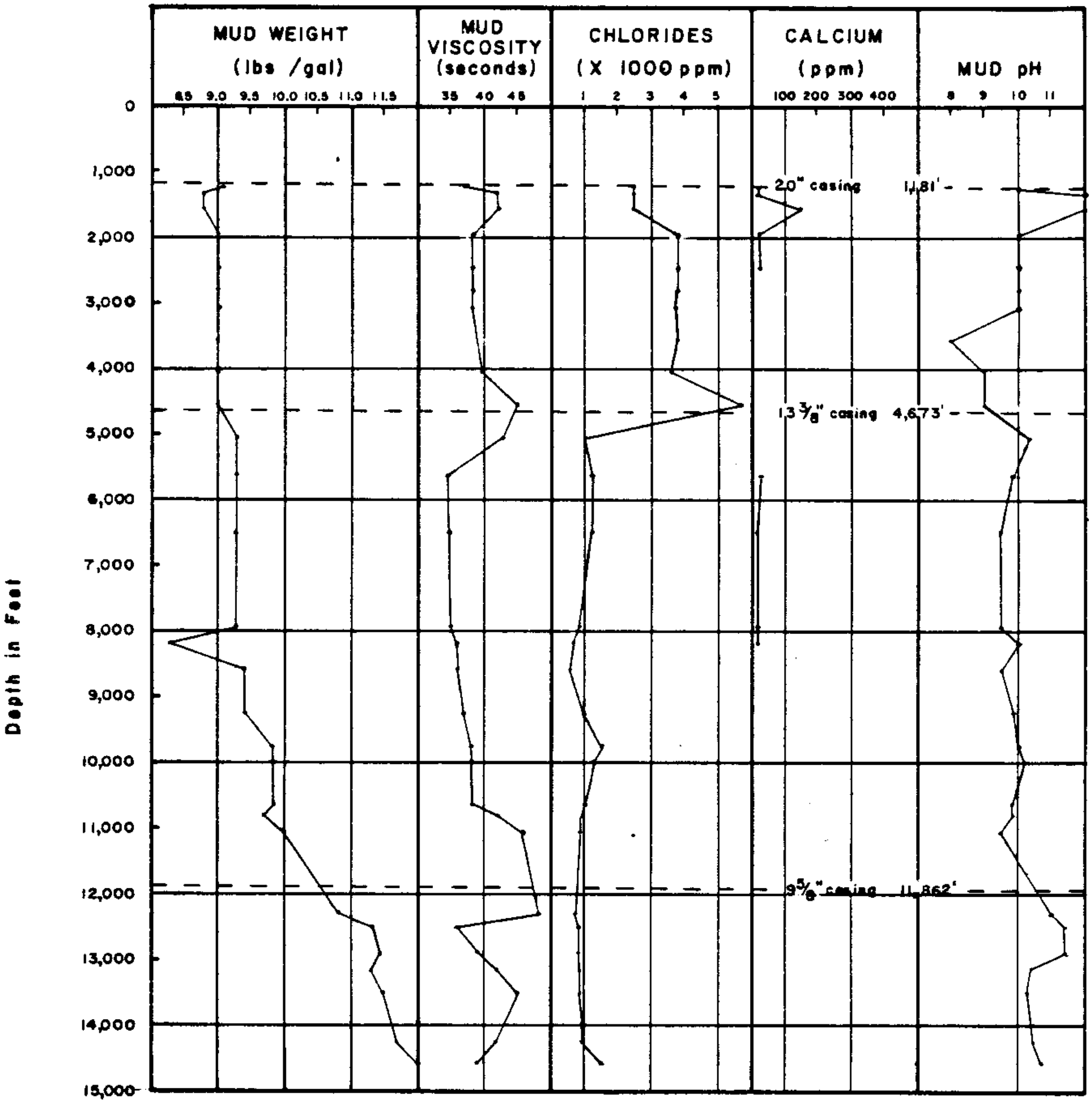


Figure 5. Changes with depth of drilling mud properties, Norton Sound COST No. 2 well, including mud weight, viscosity, total chlorides, and pH.

Samples and Tests

Drill cuttings for lithologic and paleontologic analyses were collected from 436 feet to total depth. Thirteen conventional cores were cut and analyzed for porosity, permeability, and grain density. The following are the results:

Core No.	Interval (ft)	Recovered
1	4623-4636	11.1
2	5793-5802	9
3	7018-7049	31
4	7993-8023	29.5
5	8702-8737	30
6	10,233-10,263	30
7	11,170-11,178	8
8	11,901-11,907	5.5
9	12,212-12,242	30
10	12,958-12,983	16
11	13,395-13,425.6	30.6
12	14,483-14,495	11.9
13	14,859-14,889	30

During six runs, sidewall cores were collected with the following results:

Run No.	Depth (ft)	Number Attempted	Number Recovered	Percent Recovered
1	4,700	153	115	75
2	11,907	438	282	64
3	14,889	45	33	73
4	14,889	51	20	39
5	14,889	45	21	47
6	14,889	45	28	62
TOTAL		777	499	64

Logging runs were made at depths of 4700, 11,907, and 14,889 feet. The Dual Induction-Laterlog (DIL), Borehole Compensated Sonic Log (BHC), and Spontaneous Potential (SP), Gamma Ray (GR), Long Spaced Sonic Log (LSS) with Integrated Travel Time (ITT), Repeat Formation Test (RFT), and the Four-arm, High Resolution Continuous Dipmeter (HRD), were recorded on all runs. The Compensated Neutron Log (CNL) with Neutron Gamma Tool (NGT) were recorded on the first and second runs. On the second and third runs a Vertical Seismic Profile (VSP), Lithodensity Neutron Log and Proximity Log-Microlog (MPL) were recorded. Additional logs run were a Compensated Formation Density (FDC) and a Velocity Survey on the first run, and a Cement Bond Log (CBL) and Temperature Log on the last run. A Gamma Ray Casing Collar Locator was run at 11,651 feet.

Two drill stem tests for water analysis were made through perforations in the 9 5/8-inch casing. To minimize risk, testing was conducted through the 3 1/2-inch tubing rather than drill pipe. The first test was made between 10,901 and 10,909 feet and the second between 8116 and 8124 feet.

The cumulative cost for the well was $32.2 million.

SHALLOW GEOLOGIC SETTING
NORTON SOUND COST NO. 2 WELL

By David Steffy

Shallow geologic characteristics of the drill site were identified in a survey conducted by Nekton, Inc., in 1980. The survey, part of the permit to drill application, included a geotechnical study of the upper 300 feet of sediment and a high-resolution seismic-reflection survey of the seafloor and its near-surface features. The regional description of Norton Sound is based on five U.S. Geological Survey maps prepared as part of the prelease investigation of the surface and near-surface geologic environment of Norton Sound (Hoose, Steffy, and Lybeck, 1981; Steffy and Hoose, 1981; Steffy and Lybeck, 1981; Steffy, Turner, and Lybeck, 1981; Steffy, Turner, Lybeck, and Roe, 1981).

Bathymetry

Norton Sound is a flat-bottomed embayment of the northeastern Bering Sea epicontinental shelf. Water depths in the OCS Sale 57 area range from 16 to 89 feet. The sale area covers part of the Yukon River delta front and prodelta, which are separated from the prograding shoreline by a subice platform (Larsen, Nelson, and Thor, 1980). This platform is 3 to 12 miles wide along the southern boundary of the sale area and occurs in water depths of less than 32 feet. The

No. 2 well is located at the base of the northward sloping Yukon delta front in 49 feet of water. The delta front is the seaward extension of Holocene, nearshore sand deposits and is characterized by a 1- to 2-degree seaward sloping seafloor. Seaward, the front becomes the prodelta, a very gently sloping area that marks the edge of deltaic sedimentation. In the sale area the prodelta slopes less than 1 degree and is 52 to 89 feet deep.

Sea-floor Geology

The sea-floor topography of the Norton Sound area is the result of the interactions of wind, water, ice, and sedimentation processes. Surface sediments range in size from fine sand at the delta front to sandy silt and silt in the prodelta area. These unconsolidated sediments are continually reworked by ice gouging, current scour, storm surging, and release of biogenic gas.

Single-keeled and multikeeled ice floes driven by wind and water currents furrow the seafloor parallel to the bathymetric contours. These furrows occur in water depths down to 79 feet, and are most dense between depths of 32 and 56 feet. The No. 2 well is located in a relatively intense ice-gouging zone caused by the westward-moving ice pack of Norton Sound shearing against the shorefast ice that extends offshore from the delta. The single-keeled ice gouges identified by side-scan sonar range in width from 16 to 164 feet and are seldom greater than 3 feet deep. Active sedimentation infills the gouges in the river-dominated months of summer.

Transient features such as current scour, megaripples, and longitudinal current lineations were not found at the drill site, but were found in a limited extent north of the well site and just west of the delta. Current scour is characterized by elongated depressions 330 to 490 feet long, 115 to 330 feet wide, and less than 6 feet deep. They parallel the dominant bottom-current direction and rework the unconsolidated silty fine sand comprising the local surface sediments. Megaripples occur as a series of ripples having a wavelength of 65 to 165 feet and an amplitude of less than 1.5 feet. They occur in a subtle bathymetric trough north of the well site, and their crests are normal to the dominant westward bottom-current direction. Longitudinal current lineations occur as a series of furrows having a wavelength of 30 to 100 feet and depths of less than 1.5 feet. The lineations parallel the dominant bottom-current direction and occur just south of the megaripples.

Degassing of biogenic gas generated by buried Holocene peat layers results in gas cratering in the eastern half of Norton Sound. The cratering is usually less than 1.5 feet in relief and on side-scan sonograms appears as a patchy textural feature.

Quaternary Geology

Norton Sound was subaerially exposed in the late Pleistocene owing to a lowered sea level. Quaternary sediments consist of fluvial deposits of clayey silt to silty sand with varying amounts of wood fragments, shells, and organic matter. About 10,000 to 9,500 yr B.P., the sea transgressed over Norton Sound and began reworking and burying tundra peat deposits (Nelson, 1980). These organic deposits represent a sea-level stillstand 60 to 80 feet below present sea level and are the base of the Holocene. Transgression resulted in Holocene deposits ranging from a fine sand in the northern half of the sale area to clayey silt near the Yukon Delta. Approximately 32 to 40 feet below present sea level, a younger, less extensive, organic-rich layer is found extending seaward from the Yukon Delta. This represents a later stillstand that allowed the development of tundra peat. Subsequent transgression over the area reworked and buried the peat resulting in an organic-rich silt deposit. This deposit grades upward into clayey silt in the west and a silty sand in the east. The buried organic-rich deposits are currently generating gas as indicated by the gas cratering and by extensive, shallow acoustic anomalies that occur on both the processed and analog records of the minisparker and watergun systems.

SEISMIC REFLECTION CORRELATION
AND
VELOCITY ANALYSIS

by David Steffy

By the use of velocity information from the Norton Sound COST Nos. 1 and 2 wells and a 1978 USGS seismic reflection survey (fig. 6), seismic correlations and velocities from the 2 wells were compared to each other and to those from the nearby seismic lines. The stacking velocities used on the common-depth-point (CDP) traces were evaluated before stacking the gathers. These comparisons were used to assign geologic significance to features identified on the profiles, and the significant features were used to establish the geologic history of Norton Basin in the concluding section of this report.

Seismic Reflection Correlation

A synthetic seismogram was produced by use of borehole-compensated, interval-transit-time log of the No. 2 well, (fig. 7). The sonic log was visually averaged while being stream digitized and was measured to the nearest foot in depth and the nearest microseconds/foot in transit time. This resulted in log samples being taken at irregular intervals. However, the sampling was frequent enough to prevent aliasing in the seismogram. The digitized data were then entered into a computer program that produced a synthetic seismogram without multiples. Constant density was assumed, therefore density was not incorporated

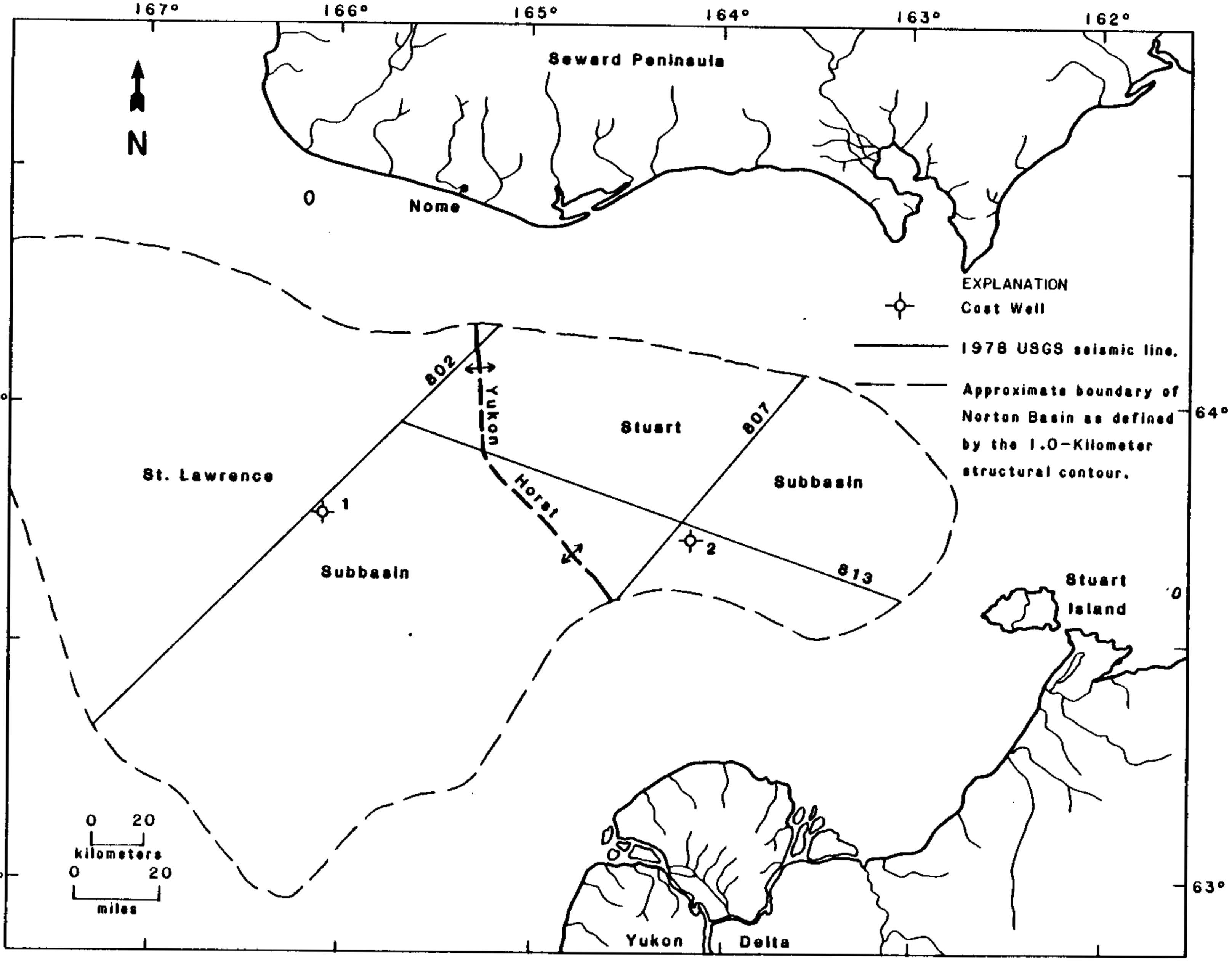
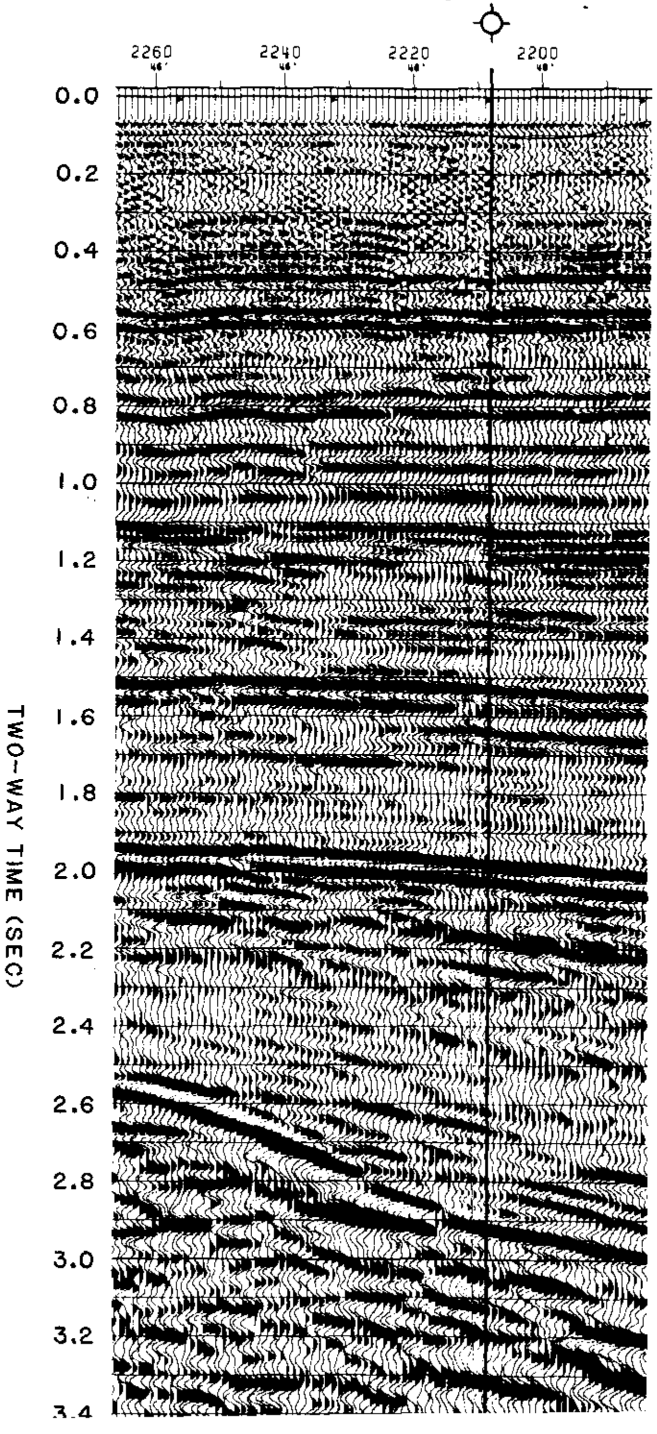


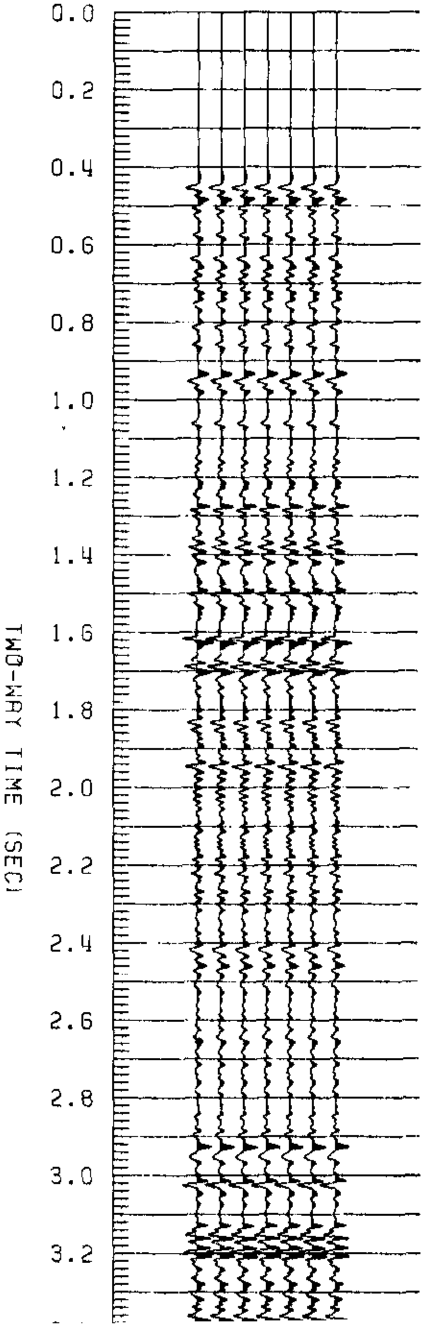
Figure 6. Location map of Norton Basin, COST Wells, and USGS seismic lines. Adopted from Fisher and others (1980).

WNS-24 SEISMIC PROFILE

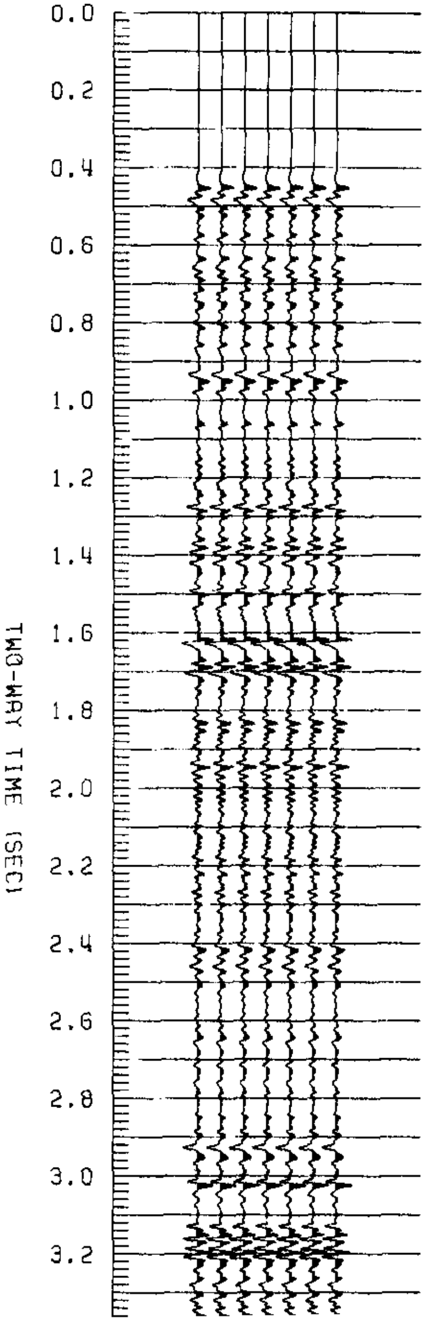
(Scaling constant P, 1.4; Scaling factor, $\frac{\text{total amplitude}}{\text{P}}$)

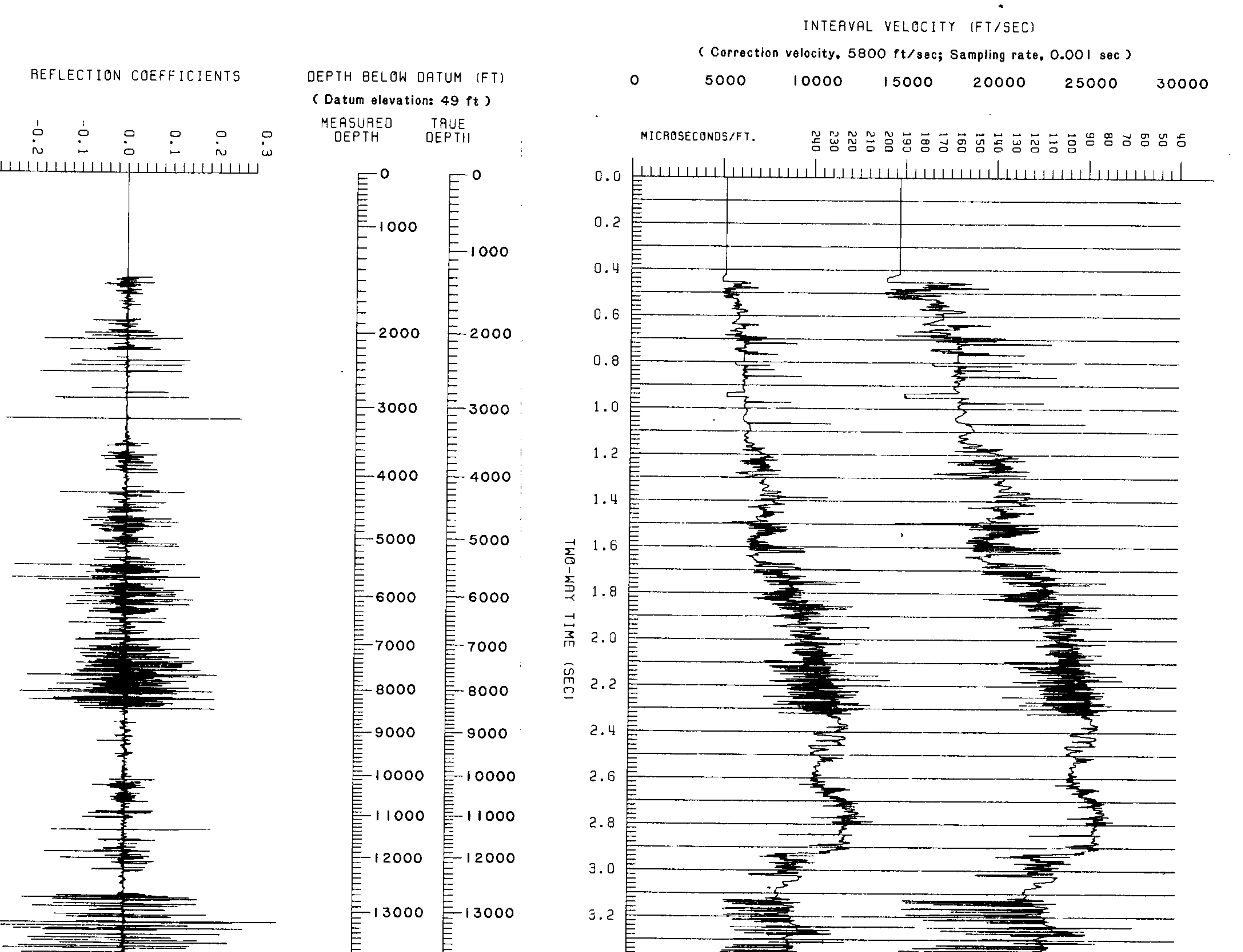


REVERSE POLARITY SYNTHETIC



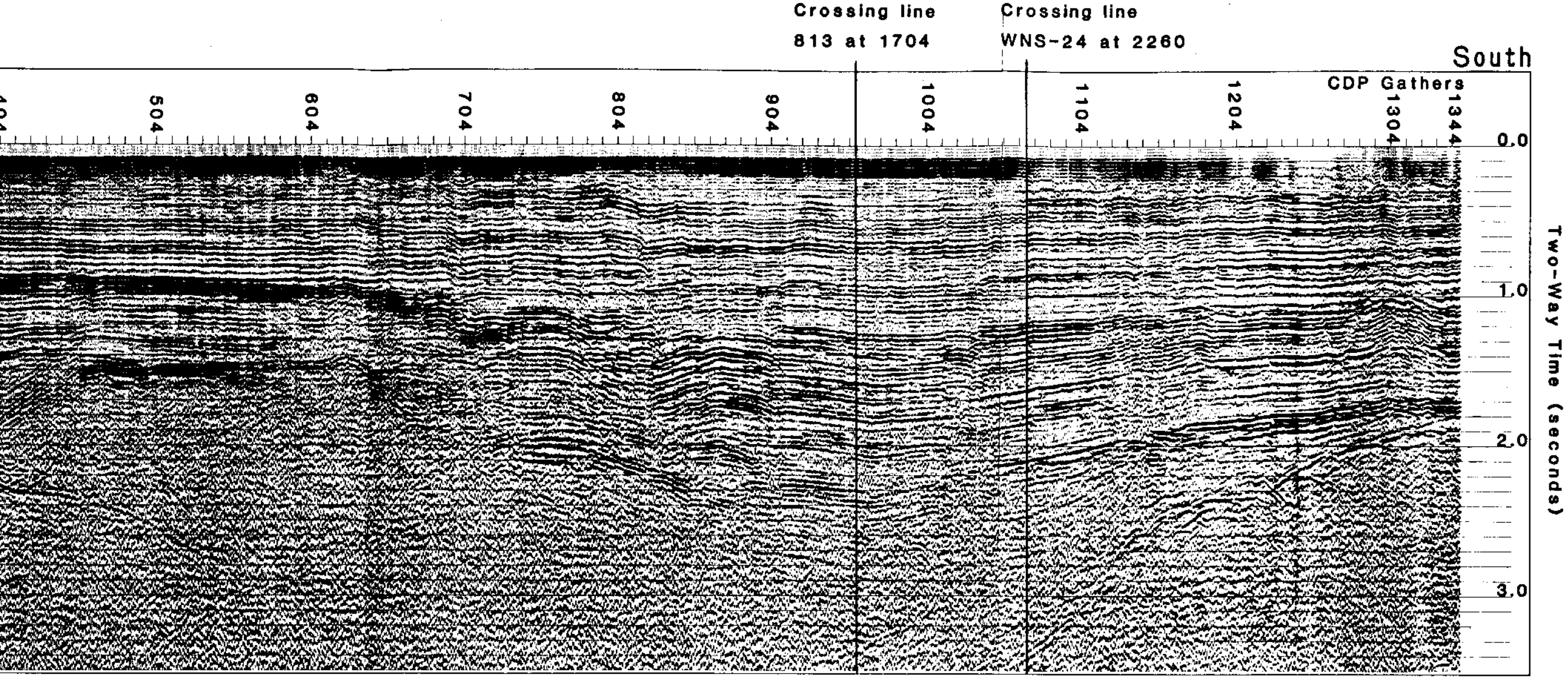
NORMAL POLARITY SYNTHETIC

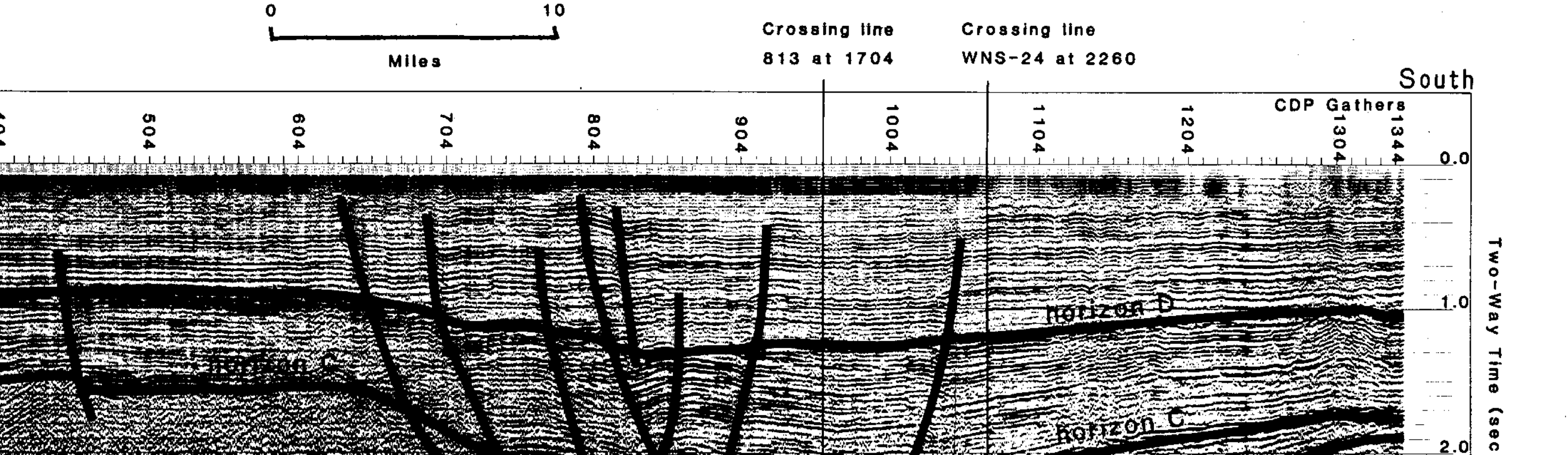



REFLECTION COEFFICIENTS
-0.2
-0.1
0.0
0.1
0.2
0.3
DEPTH BELOW DATUM (FT)
(Datum elevation: 49 ft)
MEASURED DEPTH
TRUE DEPTH
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
INTERVAL VELOCITY (FT/SEC)
(Correction velocity, 5800 ft/sec; Sampling rate, 0.001 sec)
0
5000
10000
15000
20000
25000
30000
MICROSECONDS/FT.
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
TWO-WAY TIME (SEC)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2

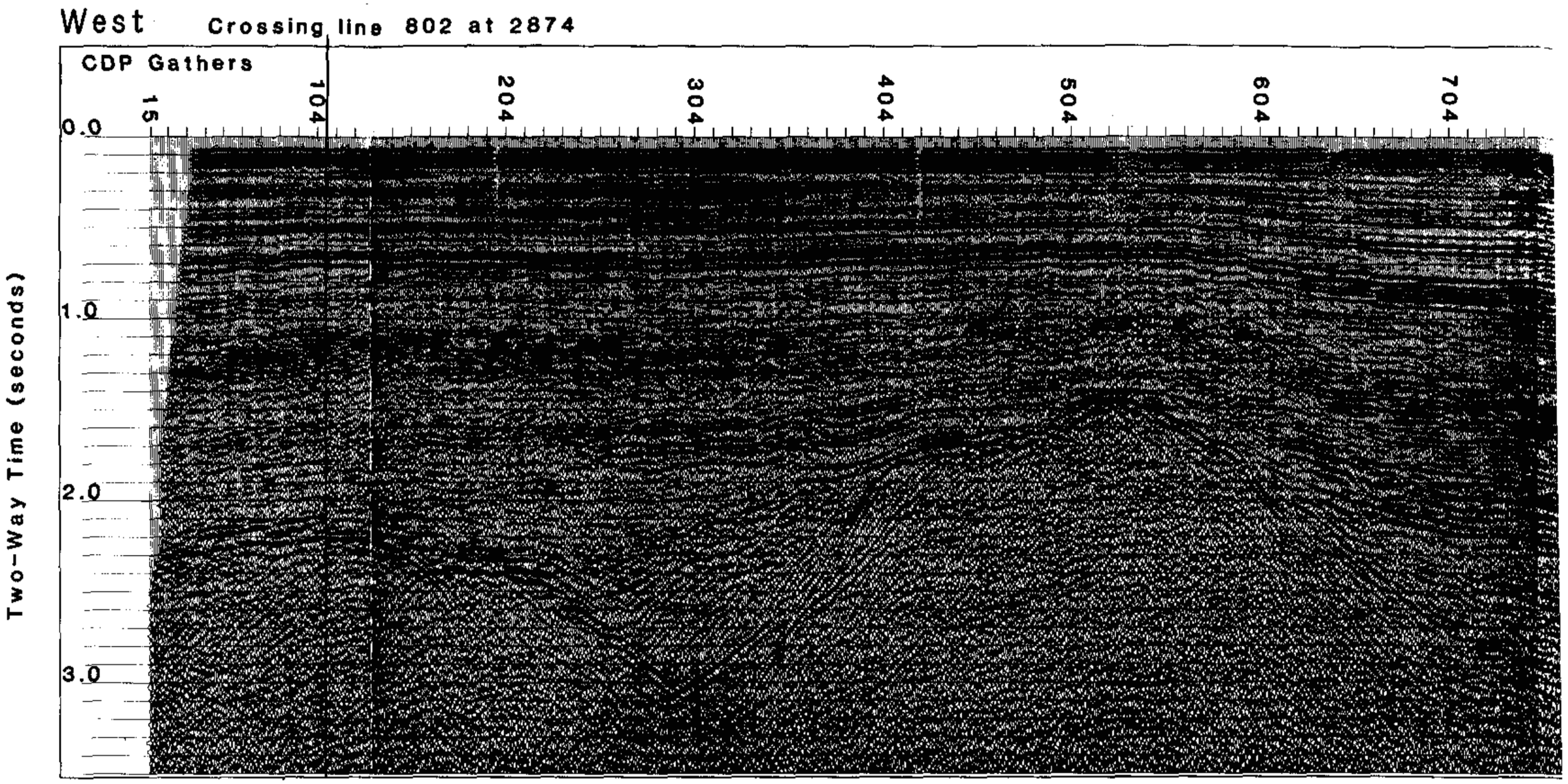
into the calculation of the reflection coefficients. This assumption apparently does not adversely affect the results of the synthetic seismogram in a simple geologic setting (Sheriff, 1978). The computer program also assumes a series of horizontal, parallel earth layers with an elastic constant, and assumes that the incident waves are normal to the reflecting surface and have planar wavefronts. The calculated reflection coefficients were then convolved with a standard ricker wavelet having a frequency range of 8-55 Hz. This convolution results in a seismogram that is displayed with both normal and reverse polarity.

The synthetic seismogram was then correlated to the 1977 Western Geophysical seismic line WNS-24 which profiles through the well location (fig. 7). By use of this correlation, four distinct horizons are identified in order to represent the structural and stratigraphic configuration of the basin. Three of the four horizons are continuous to the No. 1 well, where a similarly derived synthetic seismogram was used. Figures 8, 9, and 10 are USGS seismic lines 807, 813, and 802, respectively, which were surveyed near the wells and that display these horizons. Line 807 is a north-south profile through the Stuart subbasin. The line profiles within one mile of the No. 2 well at CDP gather 1004. Line 802 is a north-south profile through the St. Lawrence subbasin. The line profiles within one mile of the No. 1 well at CDP gather 2240. Line 813 is an east-west profile across the Stuart subbasin, the Yukon horst, and the St. Lawrence subbasin. The line profiles within 4 miles of the No. 2 well and within 16 miles of the No. 1 well at CDP gathers 1740 and 120, respectively. Figure 11 displays the time-stratigraphic column of the No. 2 well based on described in the Paleontology and Biostratigraphy section of this report.

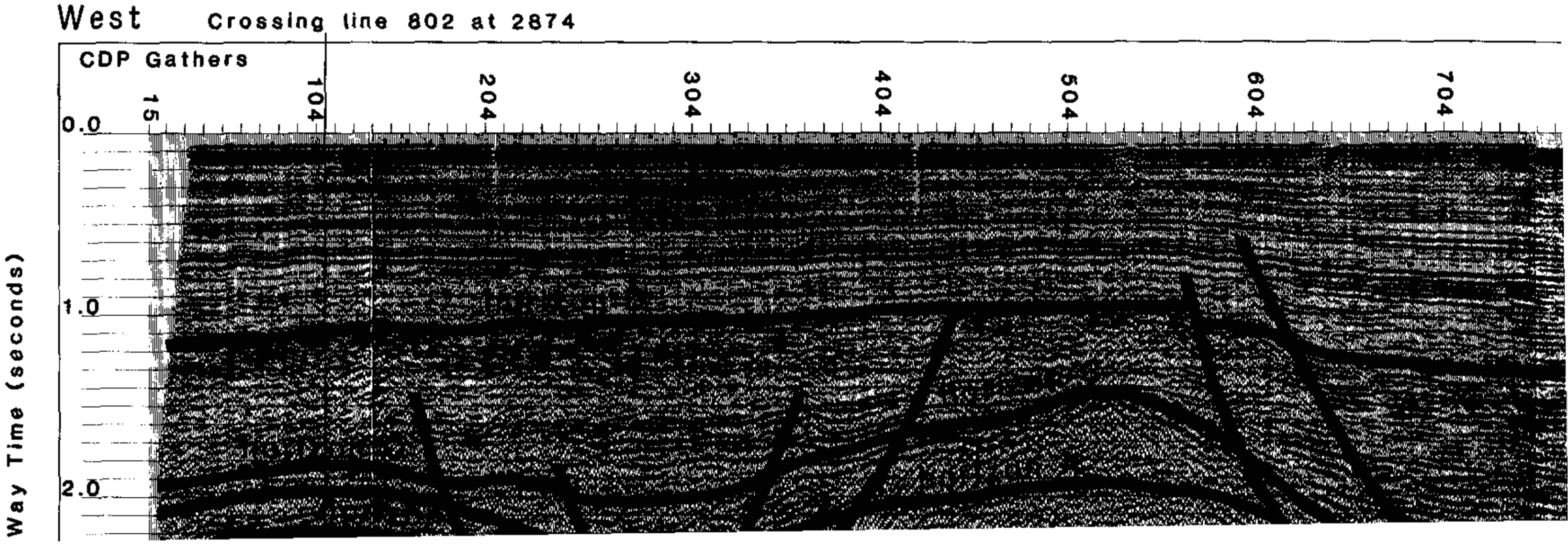

Crossing line
813 at 1704
Crossing line
WNS-24 at 2260
South
CDP Gathers
504
604
704
804
904
1004
1104
1204
1304
1344
0.0
1.0
2.0
3.0
Two-Way Time (seconds)

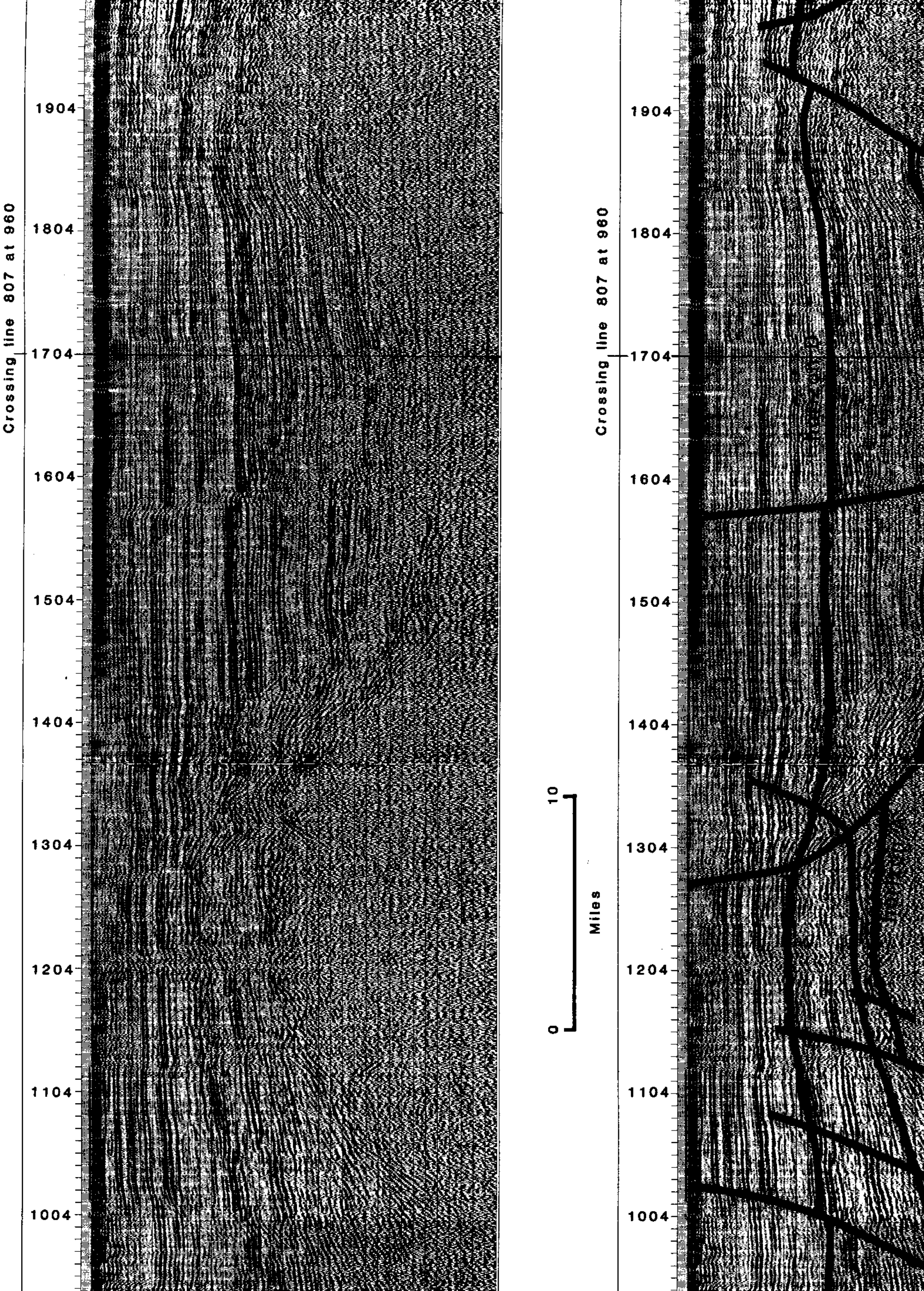

0
10
Miles
Crossing line
813 at 1704
Crossing line
WNS-24 at 2260
South
CDP Gathers
504
604
704
804
904
1004
1104
1204
1304
1344
0.0
1.0
2.0
Two-Way Time (sec
Horizon D
Horizon C
Horizon C

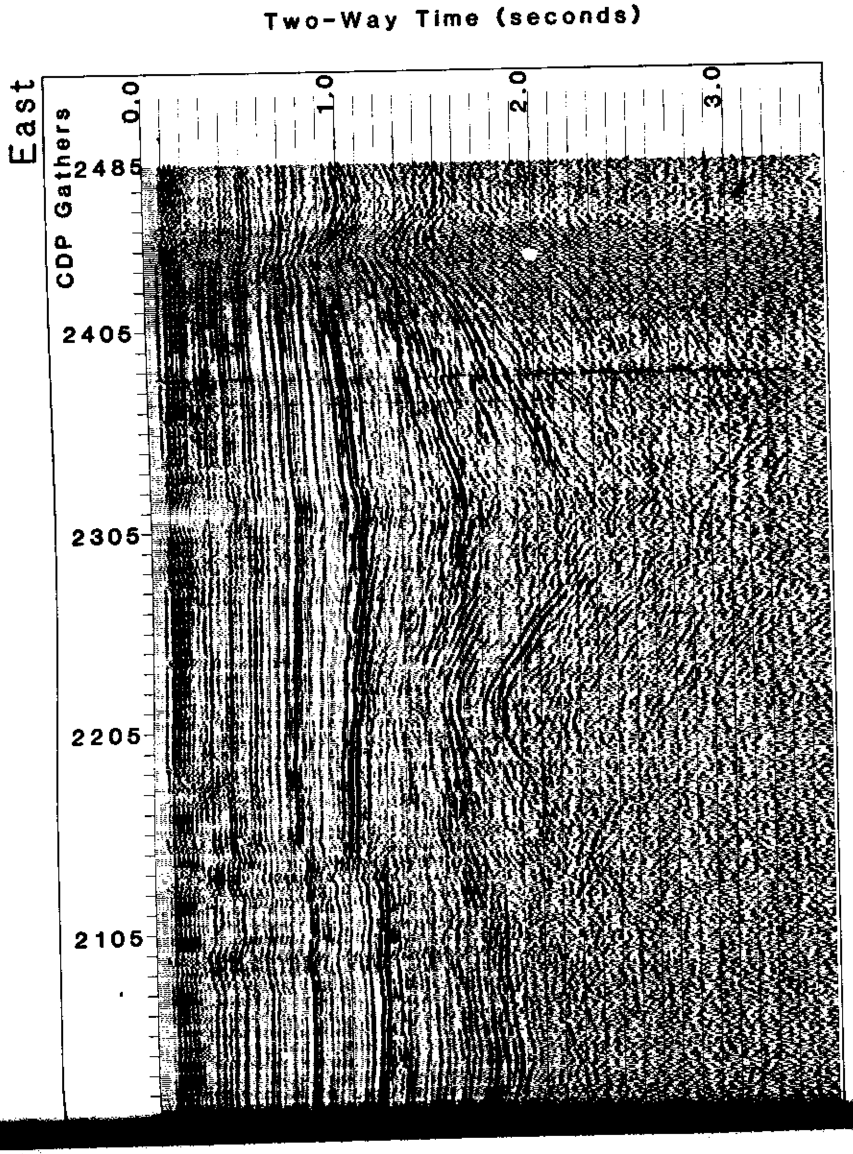
Original Seismic Line

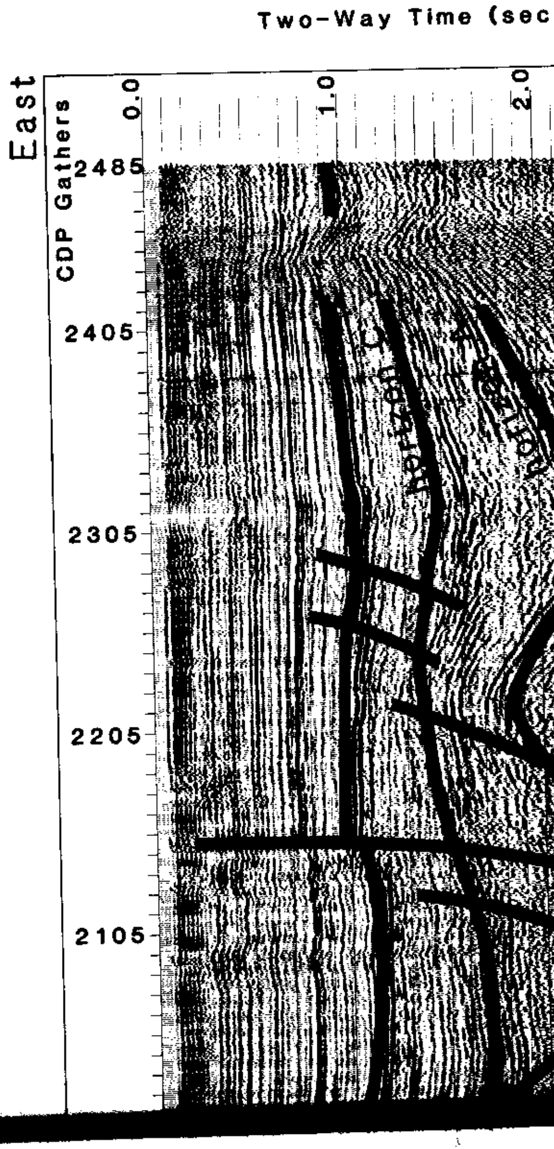


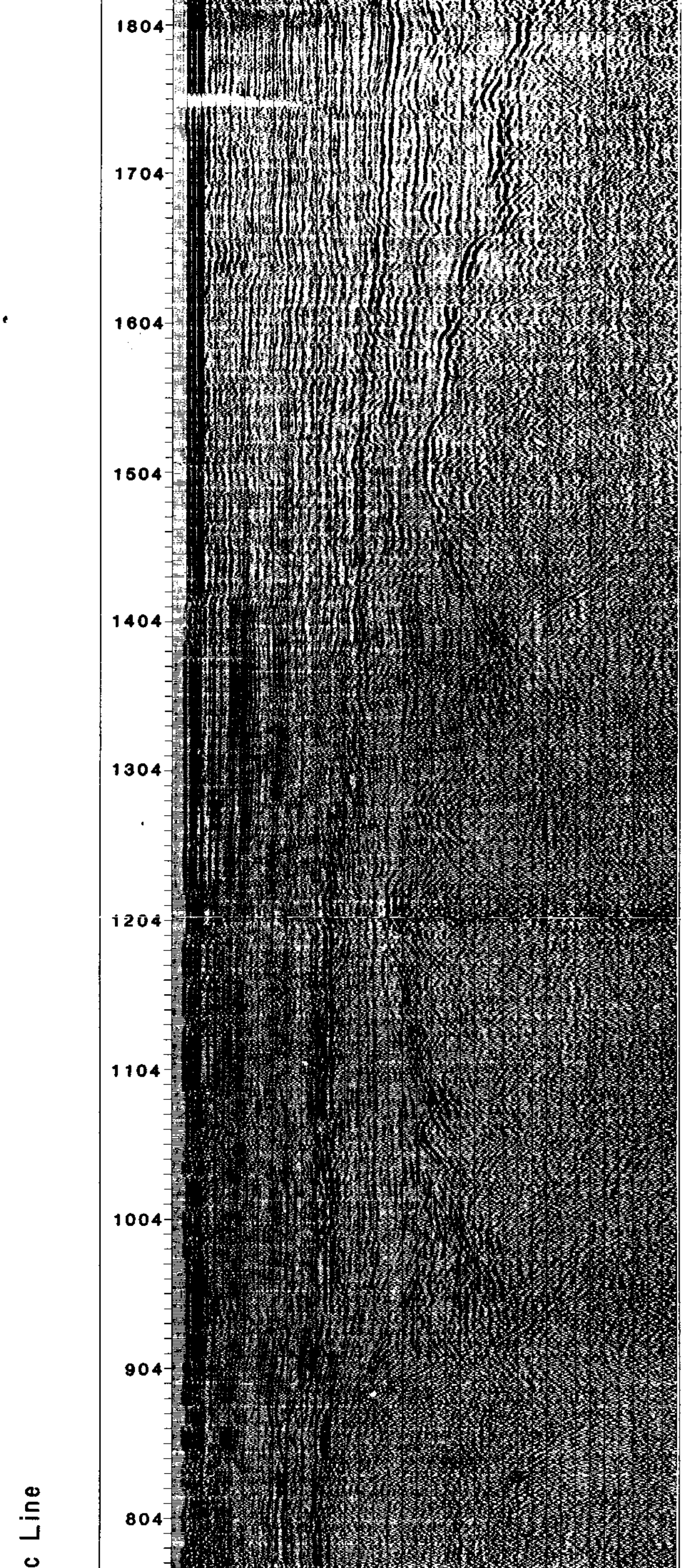
Interpreted Seismic Line




1904
1804
Crossing line 807 at 960
1704
1604
1504
1404
1304
1204
1104
1004
10
Miles
0
1904
1804
Crossing line 807 at 960
1704
1604
1504
1404
1304
1204
1104
1004


Two-Way Time (seconds)
East
CDP Gathers
0.0
1.0
2.0
3.0
2485
2405
2305
2205
2105


Two-Way Time (sec
East
CDP Gathers
0.0
1.0
2.0
2485
2405
2305
2205
2105
Horizon C
Horizon


1804
1704
1604
1504
1404
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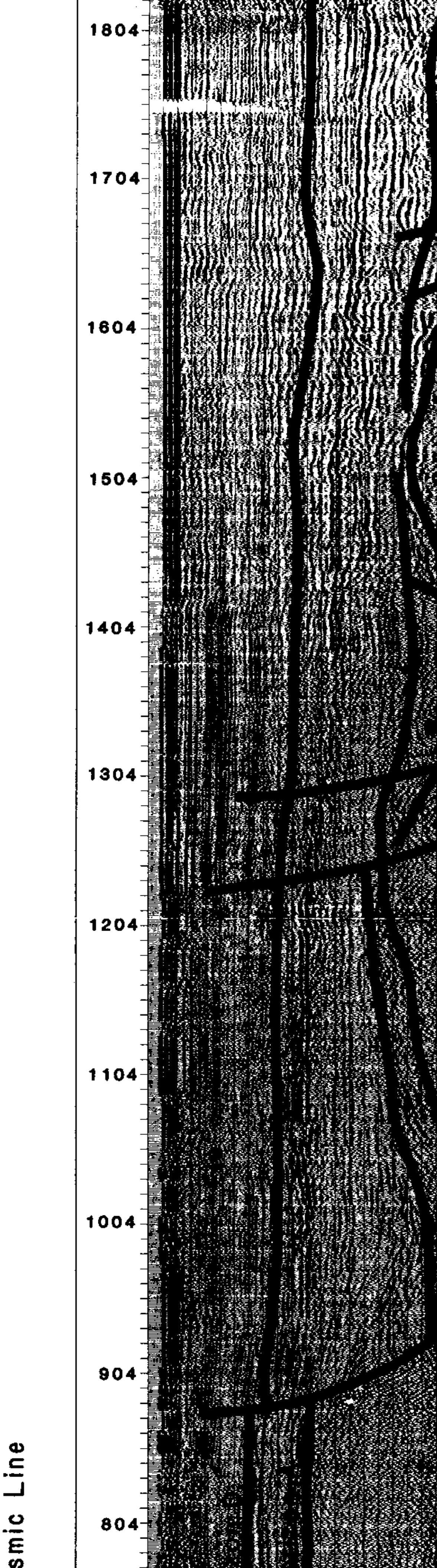
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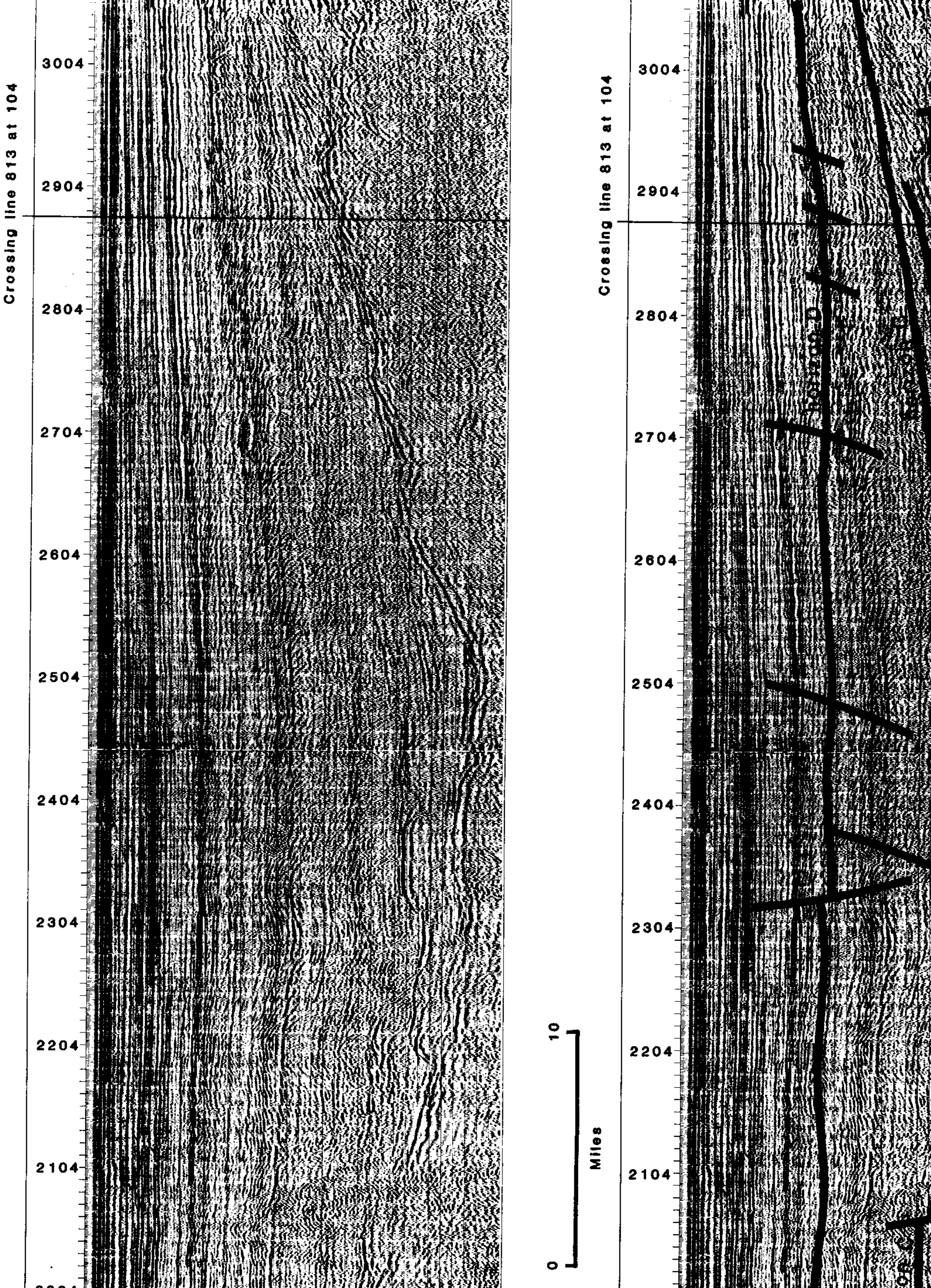
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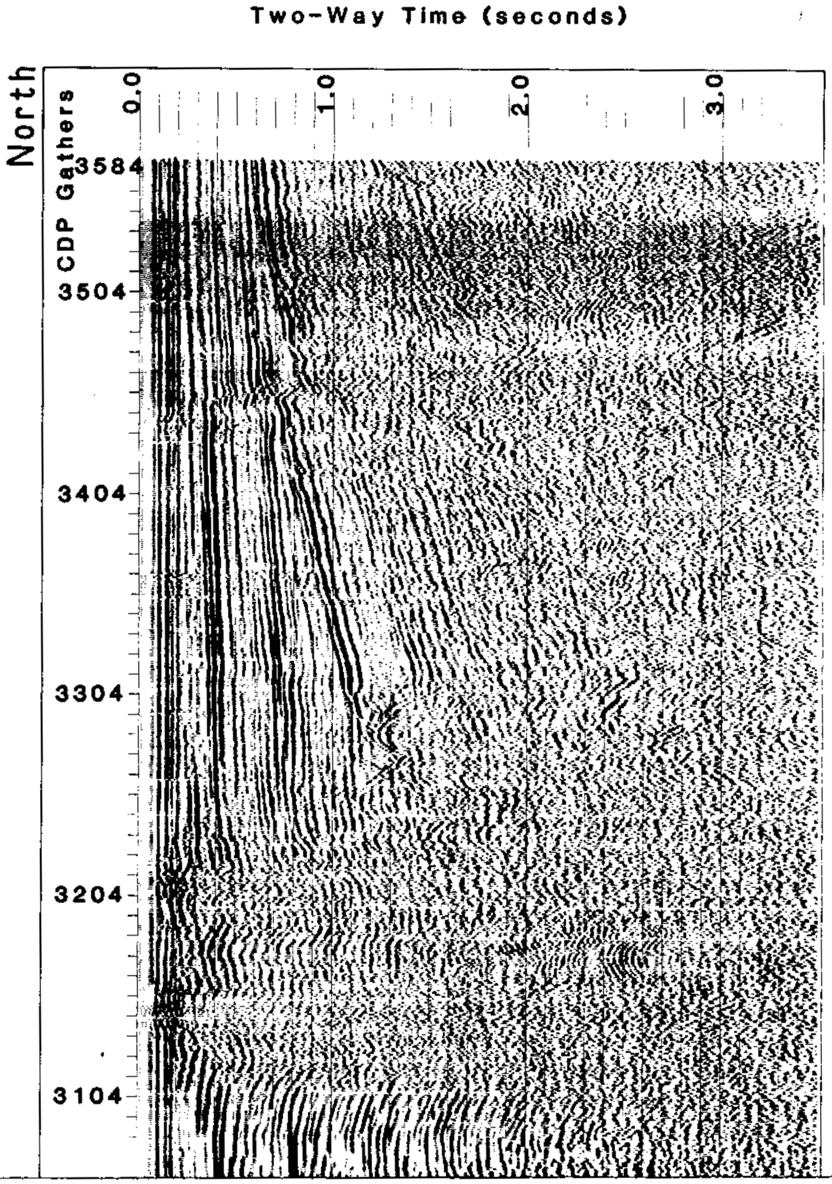
Two-Way Time (seconds)
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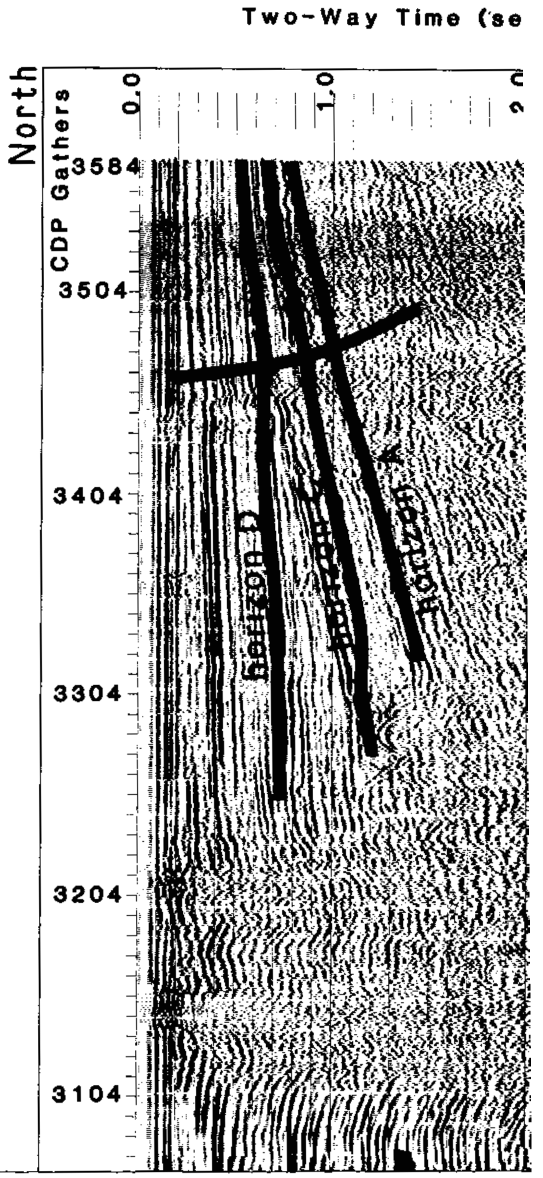
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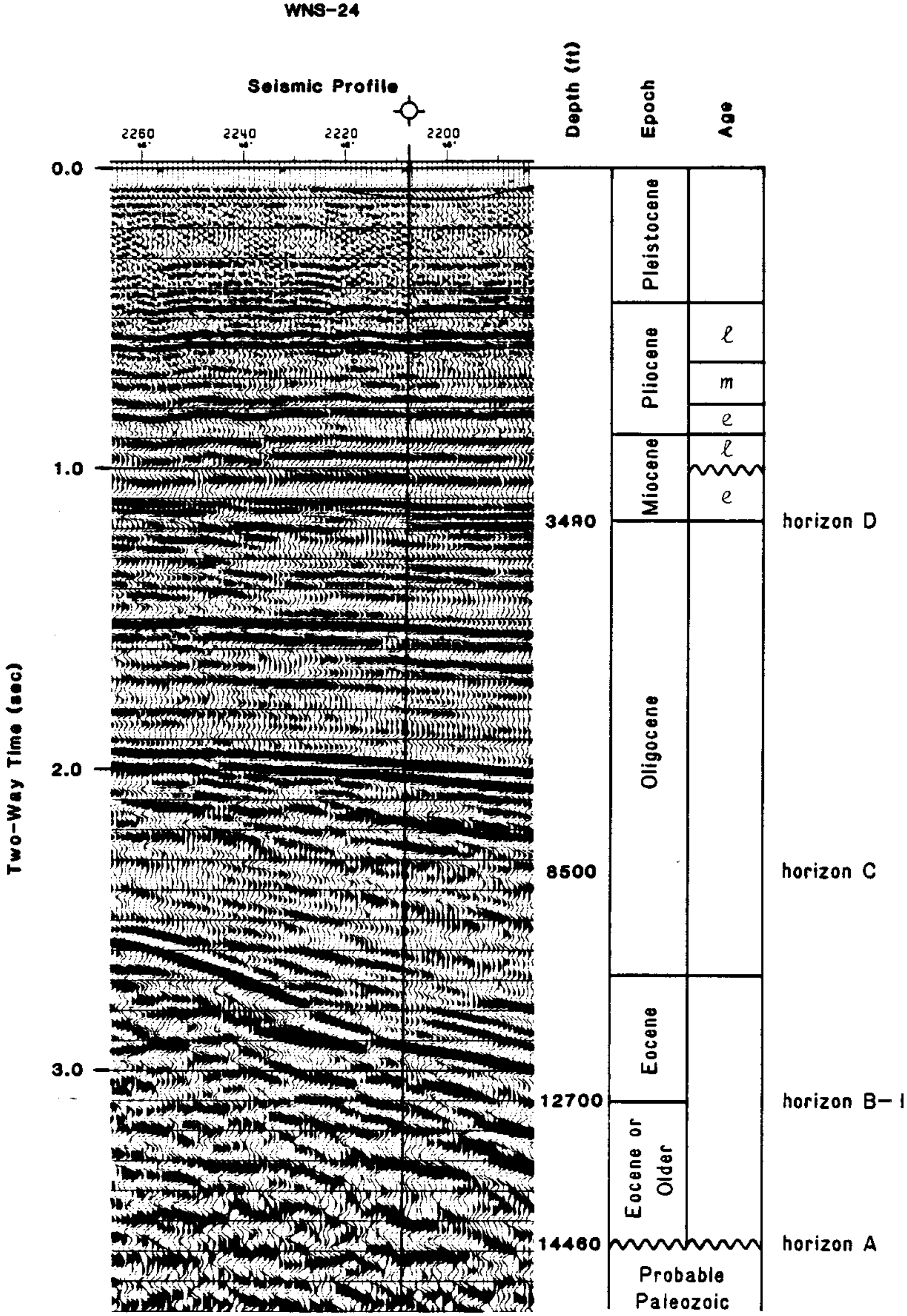


Figure 11. Time-stratigraphic column and seismic profile of COST No. 2 well

Horizon A occurs at 3.57 seconds or 14,460 feet in the No. 2 well, and at 3.10 seconds or 12,550 feet in the No. 1 well. The horizon is characterized by large amplitude, low frequency reflections that are mostly discontinuous. Below the horizon there are few areas in the basin where reflections occur. Above the horizon the reflections display an onlap relationship. The horizon represents an unconformity that separates the base of the basin fill from the underlying metamorphic basement rock. Horizon A is correlated between the wells and displays major structural deformation of an early Tertiary to late Mesozoic erosional surface. This deformation initiated the subsidence of the St. Lawrence and Stuart subbasins. During the subsidence, and their common border, the north-south trending Yukon horst, was a relatively high basement feature (fig. 9). Normal faulting delineates the structural depressions within the subbasins, and the Yukon horst. Some of these faults were active into the Pleistocene and probably the Holocene (Hoose, Steffy, and Lybeck, 1981). Normal faults with displacements of over 4500 feet offset horizon A. Downwarping of the horizon allowed over 14,000 feet of sedimentary fill to accumulate in the Stuart subbasin.

Horizon B-1 occurs at 3.12 seconds or 12,700 feet in the No. 2 well. The horizon is characterized by large amplitude, low frequency reflections. There are few reflections just below the horizon, and those that do occur have variable amplitude and are discontinuous. This horizon is an apparent unconformable surface that onlaps horizon A at structural highs and reflects syndepositional subsidence and faulting. Horizon B-1 is neither continuous throughout the Stuart subbasin nor correlated to any specific horizon in the No. 1 well. At the No.

2 well, the horizon defines the top of an Eocene coal-sandstone sequence that is bounded at the bottom by horizon A.

Horizon C occurs at 2.33 seconds or 8,500 feet in the No. 2 well, and at 2.41 seconds or 8,620 feet in the No. 1 well. In this Stuart subbasin, this horizon is the boundary between a deeper zone of smaller amplitude, discontinuous reflections and a shallower zone of larger amplitude, continuous reflections. Both zones of reflections are conformable to horizon C in the basin and thin towards structural highs where the lower zone onlaps horizons B-1 and A. Horizon C is continuous throughout the basin and is correlated to the No. 1 well. In the St. Lawrence subbasin, the horizon is not as distinct as it is in the Stuart subbasin. Both the deep and shallow zones of reflections in the St. Lawrence subbasin are more discontinuous and have smaller and more variable amplitudes than their equivalents in the Stuart subbasin. Throughout the basin, the horizon shows syndepositional warping and faulting and pinches out at some structural highs, including the Yukon horst. At the No. 1 well the horizon correlates with a shelfal marine mudstone, shale, and interbedded sandstone sequence. At the No. 2 well this horizon is correlated to the boundary between an overlying marine sandstone and an underlying coal-sandstone sequence.

Horizon D occurs at 1.18 seconds or 3,490 feet in the No. 2 well, and 1.42 seconds or 4,490 feet in the No. 1 well. Throughout the basin this horizon separates a deeper zone of large amplitude, high frequency, continuous reflections from a shallower zone of small amplitude, discontinuous reflections. The horizon is a conformable surface throughout the basin and is correlative with a late Oligocene coal-sandstone sequence. The horizon is commonly offset by normal faults that are younger than horizon C.

Velocity Analysis

RMS velocities, interval velocities and a time-depth curve were calculated (figs. 12 and 13) using the interval-transit-time log of the No. 2 well. A comparison is made between these and similar velocities and a time-depth curve that were calculated from nearby seismic reflection data. In flat-lying parallel-bedded strata, the RMS velocities derived from a sonic log are comparable to the stacking velocities that are used to correct for normal movement of CDP traces. Figure 12 displays this comparison. Stacking velocities for USGS lines 813 and 814 that were shot within 5 miles of the well were picked and averaged. Down to 1.75 seconds or 6,000 feet, the two types of velocities are in good agreement. Below 1.75 seconds, the stacking velocities become increasingly higher than the RMS velocities. Anstey (1977) pointed out that stacking velocities and borehole velocity findings might not agree because of geometric and nongeometric differences in the data collection methods. In this case, the difference below 1.75 seconds is partially explained by dipping reflectors. Reflections with dips of up to 25° are present where some of the velocity spectra were

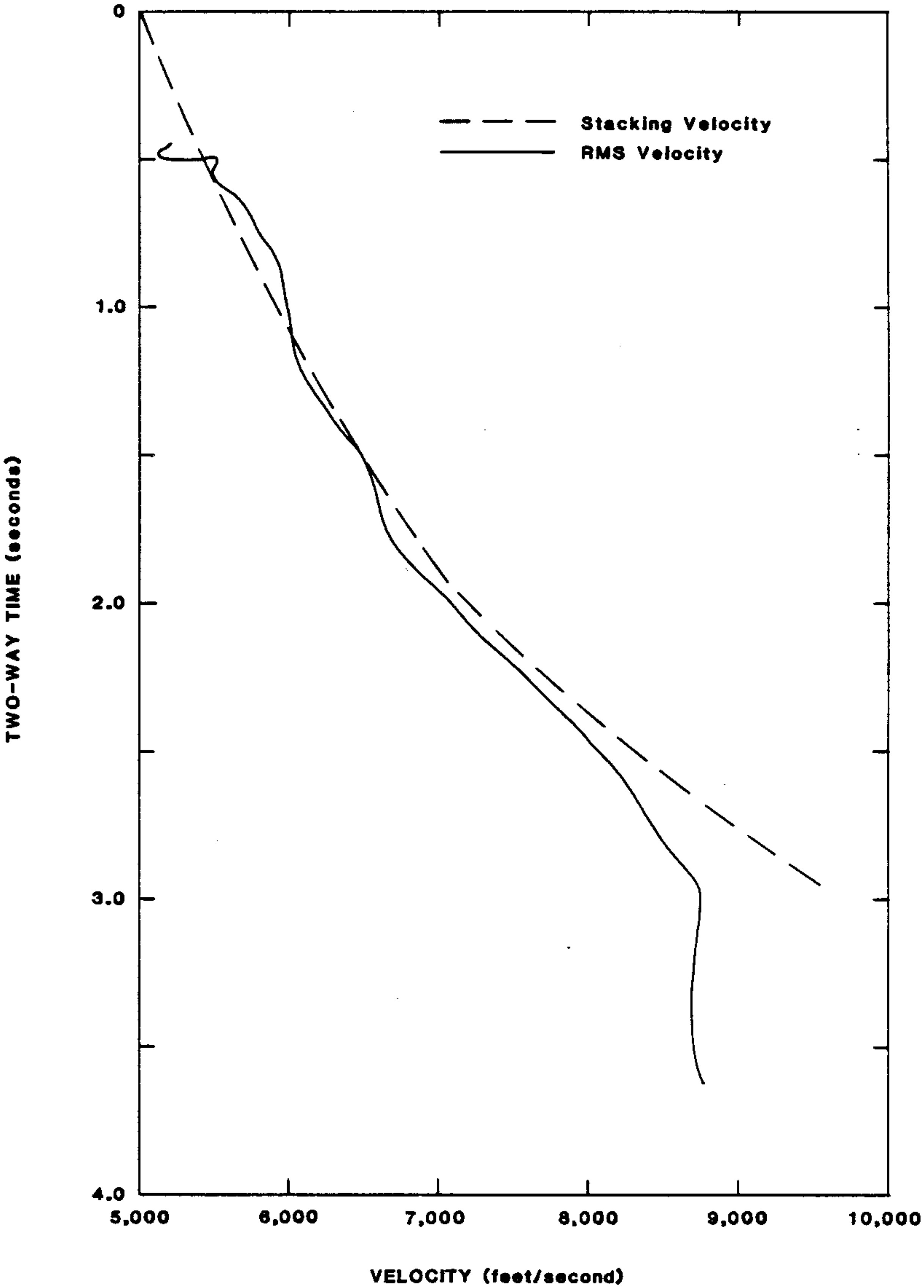


Figure 12. Comparison between stacking velocities and RMS velocities for COST No. 2 well

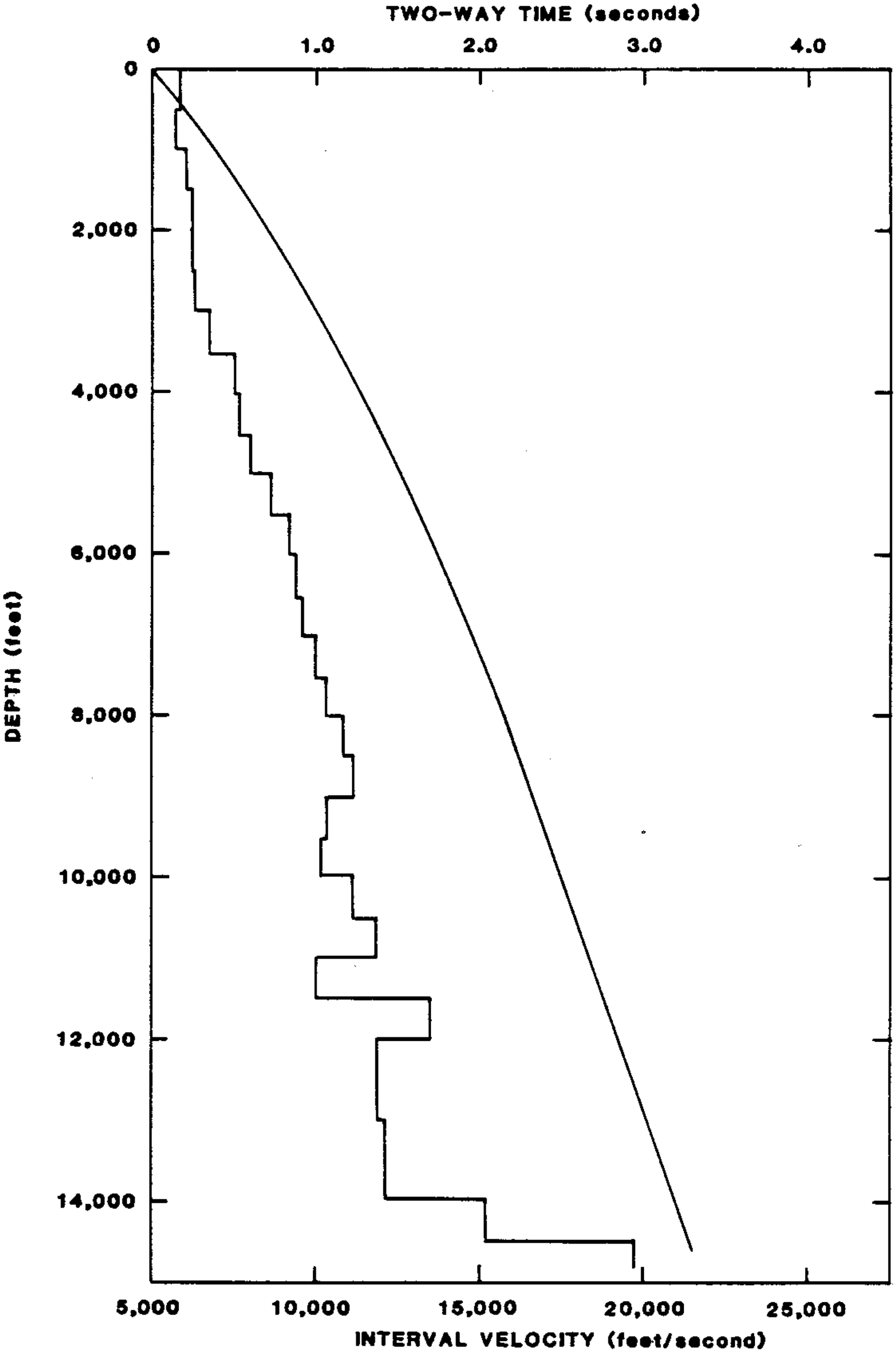


Figure 13. Interval velocities and time-depth curve from sonic log of COST No.2 well

displayed. Also, at 2.94 seconds or 12,500 feet, the RMS velocity curve becomes constant at 8800 to 8850 feet/seconds. This is approximately where horizon B-1 is located, which defines the top of a coal-sandstone sequence. The low-density coals and interbedded gaseous sandstones reduced the interval velocities of this sequence. Therefore, this sequence has lower RMS velocities.

After adjusting the stacking velocities for dip, interval velocities and a time-depth curve were calculated (fig. 14). Down to 9200 feet, these interval velocities are in close agreement with those calculated from sonic data (fig. 13). Below 9200 feet, the interval velocities derived from seismic reflection data are consistently higher than those derived from sonic data. This difference in interval velocities causes a divergence in their corresponding time-depth curves (fig. 15). The difference is probably due to geometric and nongeometric differences in data collection methods.

Figure 16 is a comparison of the time-depth curves derived from seismic reflection data collected near the wells. Down to 5,000 feet the curves are in good agreement. Below 5,000 feet, the No. 2 well displays a steeper time-depth curve. These higher velocities are probably due to lithologic differences in the wells between 5,000 and 10,000 feet. In this interval the No. 2 well penetrated a coal-sandstone sequence that has a higher average interval velocity than the marine sediments found in the No. 1 well. From 10,000 to about 12,550 feet, the interval velocities are approximately the same. Below 12,550 feet, the No. 1 well interval velocities reflect an acoustic basement of metamorphic rock, whereas the No. 2 well interval velocities reflect a relatively lower

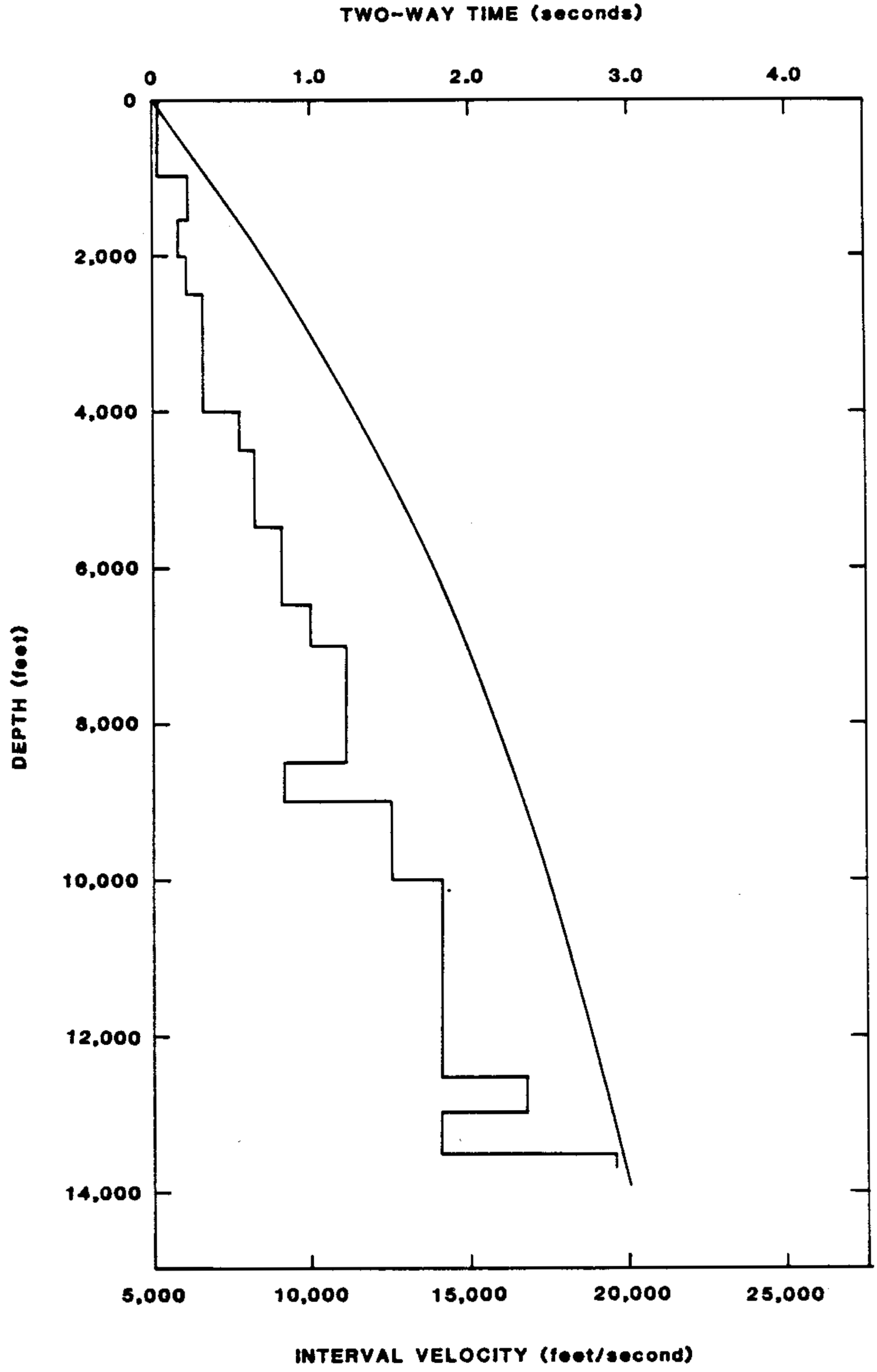


Figure 14. Interval velocities and time-depth curve from seismic data near COST No.2 well

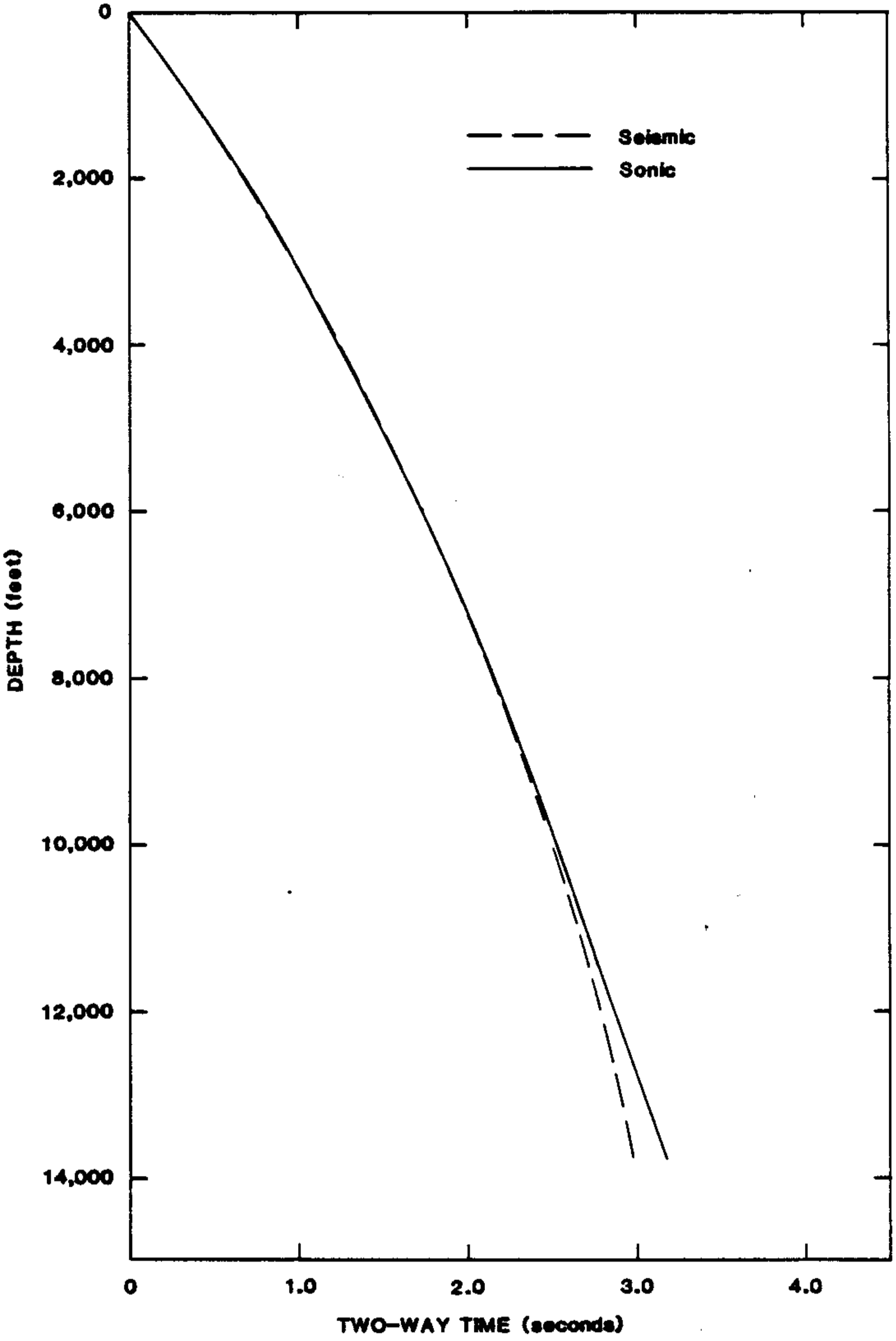


Figure 15. Comparison between time-depth curves derived from seismic and sonic data for COST No.2 well

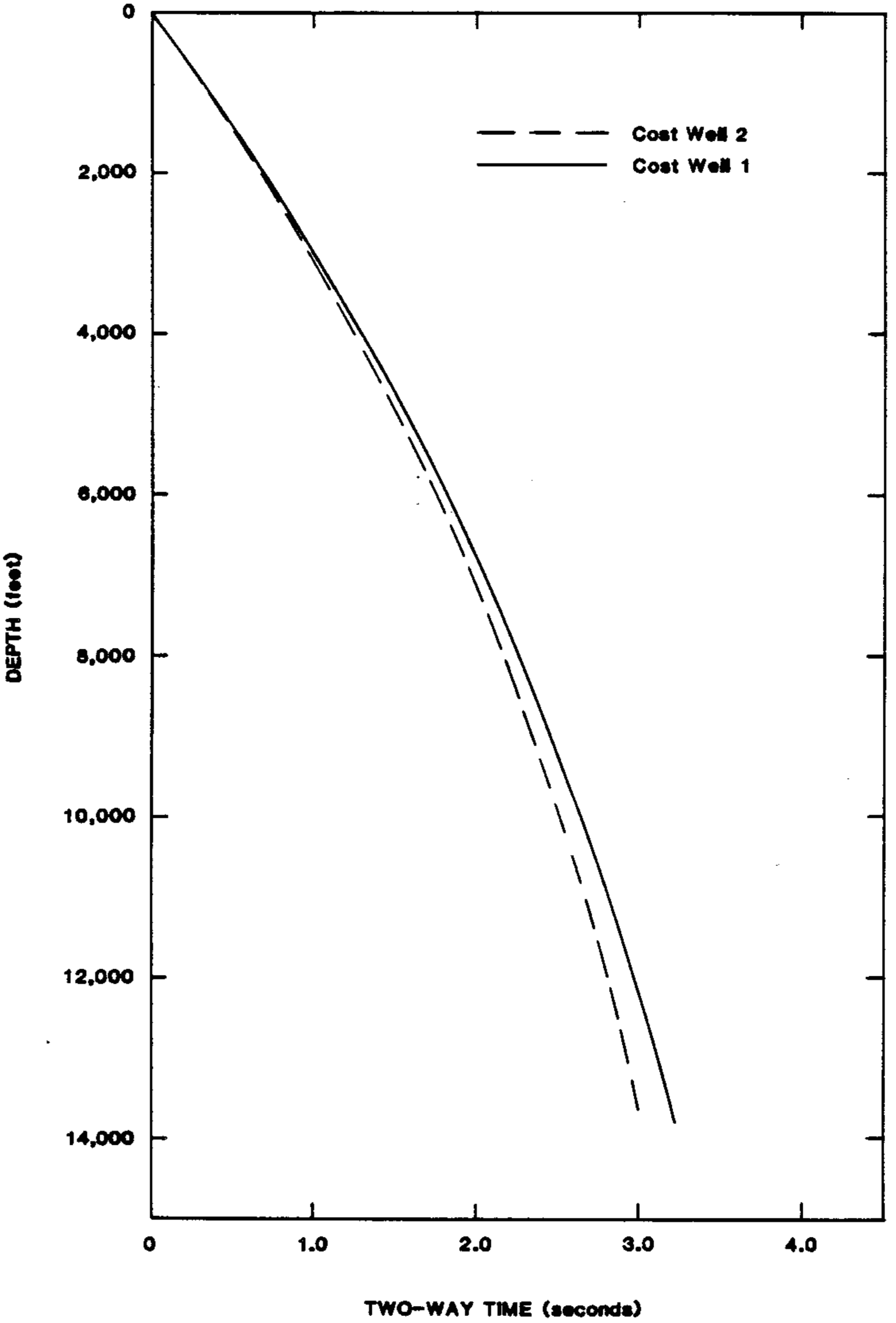


FIGURE 16 – COMPARISON BETWEEN TIME–DEPTH CURVES FOR COST WELLS 1 AND 2

velocity coal-sandstone sequence down to a depth of 14,460 feet. Below 14,460 feet the interval velocities reflect the metamorphic rock of acoustic basement. Therefore, any time-depth conversions should consider the lithologic differences in the wells below 5,000 feet. The differences probably reflect the individual subbasin histories. Below 5000 feet velocity variations within each subbasin probably will not be as great as velocity variations between the subbasins.

PALEONTOLOGY AND BIOSTRATIGRAPHY

by

Ronald F. Turner

Paleoecologic and biostratigraphic determinations in the ARCO Norton Sound COST No. 2 Well are based on detailed analyses of microfossil assemblages containing Foraminifera, silicoflagellates and diatoms, calcareous nannoplankton, and marine and terrestrial palynomorphs. Rotary drill bit cuttings were examined at 30-foot intervals from the first sample at 450 feet to the total depth of 14,889 feet. Data from conventional and sidewall cores were also examined and utilized. In addition, slides, processed samples, and reports prepared for the participants by consultants (Biostratigraphics, 1982) were examined, interpreted, and integrated into this report. Discrepancies between Minerals Management Service and consultant interpretations, principally the location of biostratigraphic tops, for the most part can be attributed to sample content variations and differences in sample preparation techniques. Foraminiferal analysis, interpretation, and synthesis of other data were done by the author. Siliceous microfossil analysis was done by Donald L. Olson.

Strata are discussed in the order that they were penetrated. The biostratigraphic units delineated represent a synthesis of data derived from various subdisciplines that do not agree in every particular. Sample depths may disagree slightly with measured depths. Following convention, fossil occurrences are listed as highest and lowest rather than the potentially confusing first and last. Data obtained from cores are given somewhat more weight than those from cuttings. Correlation with the other Norton Sound COST well is discussed at the conclusion of this report.

Paleoenvironmental determinations are based on the entire and macrofossil microfossil 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 are brackish estuaries, marshes, and hypersaline and hyposaline 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, ophuroids, and cirripeds are also utilized. The marine environment is divided into inner neritic (0-60 feet), middle neritic (60-300 feet), outer neritic (300-600 feet), and upper bathyal (600-1500 feet).

Pleistocene

The interval from 450 to 1320 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 *Quinquelculina akneriana*.

Rare, poorly preserved and broken ostracodes assignable to *Paracyprideis pseudopunctillata*, "*Acanthocythereis*" *dunelmensis*, 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 (0-60 feet). Salinity varied from normal marine to brackish.

Pliocene

The interval from 1320 to 2580 feet is here considered to represent the Pliocene section of the well. The biostratigraphic 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 complications caused by extensive reworking and downhole contamination.

The late Pliocene, 1320 to 1846 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 1846 feet mark the top of the middle Pliocene. The base of this interval is tentatively placed at 2228 feet on the basis of the highest occurrence of the early Pliocene forms *Cosmiodiscus insignis* and *Thalassiosira punctata*. The early Pliocene section, 2228 to 2580 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 palynoflora includes the dinoflagellates Lejunia spp., Spiniferites spp., and Cannosphaeropsis aff. C. sp. A Williams and Brideaux 1975. The highest occurrence of the latter species, 2310 feet, is considered a possible Miocene marker by the consultants on the basis of the occurrence of Cannosphaeropsis sp. A in the Miocene of eastern Canada. The consultants also identify a Tasmanaceae zonule between 2040 and 2670 feet that they consider to be Pliocene to Miocene in age.

The foraminiferal fauna contains all of the species present in the Pleistocene section as well as 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 ophuroids are present throughout the interval, but are neither diverse nor numerous.

Miocene

The interval from 2580 to 3524 feet is Miocene in age. The section is subdivided into late and early Miocene on the basis of siliceous microfossil assemblages. The late Miocene, 2580 to 3120 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, 3120 to 3524 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. The dinoflagellate assemblage contains *Lejunia paratenella*, *Lejunia* spp., *Spiniferites cingulatus*, *Spiniferites ramosus*, *Tuberculodinium vancampoe*, 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 3200 to 3540 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 (0-300 feet) in a cold climate. The early Miocene interval represents a shallower (inner neritic) and warmer environment (warm-temperate to subtropical).

Oligocene

The interval from 3524 to 10,160 feet is considered to be Oligocene in age. The palynofloras over this interval are abundant, diverse, and relatively diagnostic. The uppermost coal-bearing portion of the sequence, 3524 to 3930 feet, is characterized by an assemblage composed of *Alnipollenites* sp., Betulaceae, and rare to frequent *Ulmipollenites* sp., *Pterocaryapollenites* sp., and *Momipites* sp. From 3930 to 6520 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*. Fungal palynomorphs, particularly species of *Striadiporites*, are an increasingly important floral element below 7900 feet. The consultants suggest that some of the fungal taxa recovered below 9,300 feet may have Eocene affinities.

Calcareous nannoplankton are represented in the well by a single, incomplete placolith of *Coccolithus pelagicus* from 7250-7340 feet. A morphological analysis 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 Ilpensky peninsulas (Serova, 1976). However, the several species of *Caucasina* recovered from the Norton Sound No. 2 well range well up into the Oligocene.

Environment

The climate of the Oligocene was subtropical to warm-temperate and the bathymetry fluctuated from as deep as possible outer neritic to continental. Two coal sections are present in the upper part of the section, 3424 to 3930 feet and 4250 to 4440 feet. These continental to transitional intervals bracket an inner neritic (0-60 feet) section containing shallow water foraminifers that are common in hyposaline environments. Inner to middle neritic (0-300 feet) conditions prevailed from 4440 to 5150 feet. Middle to outer neritic (60-600 feet) conditions obtained from 5150 to 6770 feet. Possible outer neritic (300-600 feet) depositional depths are suggested by the Foraminifera recovered between 6290 and 6770 feet. Although rare, isolated specimens of *Cyclammina* cf. *C. pacifica* and *Martinottiella* sp. are present, they are not associated with a true deep water faunal assemblage. The dominantly shallow water fauna and the presence of thin coal seams suggest that outer shelf, upper slope depositional depths were not obtained during this transgression. Below 6770 feet, the environment is characterized by numerous fluctuations from continental and transitional to possible inner neritic. Overall, the interval from 6770 to 10,160 feet appears to represent the bay and marsh deposits of a transitional environment. There are numerous thin coal seams as well as coal beds greater than 10 feet thick.

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 indicate that these species generally occur earlier in the Canadian Arctic than in British Columbia. Presumably, the 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 Oligocene. Marine palynomorphs are rare and most are 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*, *Psammospahaera* cf. *P. carnata*, *Saccammina* sp., *Ammodiscus* sp., *Loxostomum* sp., and fragmentary polymorphinids.

A dermal scute from a juvenile sturgeon was recovered from cuttings at 10,160-170 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 (P. McClellan, personal communication).

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 (10,160-12,000 feet) may have occasionally been as deep as middle neritic (0-300 feet). Thick coal beds are not present above 12,700 feet. The presence of euryhaline Foraminifera associated with terrestrial pollen and fungal palynormorphs, 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 12,000 to 12,700 feet is dominantly continental in aspect. The climate in the Eocene was tropical to subtropical.

Eocene or Older

The interval from 12,700 to 14,460 feet is Eocene or older. Palynomorph recovery from cuttings is poor in this part of the well and the specimens are poorly preserved. Although geochemical investigations indicate a zone of reworking or a possible unconformity between 11,960 and 12,200 feet, the unconformity is placed at 12,700 feet on the basis of lithologic and dipmeter criteria.

Eocene fungal palynomorphs were recovered from sidewall cores 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 tropical 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 despite the fact that they are located approximately 49 nautical miles apart and were deposited in geographically distinct and tectonically independent subbasins (fig. 17). Depositional environments also differed. Those of the St. Lawrence subbasin, the site of the No. 1 well (fig. 18), are more marine than those of the Stuart subbasin, the site of the No. 2 well (fig. 19). However, similarities between the two wells are more pronounced than differences, particularly in the marine sequences

Figure 17. Biostratigraphic Correlation of Norton Sound COST Wells

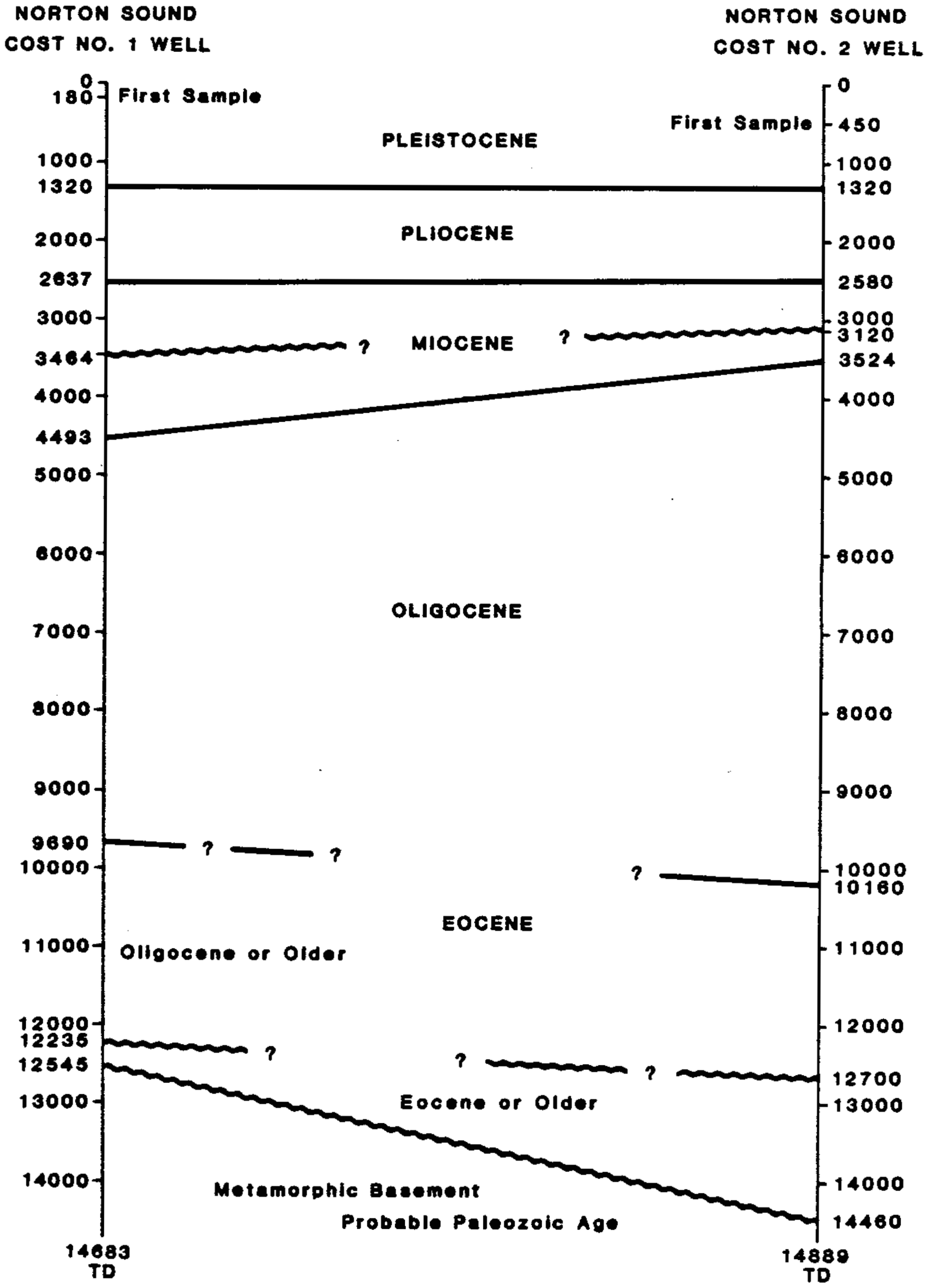


Figure 18. STRATIGRAPHIC SUMMARY of NORTON SOUND COST No. I WELL

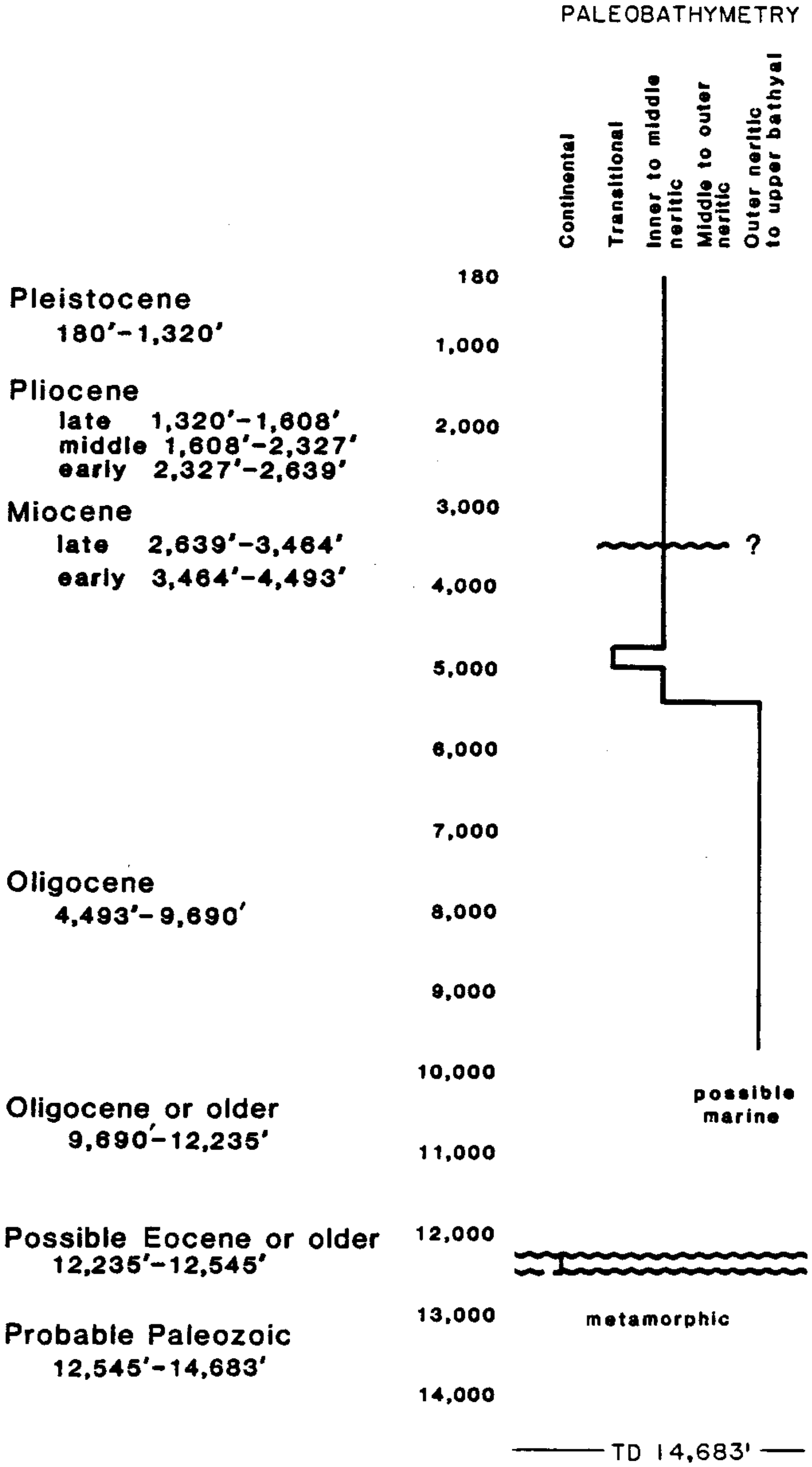
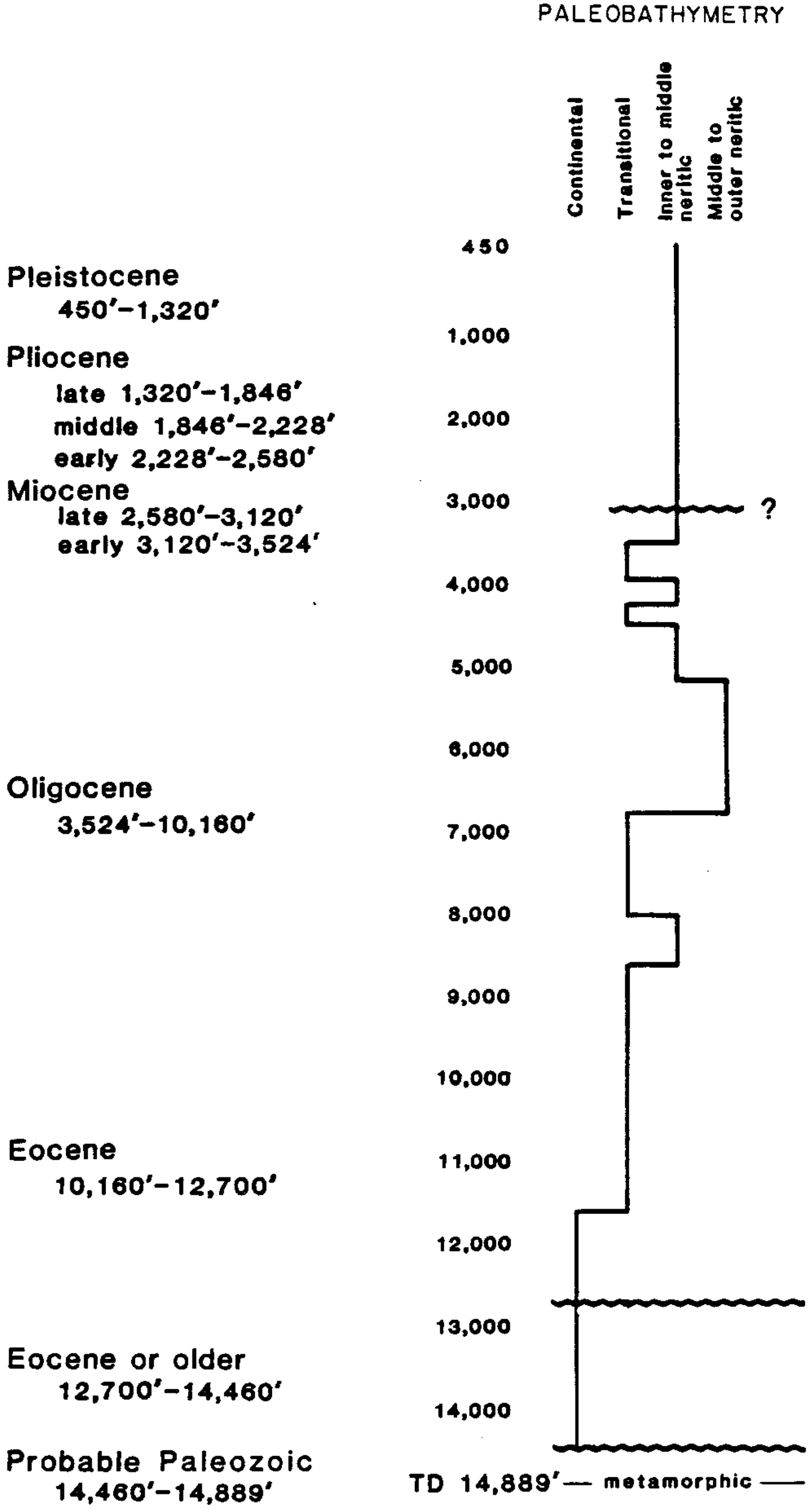


Figure 19. STRATIGRAPHIC SUMMARY of NORTON SOUND COST No. 2 WELL



seen above 6800 feet in both. Correlations are somewhat more difficult below 6800 feet in that the predominantly nonmarine 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 and older section, which is far thicker in the No. 2 well, time-equivalent units are also roughly equivalent in thickness. Sedimentation rates were not calculated because of the tentative nature of some of the biostratigraphic boundaries.

Pleistocene

The first sample in each well is Pleistocene in age, although it is almost certain that a thin Holocene section was penetrated. Sample quality is poor. The base of the Pleistocene was placed at 1320 feet in both wells. Microfossil assemblages, lithology, and depositional environments are essentially identical. Shallow seismic evidence indicates that there may be a slight unconformity between the Pliocene and the Pleistocene.

Pliocene

The top of the Pliocene is at 1320 feet in each well, the base at 2639 feet in the No. 1 well and 2580 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 subdivision tentative and provisional at best. In general, the microfossil assemblages in both wells reflect similar paleoenvironments.

Miocene

The top of the Miocene is at 2639 feet in the No. 1 well and at 2580 feet in the No. 2 well. There appears to be a middle Miocene hiatus, perhaps a paraconformity, present in both wells. This "surface" is defined in both wells by the top of the early Miocene, 3464 feet in the No. 1 well, and 3120 feet in the No. 2 well. The base of the early Miocene is at 4493 feet in the No. 1 well and at 3524 feet in the No. 2 well. Microfossil assemblages and lithologies are quite similar in both wells, though there is some evidence that deposition was at shallower depths in the No. 2 well.

Oligocene

Strata assigned to the Oligocene epoch account for roughly half of the sedimentary section penetrated by the wells, 5197 feet in the No. 1 well, 6644 feet in the No. 2 well. In the No. 1 well the Oligocene section (4493-9690 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 (3524-10,160 feet), well over half of the sediments are coal-bearing and were deposited under continental to transitional conditions.

There is a small, but pronounced, continental to transitional environment present near the top of the Oligocene section in the No. 1 well (4740-4980 feet) that is correlative with the coal beds seen in the No. 2 well at 3524 to

3930 feet and at 4250 to 4440 feet. The marine transgressive section from 5360 to 6770 feet in the No. 2 well is certainly in part correlative with the upper bathyal environments seen below 8130 feet in the No. 1 well.

Eocene

Definite late to middle Eocene strata are present from 10,160 to 12,700 feet in the No. 2 well. Although no Eocene fossils were found in the No. 1 well, it is possible that the problematic Oligocene or older section (9,690 to 12,235 feet) is in part correlative with the Eocene section in the No. 2 well.

Eocene or Older

In both wells a coal-bearing section unconformably overlies the regional early Tertiary to late Mesozoic erosional surface. This continental section, 310 feet thick in the No. 1 well and 1760 feet thick in the No. 2 well, is truncated by an unconformity at 12,235 feet in the No. 1 well and at 12,700 feet in the No. 2 well. Because both deposition and erosion took place in two subbasins separated by a 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 highly likely that the Eocene or older sections in the two wells are in part correlative.

Basement Complex (Possible Paleozoic)

Both wells penetrated metasedimentary sections below the regional unconformity that marks acoustic basement. The 2135-foot-thick sequence of cataclastic rocks in the No. 1 well appears quite similar to slate of Precambrian to 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. It is not presently possible to more closely relate the metamorphic sections of the two wells on the basis of either age or genesis.

LITHOLOGY

AND

GEOPHYSICAL LOG INTERPRETATION

by J. G. Bolm

Examination of cuttings, conventional and sidewall cores, and geophysical (electric) logs from the well provided information on lithologies, ages, depositional environments, reservoir characteristics, and hydrocarbon source-rock potentials of the strata penetrated. Lithology and reservoir characteristics discussed in this section are based primarily on consultants' reports, especially the petrologic report by AGAT Consultants, Inc., and the examination of geophysical logs. The gamma-ray, spontaneous potential (SP), deep resistivity, density, and sonic logs are presented with other geological and geophysical well data in Plate 1. Framework clast compositions of sandstone samples from conventional cores are presented in Figure 20.

0-1180 feet

Geophysical logging of the well began at 1180 feet, and recovery of cuttings was poor above 1230 feet. The few cuttings recovered from this uppermost part of the well are predominantly very fine to coarse sand-size grains of quartz,

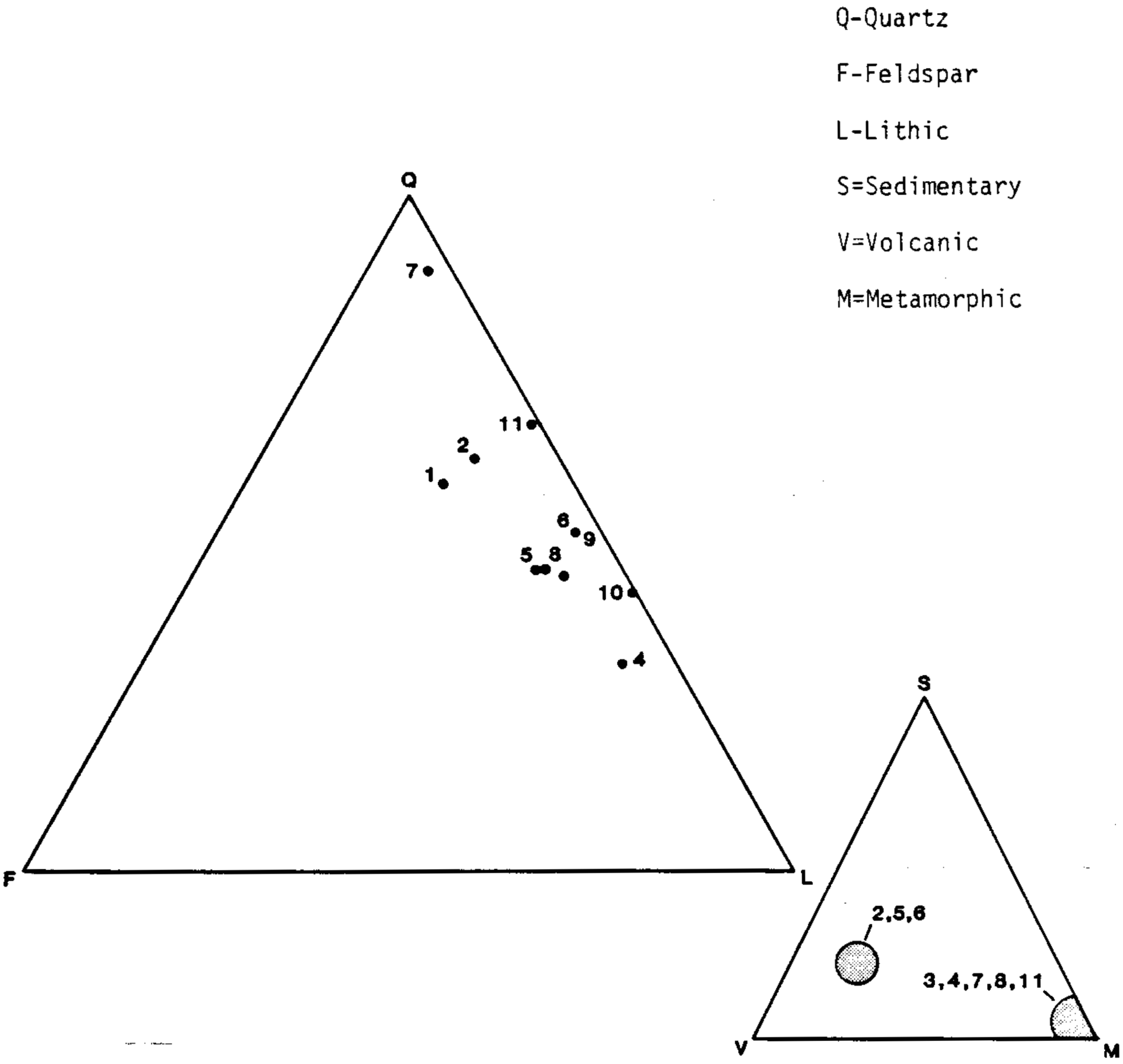


Figure 20 Ternary diagrams of framework clast composition of sandstone samples from conventional cores from the Norton Sound COST No. 2 well. The large diagram shows the average abundances of quartz, feldspar, and lithic (including mica) components, and the small diagram shows the average abundances of volcanic, sedimentary, and metamorphic (including mica) lithologic types in the lithic fraction. After AGAT Consultants, Inc.

hornblende, epidote, muscovite, and various volcanic, metamorphic, and siltstone fragments. A few silty of sandstones were cemented with iron oxide. Foraminifera and other marine fossils are present in these samples.

1180-3535 feet

The interval from 1180 to 3535 feet is characterized by diatomaceous mudstone, siltstone, and muddy sandstone. Sand clasts range from very fine to coarse and consist primarily of quartz, feldspar, muscovite, and rock fragments. Quartz clasts are subangular to subrounded. The sand grains are generally well sorted, but the muddy sandstones themselves are poorly sorted. Rocks in this interval are locally calcareous and contain minor epidote, pyrite, glauconite, shell debris, and Foraminifera. Porosities of 19 sidewall-core samples from this interval range from 28.5 to 53.6 percent. Permeabilities for these same samples range from 1.06 to 58 mD with most values under 10 mD.

The gamma-ray and SP logs suggest the presence of several 25- to 100-foot-thick, relatively coarse-grained beds associated with thinner, finer-grained interbeds in the upper part of this interval. Below 1685 feet (gamma-ray) and 1840 feet (SP) the log curves do not define individual beds. Resistivities are low with a difference of about 1 ohm-m common between the deepest and shallowest measured values above 2200 feet. Below 2200 feet there is little difference between the deepest and shallowest resistivity values.

The density and sonic logs display numerous erratic kicks due to wash outs in this interval. Where caving was not a problem, the density log indicates average densities of about 1.75 g/cm^3 for these rocks, and the sonic log shows a general decrease in interval transit time from 205 to 145 µs/feet downward through the interval.

The presence of abundant marine fossil material and glauconite in the rocks of this interval indicates deposition in a marine shelf environment.

3535-4570 feet

The interval from 3535 to 4570 feet is characterized by interbedded coal and poorly indurated mudstone, siltstone, and sandstone. The mudstone and siltstone are commonly micaceous and contain scattered sand grains. The sandstone is comprised of quartz, feldspar, and lesser rock fragments and locally is micaceous. Quartz clasts are subangular to rounded. The sandstone ranges from very fine to very coarse grained and is moderately to well sorted. The sandstone is locally muddy or silty. Pyrite is common in this interval.

Porosities of 9 sidewall cores of sandstones from this interval range from 26.1 to 33.7 percent. Measured permeability ranges from 9.89 to 976 mD. Most of the sandstone permeability values, especially the higher ones, are probably too large due to rock fabric disruption in the coring process.

The SP and gamma-ray logs display blocky characters consistent with interbedded finer- and coarser-grained rocks. Numerous sharp kicks to lower values on the gamma-ray log that correspond with high resistivities and low densities and sonic velocities on other logs are interpreted to represent coal beds. The SP and gamma-ray logs show a total of 260 feet of sandstone in 5- to 50-foot beds in this interval. The resistivity curve displays a less pronounced blocky character than the SP and gamma-ray curves. Separation of about 1 ohm-m is common between the shallow and deep resistivity curves in coarser-grained beds. The shallow and deep resistivity values are commonly the same for finer-grained beds. Sharp kicks to higher resistivity values are present where the gamma-ray log indicates coal beds. The density log indicates densities ranging from 2 to 2.25 g/cm^3, but densities as low as 1.3 mark the locations of coal beds. The density log indicates porosities ranging from 28 to 39 percent for sandstone in this interval. The sonic log shows interval transit times generally ranging from 130 to 115 ms/foot. The higher interval transit times are associated with coal beds, although these coal beds are not as well defined on the sonic log as on the gamma-ray and density logs. The sonic log, when corrected for undercompaction, indicates sandstone porosities ranging from 29 to 34 percent.

At least part of this coal-bearing interval was deposited in a fluvial or deltaic environment, but the recovery of marine fossils (see Paleontology and Biostratigraphy section of this report) indicates that some of the rocks were deposited in a nearshore marine environment.

4570-6000 feet

The interval from 4570 to 6000 feet is characterized by interbedded mudstone, siltstone, and sandstone with minor amounts of coal. Conventional cores 1 and 2 are from this interval and are described in figures 21 and 22. The mudstone generally contains very fine sand, and sandstone is generally muddy or silty. Sand clasts range from very fine to fine grain and consist of both monocrystalline and polycrystalline quartz, plagioclase, and potassium feldspar in generally subequal amounts, as well as volcanic, metamorphic, and sedimentary rock fragments. Minor glauconite and framboidal pyrite are present locally in the sandstone. The sandstone contains scattered bivalve fragments and in conventional cores is seen to be laminated or cross-laminated and burrowed.

Some ductile grains have been deformed in the sandstone of this interval, and authigenic calcite or, less commonly, siderite cement is present in intergranular spaces that are not filled with matrix. Measured porosities from 13 sidewall and conventional core samples of sandstone range from 1.5 to 27.9 percent. Permeabilities range from 0.15 to 173 mD. The lowest values in both categories are from calcite-cemented rocks, and most samples have porosities in the 20-percent range and permeabilities of at least 1 mD. The highest permeability

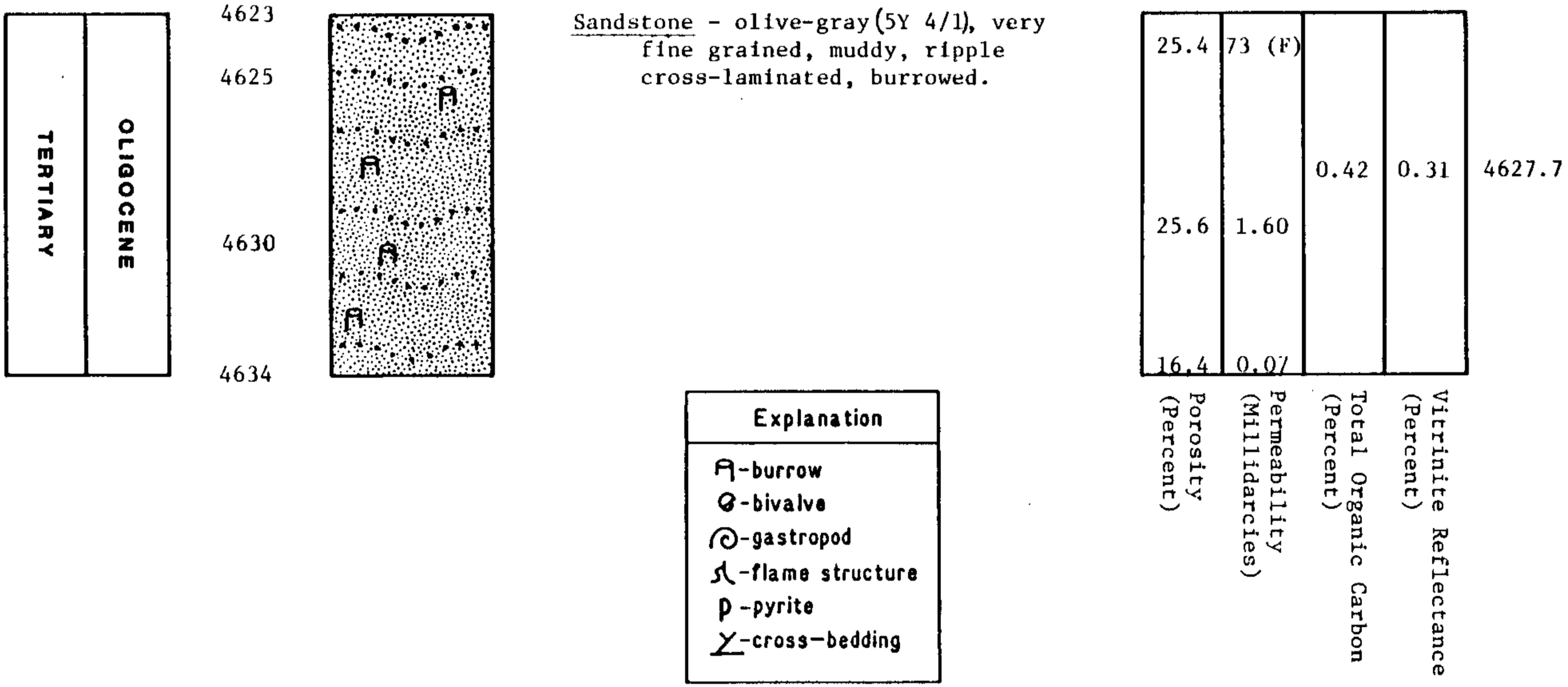
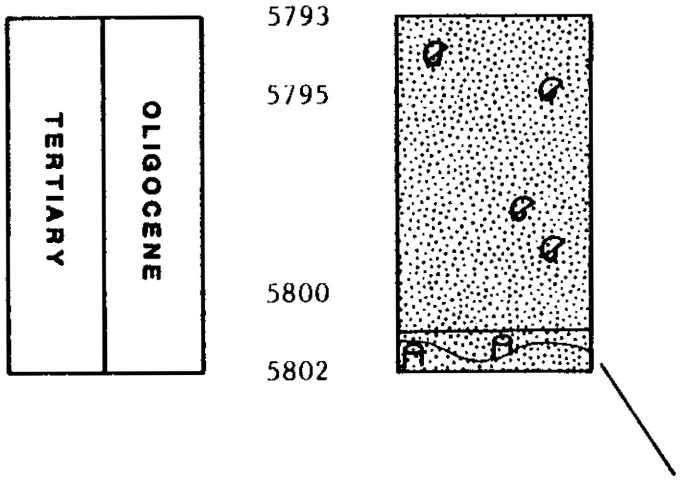


Figure 21. Description of conventional core 1, Norton Sound COST No. 2 well (Porosity and permeability data from Core Laboratories, Inc.: geochemical data from Core Laboratories, Inc.)



Sandstone - olive-gray (5Y 3/2), weakly mottled, very fine grained, silty, bivalve fragments common, massive with some laminated and cross-laminated zones.

Sandstone - dark-olive gray (5Y 2/2), very fine to fine grained, massive with uneven burrowed basal contact.

Sandstone - olive-gray (5Y 3/2), weakly mottled, very fine grained, silty, massive with burrows filled with material from unit above.

Porosity (Percent)	Permeability (Millidarcies)	T.O.C. (%)	Ro (%)	
20.5	1.29			
23.2	5.88			
7.8	0.54	0.28		5799.9
1.5	0.15			

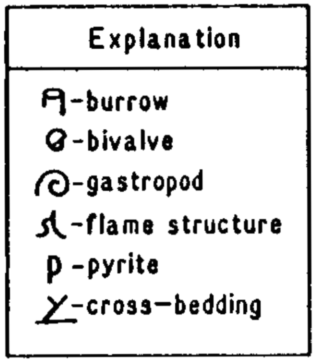


Figure 22. Description of conventional core 2, Norton Sound COST No. 2 well (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)

from an unfractured conventional core sample is 5.88 mD. Many of the higher values from sidewall cores probably resulted from fabric disruption consequent to shooting the cores.

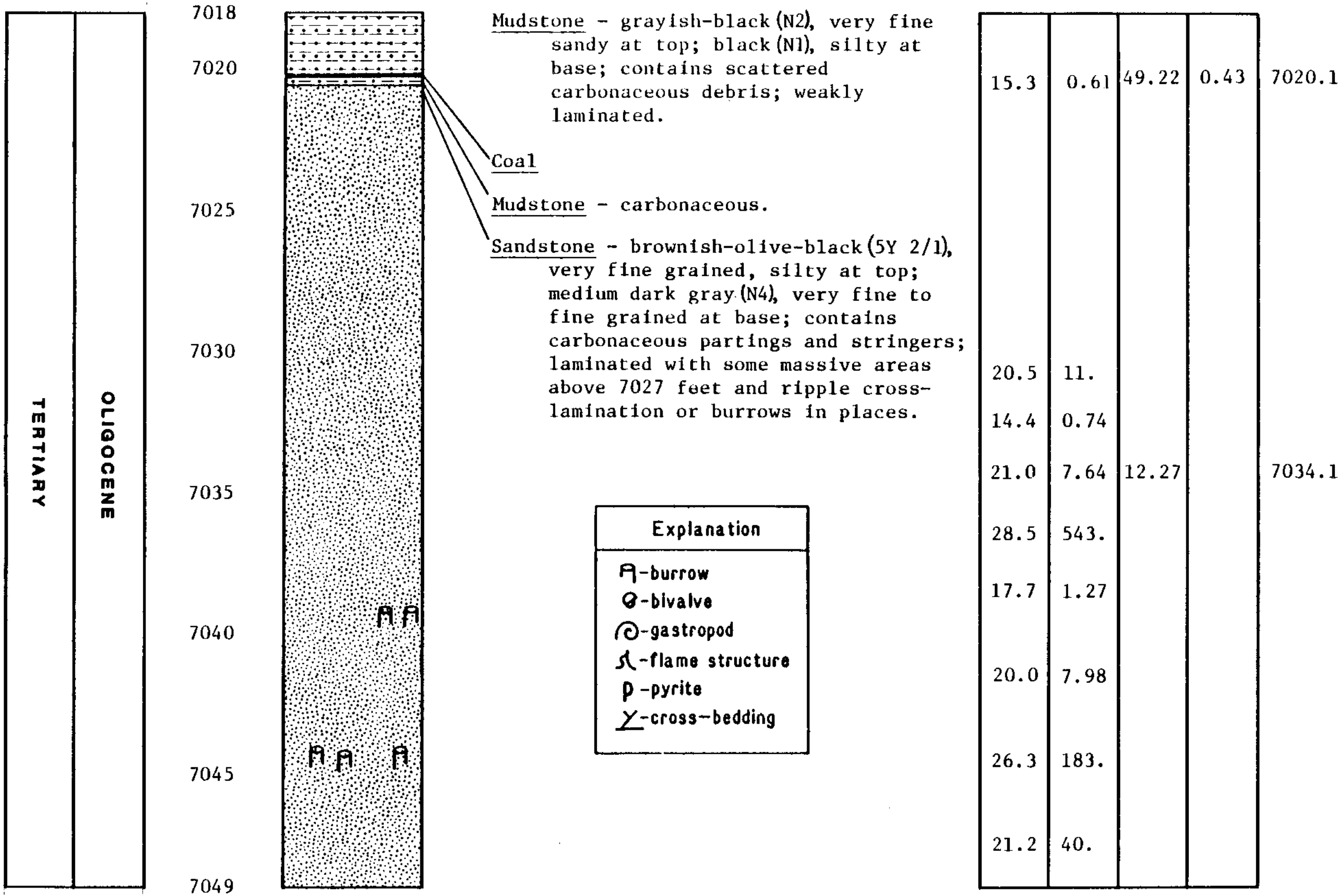
Coal is present in small but significant amounts in some of the cuttings sampled from this interval. This coal is interpreted as representing thin beds scattered through the interval.

The SP curve is relatively flat with some blocky excursions that are interpreted to be sandstone beds. There is a 200-foot total thickness of sandstone in beds 5 to 65 feet thick defined by the SP log in this interval, but the presence of sandstone in conventional and sidewall cores where there is no such SP deflection indicates that the interval contains more sandstone than the SP log suggests. The gamma-ray curve is flat and lacks interpretable character over this interval. The resistivity log is blocky, and there is generally no separation between shallow and deep resistivity values except in a 65-foot-thick sandstone bed (5710-5775 feet) where there is a separation of about 1.5 ohm-m. The density log indicates densities of from 2.1 to 2.25 g/cm^3. Density-derived sandstone porosities range from 25 to 32 percent. Interval transit times as recorded on the sonic log are generally between 150 and 105 ms/foot, and the sonic log, when corrected for undercompaction, indicates sandstone porosities ranging from 26 to 30 percent.

The presence of marine fossils, glauconite, and thin coal beds in this interval indicates deposition in a mixture of marine, fluvial, or deltaic environments.

6000-8425 feet

The interval from 6000 to 8425 feet is characterized by interbedded mudstone, siltstone, sandstone, and coal. Conventional cores 3 and 4 are from this interval and are described in figures 23 and 24. The mudstone and siltstone are generally laminated, carbonaceous, and are locally sandy. The sandstones are generally poorly sorted with very fine- to medium-size clasts of quartz, feldspar, and rock fragments in a detrital matrix. Both monocrystalline and polycrystalline quartz clasts are present, and potassium feldspar and plagioclase are present in subequal amounts. Rock fragments are almost entirely schistose, but a few volcanic and sedimentary rock fragments are also present. The sandstone is commonly laminated or cross-laminated, and shale partings and graded bedding were observed in the conventional cores from this interval. Burrows are present locally in both sandstone and mudstone. The sandstone has been affected by ductile grain deformation, and where there is no matrix, authigenic kaolinite, siderite, ankerite, or syntaxial quartz are present as cements. Pyrite framboids are also common, but pyrite cement was not observed. Porosity ranges from 10.1 to 31.2 percent and permeability from 0.22 to 543 mD in 37 sidewall and conventional core samples of sandstone from this interval. Most permeability values from conventional core samples are less than 10 mD. Three samples from core 3 are better sorted than the other samples and have permeabilities of 40, 183, and 543 mD.



Mudstone - grayish-black (N2), very fine sandy at top; black (N1), silty at base; contains scattered carbonaceous debris; weakly laminated.

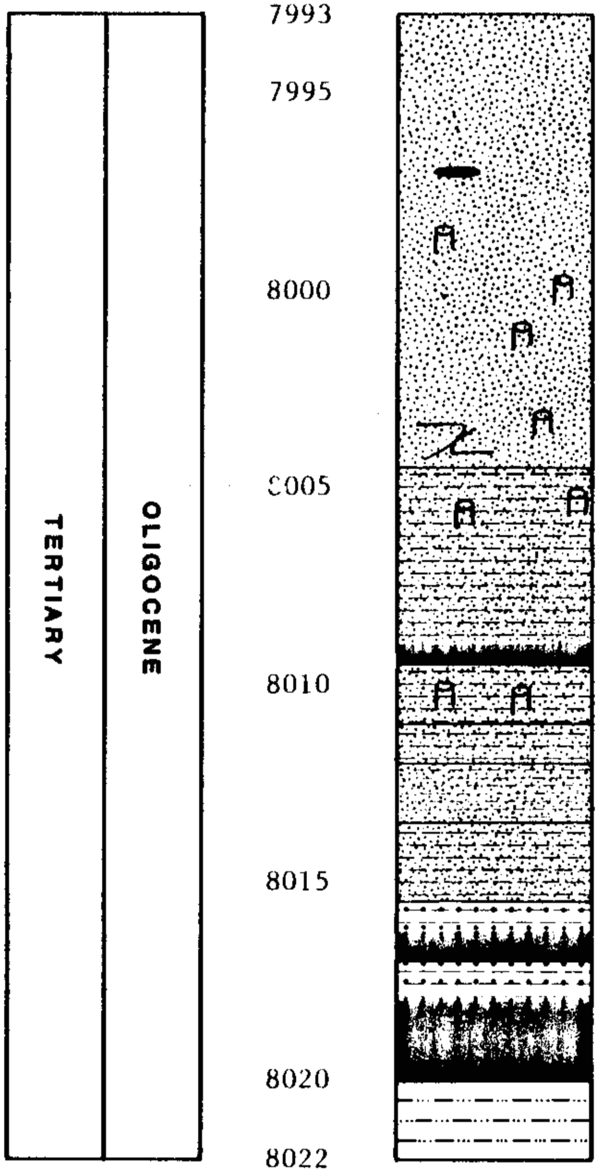
Coal

Mudstone - carbonaceous.

Sandstone - brownish-olive-black (5Y 2/1), very fine grained, silty at top; medium dark gray (N4), very fine to fine grained at base; contains carbonaceous partings and stringers; laminated with some massive areas above 7027 feet and ripple cross-lamination or burrows in places.

Porosity (Percent)	Permeability (Millidarcies)	T.O.C. (%)	Ro (%)	
15.3	0.61	49.22	0.43	7020.1
20.5	11.			
14.4	0.74			
21.0	7.64	12.27		7034.1
28.5	543.			
17.7	1.27			
20.0	7.98			
26.3	183.			
21.2	40.			

Figure 23. Description of conventional core 3, Norton Sound COST No. 2 well (Porosity Permeability, and geochemical data from Core Laboratories, Inc.)



Sandstone - grayish-black (N2), very fine grained, silty near top, thinly laminated with coaly lenses and carbonaceous stringers, burrowed in places; a small, open, asymmetrical fold with axial plane shear is located near the base of this bed.

Sandstone and mudstone - sandstone, light-olive-gray (5Y 5/2), fine- to medium-grained, grades upward to mudstone, black (N1), mottled, burrowed.

Sandstone and mudstone - sandstone, grayish-black (N2), very fine grained, grades upward to mudstone, black (N1).

Coal

Sandstone and mudstone - sandstone, brownish-gray (5 YR 4/1), very fine grained, burrowed, cut by quartz veins, grades upward to mudstone, black (N1).

Sandstone and mudstone - two graded beds.

Sandstone - medium-olive-gray (5Y 5/1), very fine grained, laminated and cross-laminated with carbonaceous shale partings.

Sandstone and mudstone - five graded beds.

Mudstone - grayish-black (N2), carbonaceous, laminated.

Coal

Mudstone - grayish-black (N2), carbonaceous, laminated.

Coal

Siltstone - grayish-black (N2), very fine sandy, carbonaceous, weakly laminated.

Porosity (Percent)	Permeability (Millidarcies)	T.O.C. (%)	Ro (%)	
7.3	0.01			
		6.04		7997.6
11.4	0.22			
10.1	0.67			
		15.26		8007.4
11.6	0.16			
		61.47	0.5	8016.5

Figure 24. Description of conventional core 4, Norton Sound COST No. 2 well. (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)

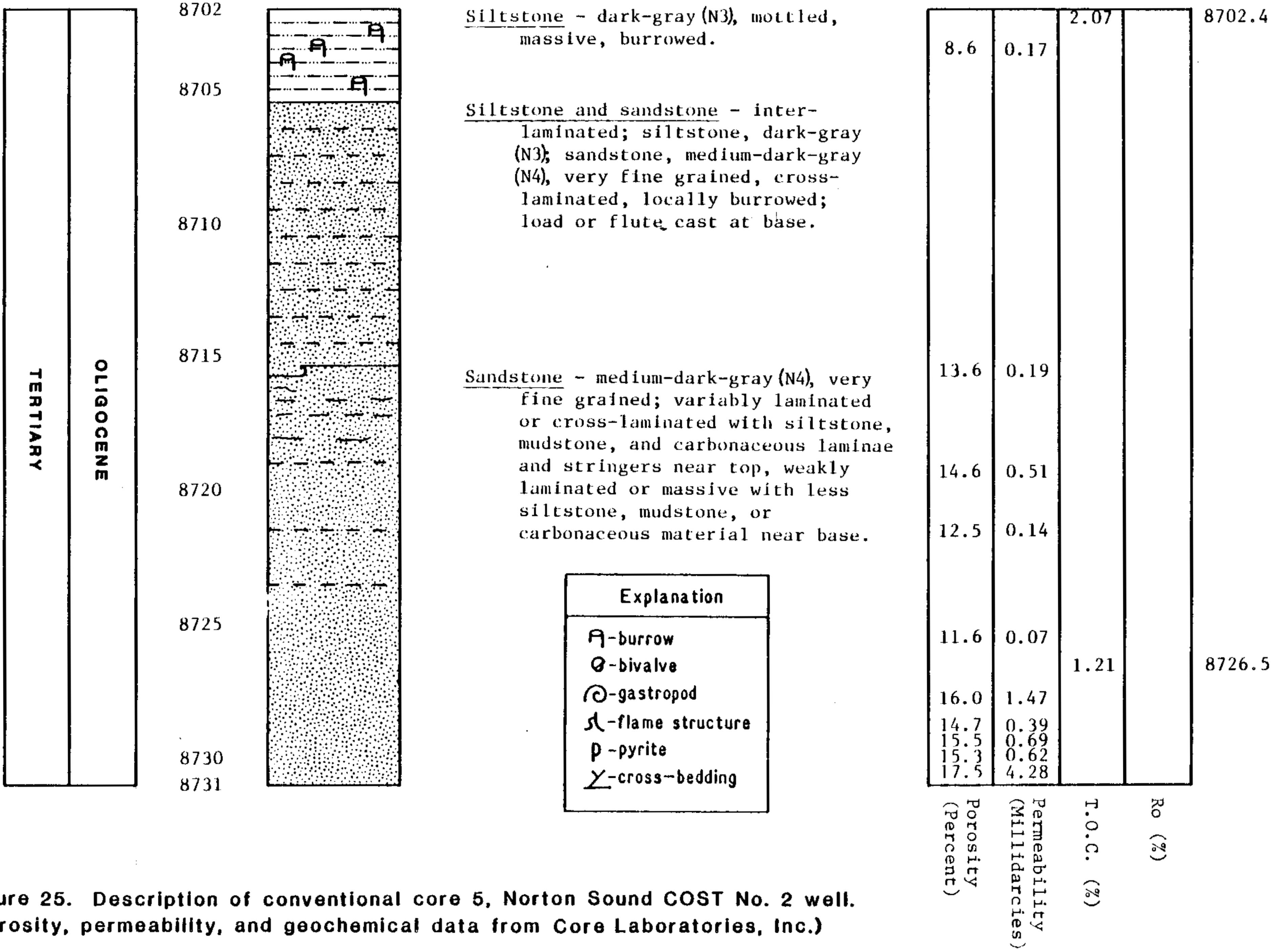
The high permeabilties that characterize most of the sidewall core samples from this interval probably resulted at least in part from fabric disruption attendant on sampling.

The SP curve has a blocky character consistent with interbedded finer- and coarser-grained lithologies. A total of 560 feet of sandstone in 5- to 50-foot beds can be recognized on the SP log. The gamma-ray curve is rather flat in the upper part of this interval but becomes quite erratic below 6700 feet. The gamma-ray log is not easily interpreted through this interval, with the exception of kicks to low values that probably correspond to coal beds. The resistivity is similar in this interval to the interval above but has numerous sharp kicks to higher values indicative of coal beds. There is also a gradual increase in resistivity downward through this interval, and separations between shallow and deep resistivity values of 2 to 4 ohm-m are common for sandstone beds. The density log indicates a gradual increase of density with densities generally from 2.2 to 2.5 g/cm^3. Numerous sharp kicks to lower values correlate with coal beds. The density log indicates porosities of from 12 to 35 percent for sandstone in this interval. The sonic log shows a general decrease in interval transit time through this interval, with values generally between 110 and 85 μs/foot. Kicks to lower interval transit times correlate with coal beds. The sonic log, when corrected for undercompaction, indicates porosities of from 9 to 29 percent for sandstone in this interval.

Marine fossils have been recovered from this interval (see Paleontology and Biostratigraphy section of this report), but the association of coal with sandstone and mudstone seen in cores and suggested by geophysical log interpretation indicates deposition in fluvial or deltaic environment. The interval as a whole was probably deposited in a transitional environment where marine and nonmarine conditions alternated. Only a few thin coal beds are present in the upper part of the interval; it is likely that more of the rock in the upper part of the interval was deposited in a marine environment than was the case in the more coaly, lower part of the section.

8425-9230 feet

The interval from 8425 to 9230 feet consists of siltstone and mudstone with minor sandstone. Conventional core 5 is from this interval and is described in figure 25. Lithologies are similar to those of the interval above except that volcanic rock fragments predominate among the lithic sand clasts. Two sidewall core sandstone samples had 23.4 percent porosity and permeabilities of 16 and 40 mD. Ten sandstone samples from core 5 had porosities from 8.5 to 17.5 percent and permeabilities from 0.07 to 4.28 mD. The higher porosities of the sidewall core samples may be real, but the higher permeabilities are probably due to fabric disruption in sampling.



Siltstone - dark-gray (N3), mottled, massive, burrowed.

Siltstone and sandstone - interlaminated; siltstone, dark-gray (N3); sandstone, medium-dark-gray (N4), very fine grained, cross-laminated, locally burrowed; load or flute cast at base.

Sandstone - medium-dark-gray (N4), very fine grained; variably laminated or cross-laminated with siltstone, mudstone, and carbonaceous laminae and stringers near top, weakly laminated or massive with less siltstone, mudstone, or carbonaceous material near base.

Porosity (Percent)	Permeability (Millidarcies)	T.O.C. (%)	Ro (%)	
		2.07		8702.4
8.6	0.17			
13.6	0.19			
14.6	0.51			
12.5	0.14			
11.6	0.07			
		1.21		8726.5
16.0	1.47			
14.7	0.39			
15.5	0.69			
15.3	0.62			
17.5	4.28			

Figure 25. Description of conventional core 5, Norton Sound COST No. 2 well. (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)

The SP curve through this interval is smooth and straight with a few gentle undulations. The lower value undulations appear to mark the locations of the sandier parts of the stratigraphic section. The gamma-ray log curve generally follows the SP log curve, but is jagged rather than smooth and displays several sharp kicks that correlate with coal beds. The resistivity curve is smooth and gently undulating except where several sharp kicks indicate coal beds. There is little or no difference between the shallowest and deepest measured resistivity values in this interval. The density and sonic log curves are relatively smooth with some sharp kicks indicative of coal beds and hard streaks. The density log indicates densities generally in the range from 1.9 to 2 g/cm^3. The sonic log indicates general interval transit times of from 85 to 90 µs/foot.

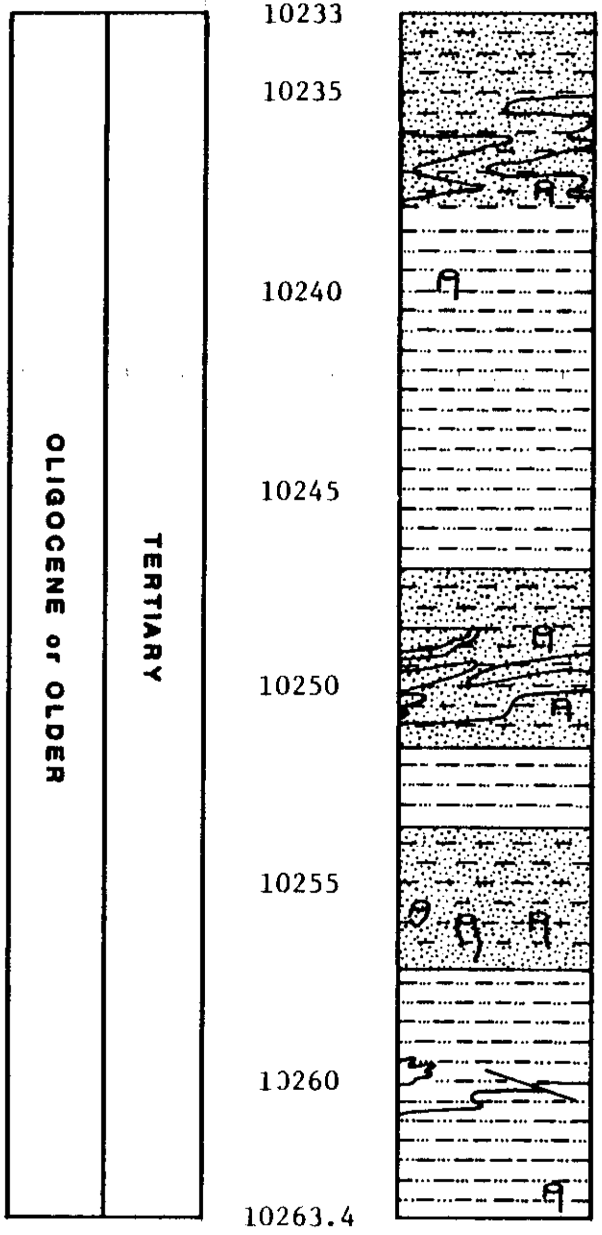
This interval contains marine fossils (see Paleontology and Biostratigraphy section of this report). There is less sandstone and coal than the interval above, and deposition was probably largely in a marine environment characterized by shifts to fluvial or deltaic conditions.

9230-11,958 feet

The interval from 9230 to 11,958 feet is characterized by interbedded siltstone, sandstone, mudstone, and shale. Conventional cores 6, 7, and 8 are from this interval and are described in Figures 26, 27, and 28. The mudstone is commmonly laminated or interlaminated with siltstone, and some is sandy or micaceous. The sandstone is composed of very fine quartz, feldspar, and lithic clasts in a detrital matrix. Both monocrystalline and polycrystalline quartz clasts are present. Rock fragments are predominantly volcanic, but there are significant metamorphic and sedimentary contributions in samples from core 6 in the upper part of the interval. Schistose metamorphic rock fragments predominate the lithic fraction in the two deeper cores. The feldspar is predominantly plagioclase. Local lamination, cross-lamination, burrows, and soft sediment structures were observed in the conventional cores.

A combination of ductile grain deformation and the presence of detrital matrix and authigenic cements affects porosity and permeability of sandstones in this interval. The authigenic cements include siderite, pyrite, quartz, calcite, and kaolinite. Porosities of 10 sandstone samples range from 2.9 to 25.3 percent, and permeabilities range from 0.07 to 147 mD. All porosity values above 5.9 percent and permeability values above 2.63 mD are from sidewall cores.

The SP curve is smooth through this interval. Above 10,450 feet it is straight, and below that depth it undulates gently. The gamma-ray log is jagged and does not clearly define any bedded units. The resistivity curves are moderately



Siltstone and sandstone - interlaminated; siltstone, grayish-black (N2); sandstone, medium-dark-gray (N4), very fine grained; small recumbent, isoclinal, similar folds below 10235 ft, burrows near base.

Siltstone - grayish-black (N2), muddy, contains scattered thin sandstone laminae and some burrows; numerous slickensided conjugate shear fractures indicate subhorizontal compression after lithification.

Siltstone and sandstone - interlaminated to thinly interbedded; siltstone, grayish-black (N2); sandstone, medium-dark-gray (N4), very fine grained; contains asymmetrical and isoclinal, recumbent folds, some burrows.

Siltstone - grayish-black (N2), muddy.

Siltstone and sandstone - interlaminated to thinly interbedded; siltstone, grayish-black (N2); sandstone, medium-dark-gray (N4), very fine grained; deformed burrows below 10255.5 feet.

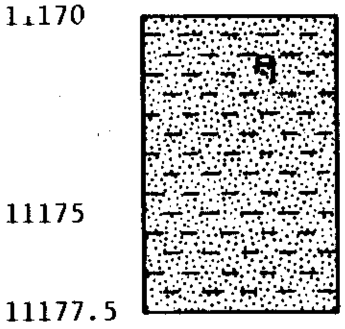
Siltstone - grayish-black (N2), muddy, contains scattered thin sandstone laminae and some burrows; contains some isoclinal, recumbent folds and slickensided fractures.

Porosity (Percent)	Permeability (Millidarcies)	T.O.C. (%)	Ro (%)	
6.3	1.59			
		1.41	0.55	10238.4
4.4	0.32			
		1.37	0.57	10259.7
3.8	0.03			

Figure 26. Description of conventional core 6, Norton Sound COST No. 2 well (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)

TERTIARY

OLIGOCENE or OLDER



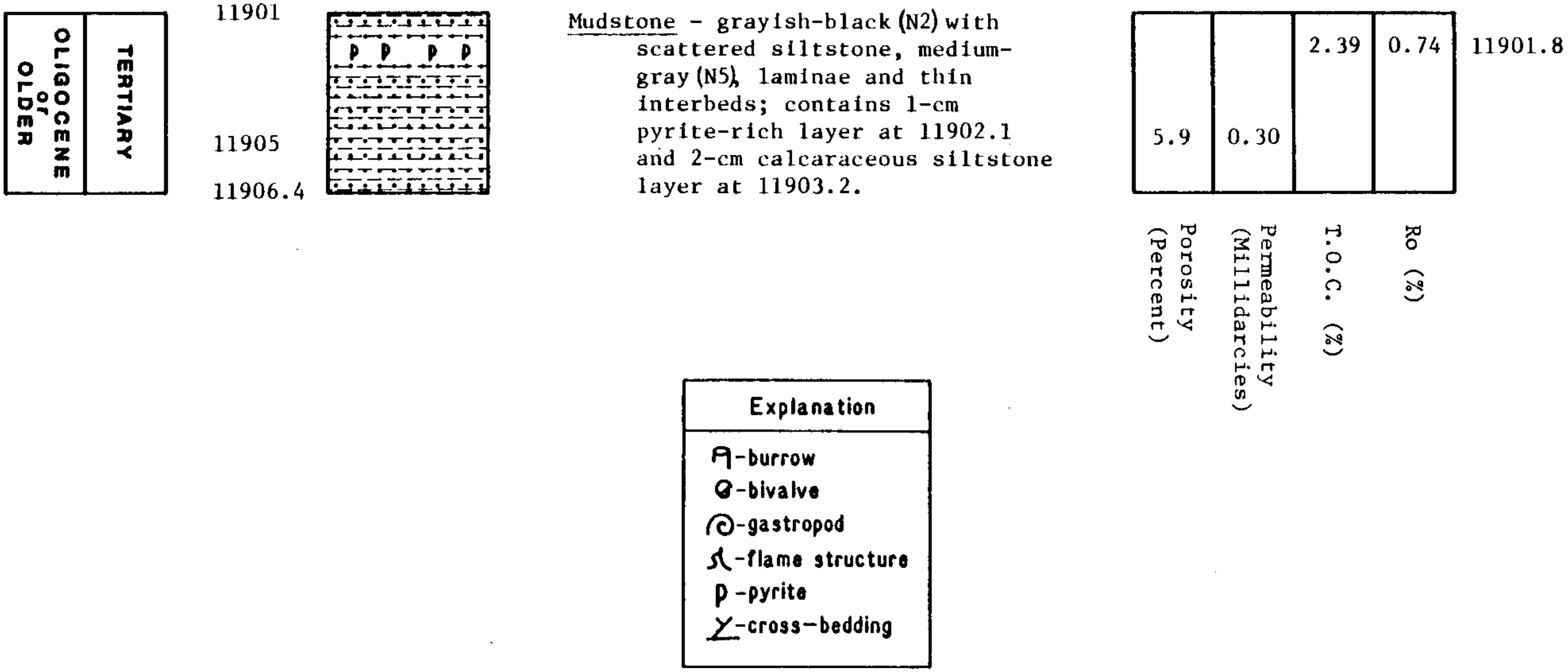
Siltstone and sandstone - normally graded beds 4 to 30 cm thick; siltstone grayish black (N2), muddy, weakly laminated to massive; sandstone, medium-brownish-gray (5 YR 5/1), very fine grained, laminated to cross-laminated in beds to 2 cm thick; unit contains some burrows.

Porosity (Percent)	Permeability (Millidarcies)	T.O.C. (%)	Ro (%)	
3.4	2.63	1.63	0.62	11170.3
3.0	0.02			
3.7	0.07			
3.1	215.(F)			
2.9	0.22			

Explanation

- ꟻ-burrow
- Q-bivalve
- ⓒ-gastropod
- ʎ-flame structure
- p-pyrite
- Y-cross-bedding

Figure 27. Description of conventional core 7, Norton Sound COST No. 2 well (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)



Mudstone - grayish-black (N2) with scattered siltstone, medium-gray (N5), laminae and thin interbeds; contains 1-cm pyrite-rich layer at 11902.1 and 2-cm calcaraceous siltstone layer at 11903.2.

Figure 28. Description of conventional core 8, Norton Sound COST No. 2 well (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)

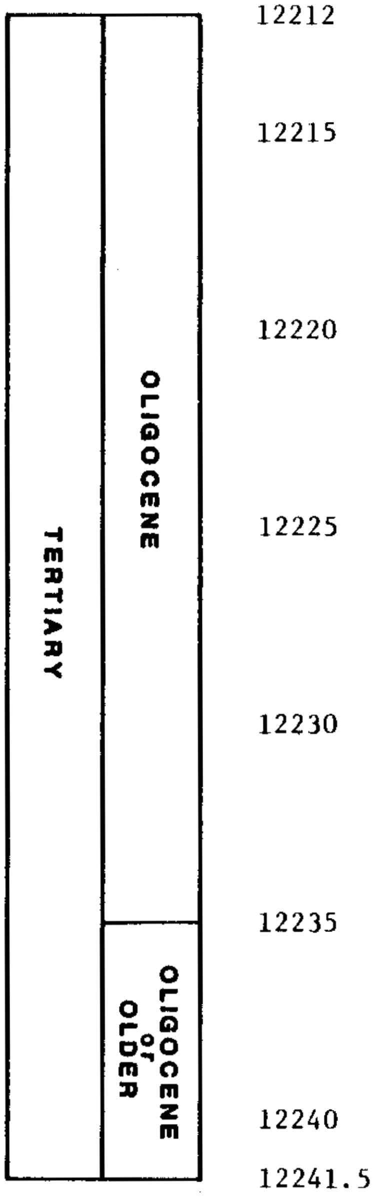
smooth to locally blocky and display a difference of about 2 ohm-m common between the deep and shallow values.

The density log curve is quite jagged in the upper part of this interval, where caving has produced an irregular hole. Average density values range from 2.4 to 2.65 g/cm^3, with a general increase downward. Below 10,650 feet, hole conditions were better and the density log is less variable. Average densities range from 2.65 to 2.7 g/cm^3 in the lower part of the interval. The sonic log curve is jagged within generally narrow limits in this interval. Average interval transit times range from 98 to 80 μs/foot.

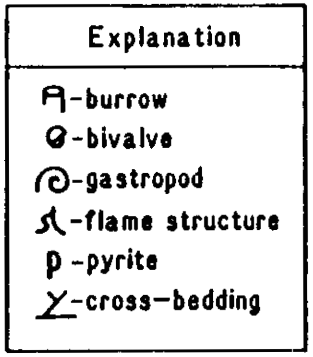
The rocks of this interval were deposited in a marine shelf environment. Sedimentation was rapid locally, as indicated by the common soft sediment structures in core 6.

11,958-12,378 feet

The interval from 11,958 to 12,378 feet is characterized by sandstone with lesser amounts of siltstone, mudstone, conglomerate, and coal. Conventional core 9 is from this interval and is described in Figure 29.



Sandstone - dark-olive-gray (5Y 3/1), very fine to fine grained, slightly calcareous locally, massive; small coal chips in top 2 feet dip 40°; subangular to rounded shale cips and pebbles common from 12215.5 to 12223 feet, thence sparse to base of core; a 3-cm layer with abundant granule-size, light colored, aphanitic volcanic rock fragments crosses the core at 12223.3 feet; similar volcanic rock fragments in coarse sand to pebble size appear again at 12224.4 feet and increase in abundance downward to constitute almost clast-supported conglomerate at base; sand grade increases gradually to fine at base of core.



Porosity (Percent)	Permeability (Millidarcies)	T.O.C. (%)	Ro (%)	
12.2	0.02			
9.3	0.06	3.66	1.09	12212.9
11.7				
24.9	0.02			
12.2				
9.3	0.06			
7.2	0.03			
7.2	0.08			
8.9	0.02			

Figure 29. Description of conventional core 9, Norton Sound COST No. 2 well (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)

The sandstone is poorly sorted and consists of very fine to medium quartz, plagioclase, and lithic clasts in an abundant detrital matrix. Angular to subangular volcanic granules and pebbles are scattered in the sandstone, and locally volcanic pebbles are so abundant as to make conglomerate. Subangular to rounded shale granules and pebbles are also present in the sandstone. Quartz sand clasts are both monocrystalline and polycrystalline, and volcanic rock fragments and shale dominate the lithic sand-grain component. Coal is present below 12,190 feet.

Porosities of 8 sandstone samples from core 9 range from 7.2 to 12.2 percent, and permeabilities range from 0.02 to 0.08 mD. Porosity and permeability are adversely affected in the sandstone by ductile grain deformation and the presence of abundant detrital matrix and authigenic siderite, pyrite, quartz, smectitic clay, chlorite, and calcite cements. Authigenic calcite is more commonly present as a replacement of volcanic rock fragments than as cement.

The SP curve undulates smoothly through this interval and cannot be meaningfully interpreted. This is probably a result of low permeability contrasts between the various lithologies. The gamma-ray log defines three major blocky units with a total thickness of 390 feet. Conventional core 9 is from the middle of the lowest of these units, and all three units are interpreted to be sandstone and conglomerate similar to that seen in core 9. The resistivity retains the finely jagged character it displayed in the interval above, but is more blocky in overall aspect. Deep and shallow resistivity values are commonly 2 to 5 ohm-m apart. The density log curve is generally smooth through this interval except for large kicks in areas of caving. Densities range generally from 2.45 to 2.65 g/cm^3, and the density log indicates porosities from 0 to 8 percent for sandstone in the interval. The sonic log curve is jagged through this interval, but the average interval transit times range only from 80 to 70 µs/foot. Porosities as indicated by the sonic log range from 11 to 18 percent.

The large scale cross-bedding, poor sorting, and coarse grain size of the sandstone seen in the core from this coal-bearing interval suggest that the rocks of this interval were deposited in a braided stream channel.

12,378-12,700 feet

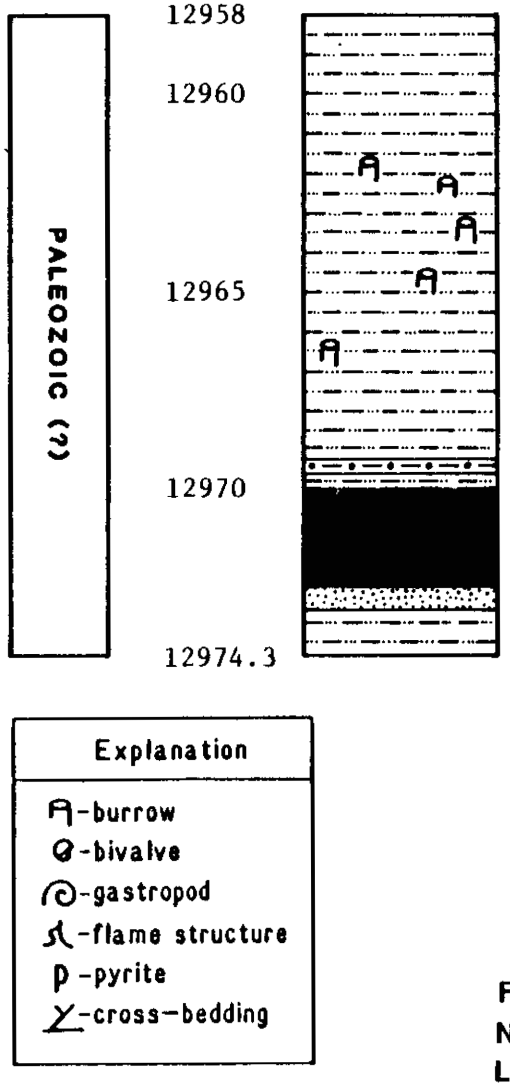
The interval from 12,378 to 12,700 feet is characterized by interbedded siltstone, mudstone, sandstone, and minor amounts of coal. No sidewall or conventional cores were taken from this interval, and the lithologies are known only from cuttings and the interpretation of geophysical logs.

The SP curve continues through this interval with the same smooth, undulating character displayed in the interval above. The gamma-ray log curve is jagged and does not clearly define any bedded units. The resistivity curves are moderately smooth with a general difference of 2 to 5 ohm-m between deep and shallow values. A few sharp kicks to lower resistivities, accompanied by the loss of deep and shallow separation, yield a weak blocky character. Densities generally range from 2.7 to 2.75 g/cm^3 in this interval. The greater variability present in the upper part of the interval appears to be related to minor caving. The sonic log is more variable in the upper part of the interval than in the lower, and indicates generally lower interval transit times in the upper part than in the lower. An examination of the cuttings indicated the presence of more sandstone above 12,500 feet than below that depth, and the change in sonic velocity probably reflects this lithologic difference. Average interval transit time above 12,500 feet is 80 μs/foot, and below 12,500 feet the average interval transit time is 87 μs/foot.

The presence of coal indicates deposition in a nonmarine environment.

12,700-14,460 feet

The interval from 12,700 to 14,460 feet is characterized by interbedded sandstone, siltstone, mudstone, and coal. Conventional cores 10 and 11 are from this interval and are described in Figures 30 and 31. The sandstone is composed of angular to subrounded, fine- to coarse-grained quartz and lithic clasts in an abundant detrital matrix. The quartz clasts are predominantly monocrystalline, and the lithic fraction consists predominantly of schistose metamorphic rock fragments (core 11) of subequal amounts of volcanic and metamorphic rock fragments (core 10). The sandstone is locally laminated or cross-laminated and contains abundant carbonaceous debris and partings. Burrows are present in a siltstone bed in core 10. Open intergranular space between the framework clasts was reduced



<u>Siltstone</u> - grayish-black (N2) laminated, some burrows; 15° apparent dip.

<u>Mudstone</u> - brownish-black (5 YR 2/1)

<u>Siltstone</u> - grayish-black (N2) laminated.

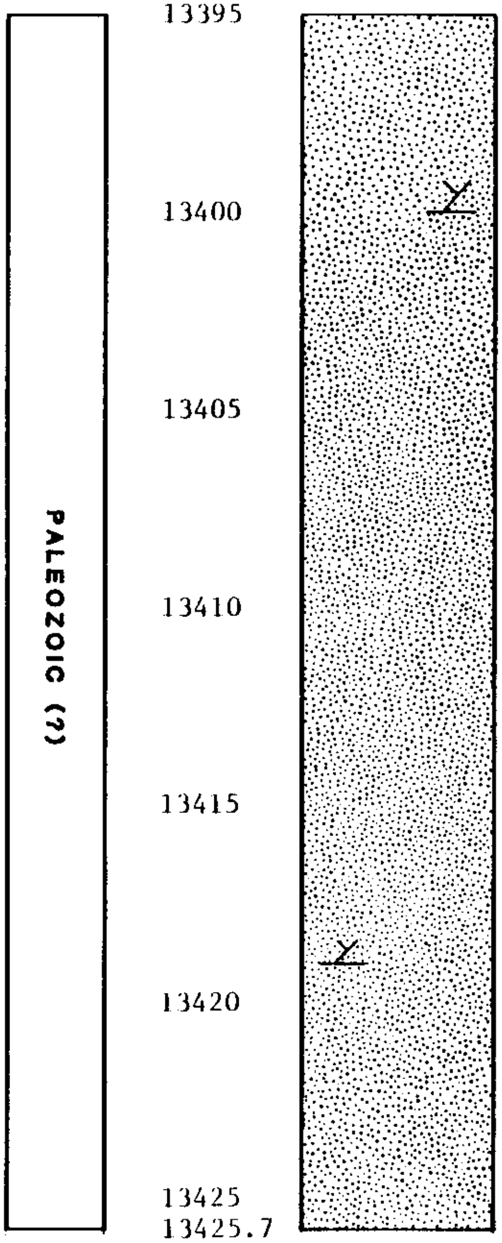
<u>Coal</u>

<u>Sandstone</u> - dark-olive gray (5Y 3/1) fine to medium grained; contains 2-cm coal seam 3 inches above base.

<u>Siltstone</u> - grayish-black (N2) laminated.

Porosity (Percent)	Permeability (Millidarcies)	T.O.C. (%)	Ro (%)	
3.8	0.02			
		2.41	1.18	12962.3
3.8	0.10			
3.9	0.03			
7.5	0.24			
		1.38	1.29	12973.6

Figure 30. Description of conventional core 10, Norton Sound COST No.2 well (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)



<u>Sandstone</u> - brownish-gray (5 YR 4/1), medium to coarse grained, scattered shale partings, generally massive with scattered laminated and cross-laminated zones.

Explanation

- ꟼ-burrow
- ɵ-bivalve
- @-gastropod
- ⅄-flame structure
- p-pyrite
- ⅄-cross-bedding

Porosity (Percent)	Permeability (Millidarcies)	T.O.C. (%)	Ro (%)	
11.2	0.14			
11.3	0.30			
11.7	0.23			
12.6	0.21			
6.8	0.17			
10.9	0.14			
11.1	0.14			
5.9	0.02			
12.0	0.32			
10.3	0.29			
		5.17	1.23	13404.9
11.1	3.47			
11.8	0.16			
11.4	0.43			
7.5	0.09			
12.1	0.23			
8.4	0.11			
12.3	0.23			
10.7	0.21			
12.5	0.18			
9.4	2.43			
11.1	0.14			
9.7	0.14			
8.1	0.12			
12.8	0.37			
9.6	0.15			
10.6	0.96			
11.9	0.14			
7.1	0.05			
10.1	0.15			
11.7	0.11			
10.4	0.11			

Figure 31. Description of conventional core II, Norton Sound COST No. 2 well (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)

by deformation of ductile framework clasts and the presence of detrital matrix and authigenic siderite, ankerite, smectitic clay, and chlorite cements. In 35 conventional and 7 sidewall cores of sandstones the porosities range from 3.8 to 26.2 percent and permeabilities from 0.02 to 119 mD. The highest porosity from a conventional core is 12.8 percent, however, and the highest permeability from a conventional core is 3.47 mD.

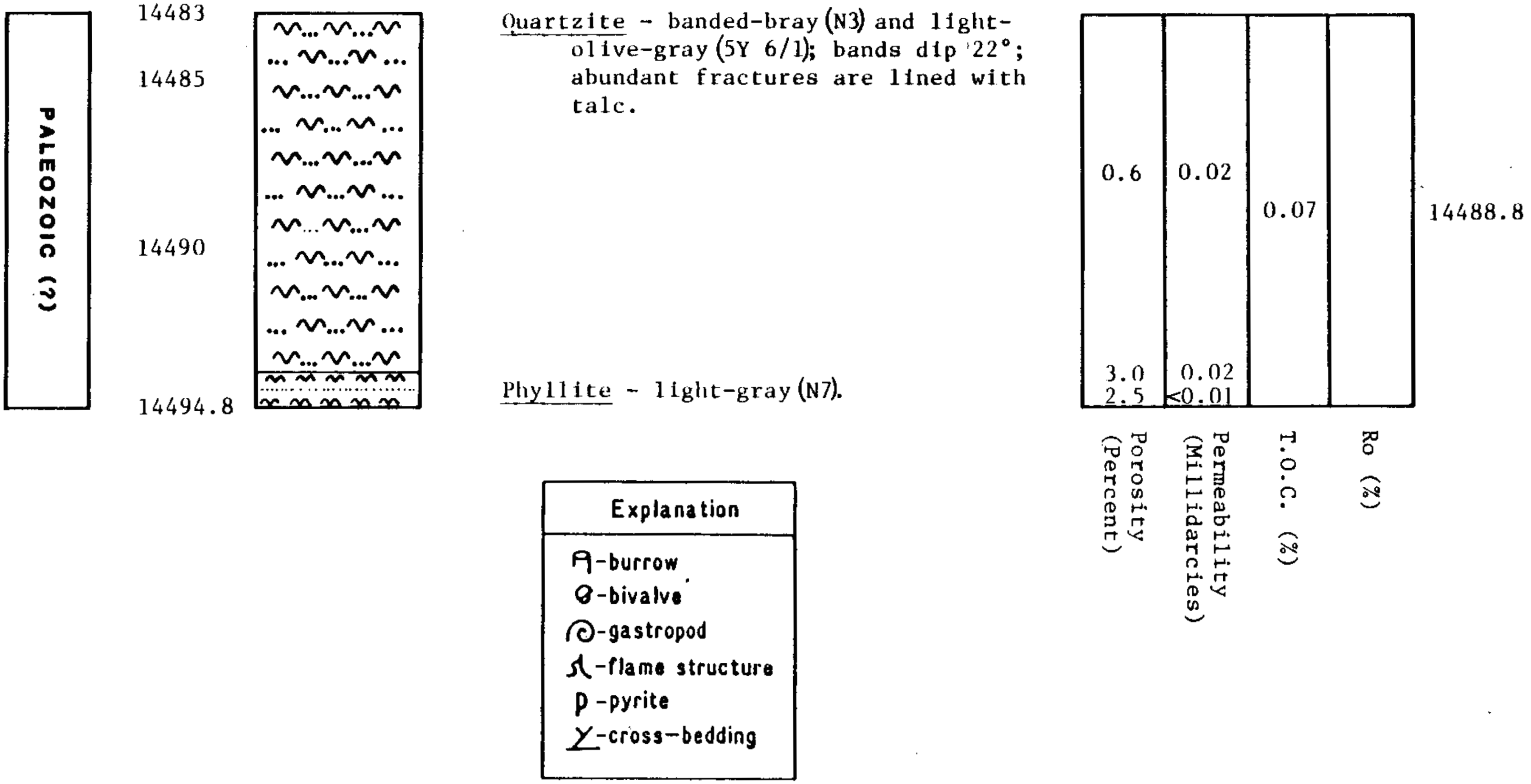
The SP curve wanders erratically and cannot be meaningfully interpreted. The gamma-ray log curve displays a blocky character indicative of sandstone beds to 60 feet thick and coal beds to 20 feet thick. With the exception of many extreme kicks correlative with coal beds, the resistivity log curve is relatively smooth. Separation of deep and shallow resistivity values of 2 to 5 ohm-m are general except in coal beds. Both the density and sonic log curves have many large kicks correlative with coal beds in this interval. Except for the extreme values of such kicks, densities generally range from 2.5 to 2.8 g/cm^3, and interval transit times from 82 to 70 μs/foot. Density-derived sandstone porosities range from 0 to 15 percent, and the sonic log indicates sandstone porosities from 7 to 11 percent.

The association of coal, sandstone, and mudstone in this interval indicates deposition in a fluvial or deltaic environment. The great abundance of coal throughout the interval makes it unlikely there was any marine deposition.

14,460-14,889 feet

The bottommost interval of the well, from 14,460 to 14,889 feet, is characterized by low grade dynamothermal metamorphic rocks. Conventional cores 12 and 13 are from this interval and are described in figures 32 and 33. Lithologies present include quartzite, marble, siliceous marble, and phyllite. The quartzite and marble have mosaic fabrics and the phyllite is foliated. Quartzite layers with mosaic structure alternate with schistose white mica layers. The quartzite is banded, and the banding has been isoclinally folded. Marble is locally foliated in the cores. The quartzite and phyllite of core 12 have measured porosities of 0.6 to 3.0 percent and permeabilities of 0.01 to 0.02 mD.

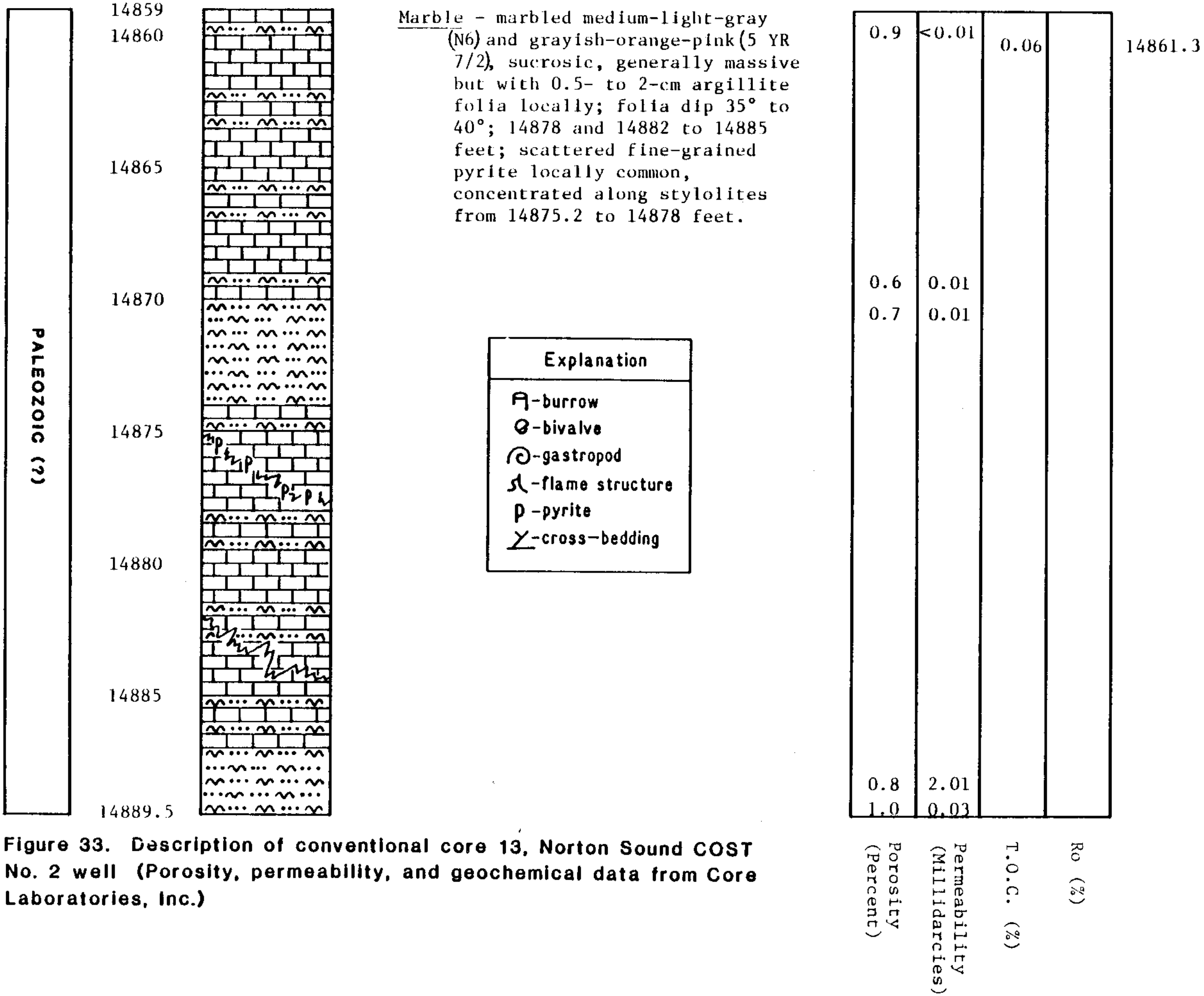
The SP curve wanders and cannot be meaningfully interpreted. The gamma-ray curve is jagged above 14,680 feet but relatively smooth below this depth. There is a sudden decrease in the average gamma-ray value of about 45 API units at 14,680 feet. These changes in the character of the gamma-ray log curve probably reflect a change from quartzite to marble. There is a sharp increase in resistivity at the top of this interval. The resistivity curve is largely off scale below 14,640 feet, and the absence of any general increase in resistivity above that depth indicates the resistivity increase is sudden. The resistivity log is quite jagged where it is on scale. The density and sonic logs are moderately smooth. The density log indicates densities generally from 2.75 to 2.8 g/cm^3 above 14,680 feet and of about 2.72 g/cm^3 below that depth. Interval transit times generally range from 60 to 55 μs/foot above 14,680 feet and stay right at 50 us/foot below that depth.



Quartzite - banded-bray (N3) and light-olive-gray (5Y 6/1); bands dip 22°; abundant fractures are lined with talc.

Phyllite - light-gray (N7).

Figure 32. Description of conventional core 12, Norton Sound COST No. 2 well (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)



Marble - marbled medium-light-gray (N6) and grayish-orange-pink (5 YR 7/2), sucrosic, generally massive but with 0.5- to 2-cm argillite folia locally; folia dip 35° to 40°; 14878 and 14882 to 14885 feet; scattered fine-grained pyrite locally common, concentrated along stylolites from 14875.2 to 14878 feet.

Figure 33. Description of conventional core 13, Norton Sound COST No. 2 well (Porosity, permeability, and geochemical data from Core Laboratories, Inc.)

Porosity and Permeability

Porosity and permeability determinations for samples from sidewall and conventional cores in the well are presented in Table 1. Sidewall core porosities are generally higher than nearby conventional core porosities, and this disparity increases with depth. Also, sidewall core samples display higher permeabilities than do conventional core samples of similar porosity. Figure 34 presents a plot of average porosity against depth for sandstone samples from conventional cores. Figure 35 presents a plot of average permeability against average porosity for the same samples. There is considerable scatter in the data. However it can be seen that to have 1 mD permeability a sandstone must have at least 13 percent porosity and that all conventional core sandstone samples with 13 percent or more porosity are from depths shallower than 9000 feet. Porosity and permeability data from sandstone samples are also presented graphically in Plate 1. Because of irregular sample distribution, porosity and permeability values have been integrated over a 500-foot thickness and are represented by symbols that show the mean values and range for each such interval. The number of sandstone samples in each interval is given under the applicable symbol.

Table 1. POROSITY AND PERMEABILITY
Norton 2
[from Core Laboratories, Inc.]

Depth (feet)	Lithology	Porosity (Percent)	Permeability (Millidarcies)	Remarks
1331.0	sltst;sdy	31.2	1.47	Sidewall
1390.0	same	33.8	15.	Sidewall
1548.0	volcanic ash?	42.6	2.24	Sidewall
1594.0	same	41.2	9.12	Sidewall
1863.0	same	44.4	9.49	Sidewall
1948.0	same	50.0	--	Sidewall
2155.0	same;sdy	46.7	21.	Sidewall
2228.0	same;sdy	44.9	58.	Sidewall
2380.0	same	46.4	4.04	Sidewall
2528.0	same	49.4	3.32	Sidewall
2872.0	same	53.6	2.93	Sidewall
2920.0	same	51.0	1.06	Sidewall
3158.0	same	47.7	6.41	Sidewall
3254.0	same	45.7	1.99	Sidewall
3344.0	same	41.9	5.88	Sidewall
3390.0	same	47.1	7.66	Sidewall
3420.0	same;shy	40.5	18.	Sidewall
3482.0	sltst;sdy,ash?	35.5	6.72	Sidewall
3514.0	sltst	28.5	1.79	Sidewall
3601.0	ss;vf-fgr,vslty	31.1	47.	Sidewall
3679.0	coal	32.0	19.	Sidewall
3718.0	ss;f-cgr,slty	26.1	218.	Sidewall
3724.0	same	27.2	114.	Sidewall
3751.0	coal	38.0	--	Sidewall
3870.0	ss;f-mgr,vslty	29.5	46.	Sidewall
3900.0	ss;f-cgr,sl slty	33.7	976.	Sidewall
4053.0	ss;f-mgr,vshy	26.2	88.	Sidewall
4122.0	sltst;sdy	29.8	2.22	Sidewall
4180.0	ss;vf-fgr,vslty	30.1	11.	Sidewall
4214.0	sltst;ss lam	27.6	0.62	Sidewall
4285.0	ss;f-cgr,slty	28.1	162.	Sidewall
4378.0	ss;vf-fgr,slty	29.5	9.89	Sidewall
4510.0	sltst;sl sdy	29.1	1.16	Sidewall
4623.9	ss;vfgr	25.4	73.	Core 1;frac
4629.5	same	25.6	1.60	Core 1
4633.9	sltst;sdy,sid	16.4	0.07	Core 1
4983.0	sltst;sid	25.7	136.	frac
5082.0	same	26.9	65.	frac
5127.0	ss;vf-fgr	25.5	24.	
5323.0	same;fn carb incls	26.8	117.	

Table 1. POROSITY AND PERMEABILITY
Norton 2

Depth (feet)	Lithology	Porosity (Percent)	Permeability (Millidarcies)	Remarks
5452.0	sltst;sl sdy,sid	27.8	0.90	Sidewall
5536.0	ss;vf-mgr,mica sc carb incls	18.6	93.	Sidewall
5626.0	sltst	27.5	173.	frac
5720.0	ss;vf-fgr,mica	23.9	2.52	Sidewall
5780.0	same	23.7	17.	Sidewall
5794.5	ss;vf-mgr,sc fos	20.5	1.29	Core 2
5796.5	same	23.2	5.88	Core 2
5799.5	ss;vf-fgr,shy,mica	7.8	0.54	Core 2
5801.4	ss;vf-fgr,foss,vcalc	1.5	0.15	Core 2
5836.0	ss;vf-fgr,mica,fn carb incls	25.3	12.	Sidewall
5890.0	ss;vf-mgr,fn carb incls	27.9	115.	Sidewall
5923.0	ss;vfgr,sl shy	22.3	2.97	Sidewall
6010.0	ss;vf-fgr	28.2	123.	Sidewall
6020.0	same	30.8	33.	Sidewall
6162.0	same;sltst inbd	28.0	76.	Sidewall
6224.0	ss;vf-mgr	31.2	321.	Sidewall
6240.0	same	28.4	195.	Sidewall
6342.0	ss;vfgr	22.9	5.24	Sidewall
6370.0	ss;vf-mgr,mica	30.3	162.	Sidewall
6466.0	ss;vf-fgr,mica,carb lams	28.2	98.	Sidewall
6637.0	same	23.2	21.	Sidewall
6730.0	ss;vfgr,mica	20.2	2.56	Sidewall
6750.0	sltst	25.5	0.62	Sidewall
6792.0	ss;vfgr	23.3	16.	Sidewall
6859.0	ss;vf-fgr,mica	30.8	84.	Sidewall
6876.0	same	30.7	242.	Sidewall
6909.0	same;carb lams	22.4	61.	Sidewall
6952.0	same;carb lams	29.5	79.	Sidewall
7020.6	ss;vf-fgr,mica,fn carb incls	15.3	0.61	Core 3
7026.0	sltst;mica	20.3	0.78	Sidewall
7030.7	ss;vf-mgr,mica,fn carb lams	20.5	11.	Core 3
7032.5	ss;vf-fgr,mica,carb lams	14.4	0.74	Core 3
7034.3	ss;vf-fgr,mica	21.0	7.64	Core 3
7036.5	ss;f-mgr,mica	28.5	543.	Core 3
7038.6	ss;vf-mgr,mica,fn carb lams	17.7	1.27	Core 3

Table 1. POROSITY AND PERMEABILITY
Norton 2

Depth (feet)	Lithology	Porosity (Percent)	Permeability (Millidarcies)	Remarks
7040.0	ss;vfgr,mica,sltst inbd	22.5	23.	Sidewall
7041.3	ss;vf-mgr,mica, fn carb lams	20.0	7.98	Core 3
7044.4	ss;f-mgr,mica	26.3	183.	Core 3
7047.5	same;fn carb lams	21.2	40.	Core 3
7232.0	ss;vfgr,mica	25.3	--	
7370.0	sltst;sdy,mica	16.5	6.03	Sidewall
7448.0	ss;vf-fgr,mica	24.4	67.	Sidewall
7546.0	sh	16.0	--	Sidewall
7626.0	ss;vf-fgr,mica	24.1	42.	Sidewall
7657.0	same	26.1	173.	Sidewall
7690.0	sltst;sdy	18.1	181.	frac
7833.0	ss;vfgr,fn carb lams	22.5	22.	Sidewall
7925.0	same	18.7	117.	frac
7955.0	same	18.7	10.	Sidewall
7995.3	sltst;sdy,mica	7.3	0.01	Core 4
8000.3	ss;vf-fgr,mica	11.4	0.22	Core 4
8001.6	ss;vfgr,mica,slty,shy	10.1	0.67	Core 4
8012.5	sltst;sdy	11.6	0.16	Core 4
8072.0	ss;vfgr	23.0	12.	Sidewall
8089.0	sltst;vcarb	19.8	127.	frac
8120.0	ss;vf-fgr,mica,fn carb lams	22.9	39.	Sidewall
8245.0	same	24.0	57.	Sidewall
8264.0	sh	16.6	--	frac
8406.0	ss;vf-fgr,mica	25.8	13.	Sidewall
8703.6	ss;vfgr,carb lams	8.6	0.17	Core 5
8715.7	ss;vf-fgr,cly	13.6	0.19	Core 5
8719.3	same	14.6	0.51	Core 5
8721.4	same	12.5	0.14	Core 5
8725.5	same	11.6	0.07	Core 5
8727.6	same	16.0	1.47	Core 5
8728.8	same	14.7	0.39	Core 5
8729.4	same	15.5	0.69	Core 5
8730.3	same	15.3	0.62	Core 5
8731.3	same	17.5	4.28	Core 5
8735.0	ss;vf-fgr,mica,carb lams	23.4	40.	Sidewall

Table 1. POROSITY AND PERMEABILITY
Norton 2

Depth (feet)	Lithology	Porosity (Percent)	Permeability (Millidarcies)	Remarks
8840.0	sltst;sdy,carb lams	19.2	14.	Sidewall
9105.0	same	18.3	15.	Sidewall
9224.0	ss;vfgr,mica,carb incls	23.4	16.	Sidewall
9567.0	sh	19.9	106.	frac
10233.5	sltst;sdy	6.3	1.59	Core 6;sl frac
10250.5	same	4.4	0.32	Core 6
10263.4	same	3.8	0.03	Core 6
10811.0	ss;vfgr,vcalc	25.1	10.00	Sidewall
10904.0	ss;vfgr,sl calc	23.9	14.	Sidewall
10905.0	same	23.7	26.	Sidewall
10906.0	same	23.2	147.	Sidewall
10907.0	same	25.3	48.	Sidewall
11025.0	same;mica	18.5	17.	Sidewall
11170.5	ss;vf-fgr,mica,sh inbd	3.4	2.63	Core 7
11171.6	sltst;sdy	3.0	0.02	Core 7
11172.1	ss;vf-fgr,mica,sh inbd	3.7	0.07	Core 7
11177.7	sh	3.1	215.	Core 7;frac
11178.0	ss;vfgr,vshy	2.9	0.22	Core 7
11904.7	same	5.9	0.30	Core 8
11957.0	ss;vf-fgr,mica	21.5	--	Sidewall
11980.0	ss;vf-mgr,shy,calc	20.2	--	Sidewall
12063.0	ss;vfgr,mica,carb lams	21.4	--	Sidewall
12184.0	ss;vf-fgr,mica,calc	21.6	34.	Sidewall
12187.0	ss;vf-mgr,mica,sl calc	17.7	8.79	Sidewall
12192.0	ss;vf-fgr,mica,sl calc	20.4	32.	Sidewall
12212.2	ss;vf-fgr,mica,carb incls	12.2	0.03	Core 9
12212.2	ss;vf-mgr,mica,fn carb incls,sl calc	9.0	0.05	Core 9
12213.0	same	11.7	--	Core 9
12214.0	ss;vf-fgr,mica, sl calc	24.9	--	Sidewall
12214.6	ss;vf-mgr,mica,fn carb incls, sl calc	12.2	0.02	Core 9
12230.8	same;sc peb	9.3	0.06	Core 9
12234.4	same;sc peb	7.2	0.03	Core 9
12239.8	same;sc peb	7.2	0.08	Core 9
12241.3	same;sc peb	8.9	0.02	Core 9
12882.0	ss;vf-fgr,mica	21.3	--	Sidewall

Table 1. POROSITY AND PERMEABILITY
Norton 2

Depth (feet)	Lithology	Porosity (Percent)	Permeability (Millidarcies)	Remarks
12958.5	ss;vfgr,shy	3.8	0.02	Core 10
12963.1	same	3.8	0.10	Core 10
12964.5	same	3.9	0.03	Core 10
12972.9	ss;vf-fgr,calc	7.5	0.24	Core 10
12980.0	ss;vf-mgr,mica,sl calc	26.2	119.	Sidewall
12984.0	same	23.1	41.	Sidewall
13015.0	ss;vfgr,shy,vmica	15.6	--	Sidewall
13395.5	ss;f-mgr,mica	11.2	0.14	Core 11
13396.5	same	11.3	0.30	Core 11
13397.4	ss;f-cgr,mica	11.7	0.23	Core 11
13398.5	ss;f-mgr,mica	12.6	0.21	Core 11
13399.2	same	6.8	0.17	Core 11;FD
13400.5	same	10.9	0.14	Core 11
13401.6	same	11.1	0.14	Core 11
13402.4	same;mica	5.9	0.02	Core 11
13403.5	ss;f-cgr,mica	12.0	0.32	Core 11
13404.2	same	10.3	0.29	Core 11;FD
13405.4	same	11.1	3.47	Core 11
13406.5	same	11.8	0.16	Core 11
13407.4	same	11.4	0.43	Core 11;FD
13408.6	ss;vf-mgr,mica	7.5	0.09	Core 11
13409.5	ss;f-cgr,mica	12.1	0.23	Core 11
13410.6	same	8.4	0.11	Core 11
13411.4	same	12.3	0.23	Core 11
13412.6	same	10.7	0.21	Core 11
13413.6	same	12.5	0.18	Core 11
13414.0	same	9.4	2.43	Core 11;FD
13414.0	ss;vf-mgr,mica,sl calc	21.8	--	Sidewall
13415.4	ss;f-cgr,mica	11.1	0.14	Core 11
13416.4	same	9.7	0.14	Core 11
13417.0	same	8.1	0.12	Core 11;FD
13418.5	same	12.8	0.37	Core 11
13419.4	same	9.6	0.15	Core 11;FD
13420.4	ss;f-mgr,mica,fn carb lams	10.6	0.96	Core 11
13421.4	ss;f-mgr,mica	11.9	0.14	Core 11

Table 1. POROSITY AND PERMEABILITY
Norton 2

Depth (feet)	Lithology	Porosity (Percent)	Permeability (Millidarcies)	Remarks
13422.3	same	7.1	0.05	Core 11
13423.1	same	10.1	0.15	Core 11;FD
13424.3	same	11.7	0.11	Core 11
13425.4	same;fn carb lams	10.4	0.11	Core 11
13730.0	ss;vf-mgr,mica,sl calc	19.5	--	Sidewall
14175.0	same;fn carb lams, calc	17.2	38.	
14487.7	sltst	0.6	0.02	Core 12
14493.9	same	3.0	0.02	Core 12
14494.4	same	2.5	<0.01	Core 12
14859.7	ls	0.9	<0.01	Core 13
14869.3	same	0.6	0.01	Core 13
14871.6	same	0.7	0.01	Core 13
14888.3	same	0.8	2.01	Core 13
14889.2	same	1.0	0.03	Core 13

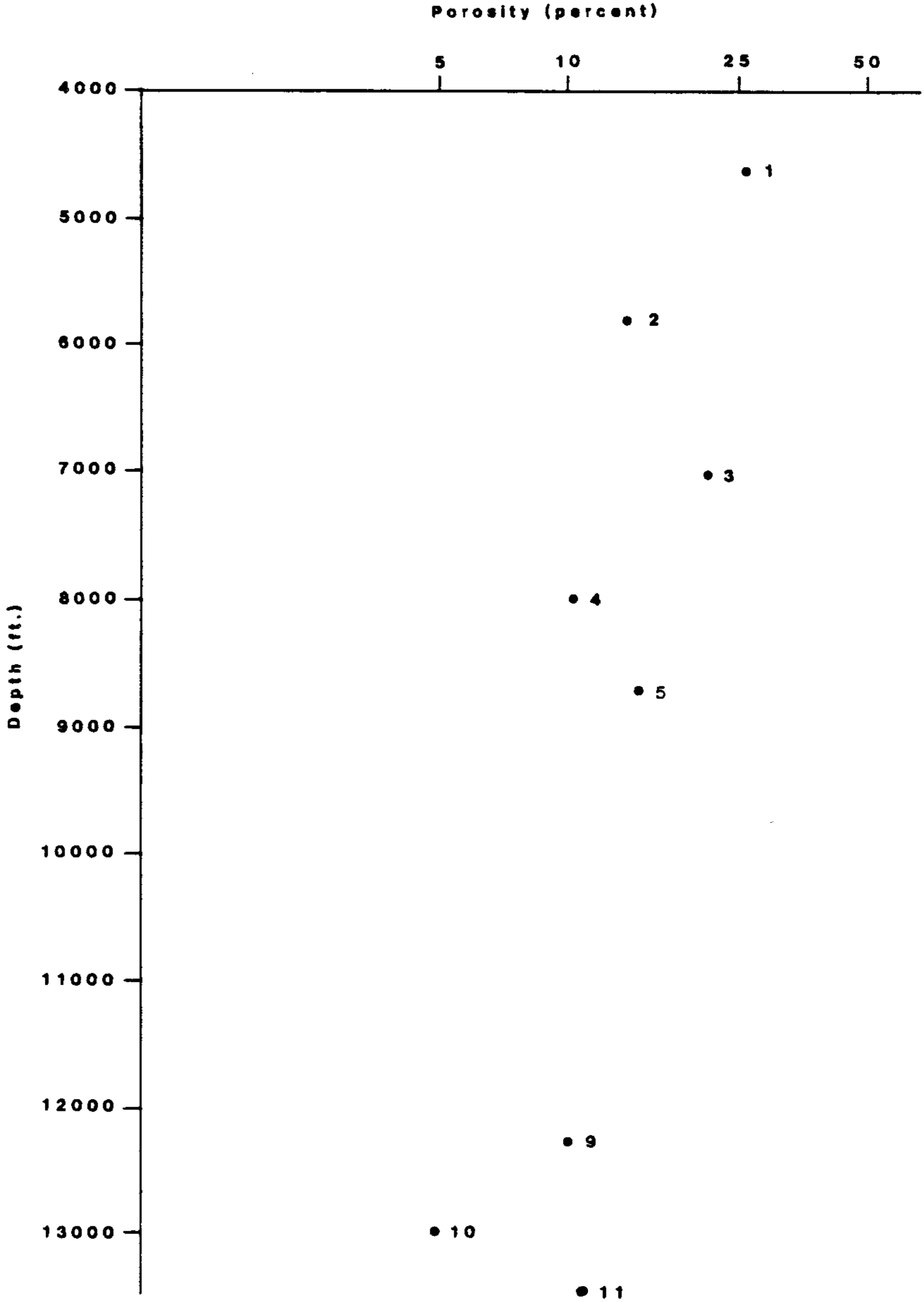
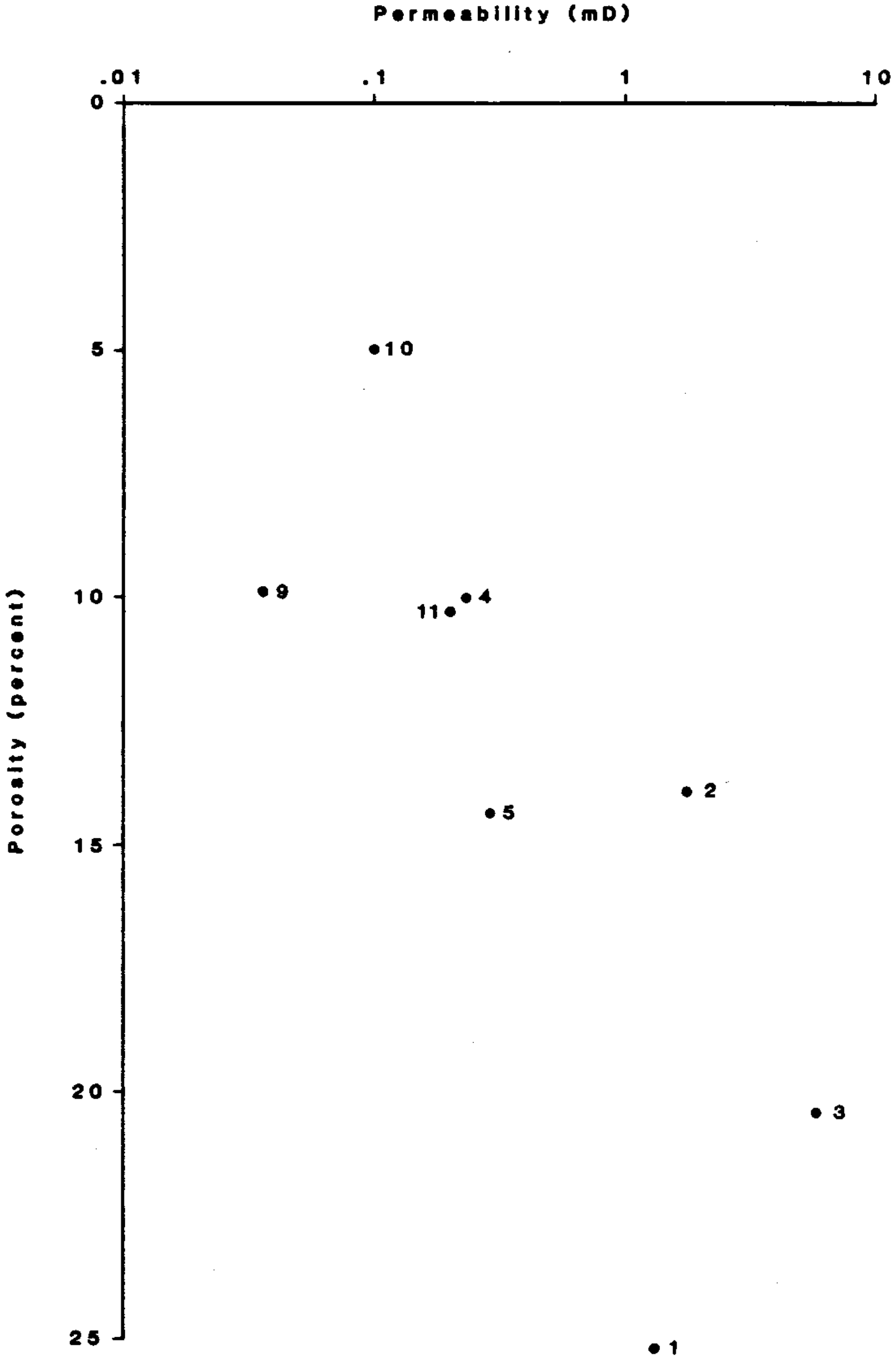


Figure 34. Plot of average porosity against depth for conventional core sandstone samples from Norton Sound COST No.2 well

Figure 35. Plot of average permeability against average porosity for conventional core sandstone samples from Norton Sound COST No. 2 well



Postdepositional porosity and permeability reduction are primarily due to compaction and ductile grain deformation in the matrix-rich sandstones encountered in the well. Authigenic cementation has played a subsidiary role in the deterioration of reservoir quality. Pyrite, smectitic clay, and siderite are present as authigenic cements in samples from core 1 (4623 to 4634 feet). Calcite cement is first reported in samples from core 2 (5793 to 5802 feet), and authigenic quartz and kaolinite are first reported in samples from core 3 (7018 to 7049 feet). Ankerite cement is first reported in samples from core 4 (7993 to 8022 feet), and authigenic chlorite is first reported in samples from core 9 (12,212 to 12,241.5 feet).

Hydrocarbons

During the drilling of this well, good gas shows consisting of methane with lesser amounts of ethane, propane, and butane were encountered between 12,190 and 14,460 feet. An examination of the geophysical logs shows neutron-density gas anomalies for much of the sandstone and interbedded coal between 12,880 and 13,942 feet. No tests were run to evaluate the degree of gas saturation in the sandstone beds with neutron-density gas anomalies. These anomalies probably represent partial saturation of the sandstone with gas generated in adjacent coal beds and unable to migrate further because of low permeability. This sequence might conceivably be productive elsewhere in the basin.

GEOCHEMISTRY

NORTON SOUND COST WELL NO. 2

by

TABE O. FLETT AND DAVID BLUNT

Introduction

The organic geochemistry for the COST No. 2 well was designed to evaluate the petroleum source potential of rocks in the eastern region of the Norton Sound lease area. The analytical program was recommended and undertaken by Robertson Research (U.S.), Inc., and was approved, with modifications, by Atlantic Richfield Oil Company (ARCO) who acted as operator on behalf of a group of companies. All organic geochemical analyses from Norton basin COST No. 2 well summarized in this report were obtained from Robertson Research (U.S.), Inc., (Dow, 1982). All depths were measured from the Kelly Bushing which was located 104.7 feet above mean sea level and 154 feet above the sea floor.

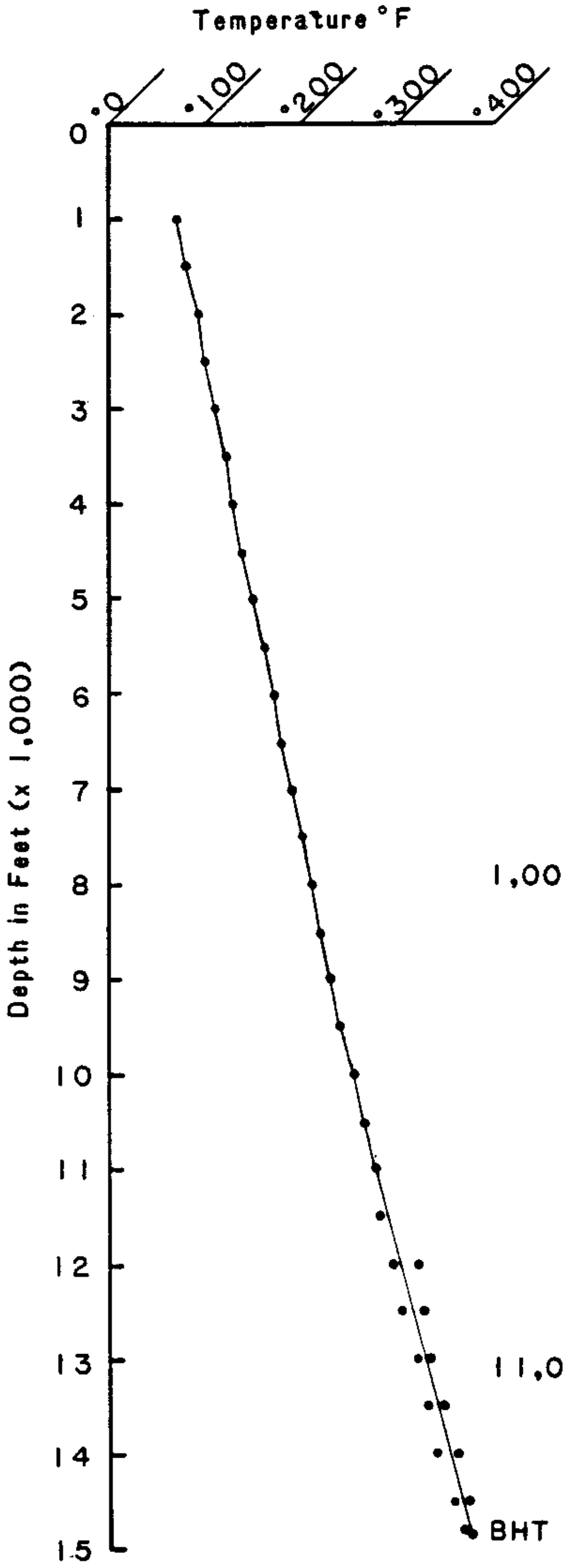
Samples were selected by ARCO and include cuttings (226 samples), sidewall cores (164 samples) and thirteen conventional cores (53 samples). Cutting samples at 60-foot intervals were canned and analyzed for headspace gas, washed, described, and a representative sample selected for total organic carbon (TOC) analysis. Samples with about 0.3 weight percent TOC were analyzed with rock-eval pyrolysis. Samples from cuttings and sidewall cores at 300-foot intervals and samples from each conventional core were selected for kerogen isolation, vitrinite reflectance, spore coloration index, and elemental analysis. Soxhlet extraction, elution chromatography, and saturate fraction gas chromatography were restricted to conventional core samples. The original data is on file at the Minerals Management Service, 800 A Street, Anchorage, Alaska, and is available for examination.

Geothermal Gradient

The apparent mean geothermal gradients for the No. 2 well were computed from raw data plotted on Figure 36. Observed temperatures from 1000 feet below the Kelly Bushing to 14,870 feet (Bottom Hole Temperature [BHT]) are taken from the temperature log. Two runs were made below 11,700 feet which resulted in two data sets. The mean thermal gradient for this part of the No. 2 well was computed from 275°F at 11,000 feet to the maximum BHT of 370° F at 14,870 feet. The geothermal gradient from 1000 feet to 11,000 feet may be computed by taking the arithmetic mean of the gradients for the 500-foot increments within this interval or by computing the mean value for the two extreme measurements at 1000 feet and 11,000 feet.

Organic Richness

Total organic carbon content from cuttings, sidewall cores, and conventional cores are displayed on Plate 1. From the sea floor to 3,540 feet below the Kelly Bushing, TOC values from sidewall cores are marginal, averaging 0.61 percent. From 3540 to 4570 feet, significant amounts of coal occur in the samples and TOC values are highly variable ranging from around 1 percent



Depth (ft)	Temperature (°F)
1,000	73
3,000	112
5,000	151
7,000	190
9,000	233
11,000	275
14,870 BHT	370

Mean thermal gradient
1,000 to 11,000 ft : 2.02 °F/100 ft

Mean thermal gradient
11,000 to 14,870 ft (TD) : 2.50 °F/100 ft

Figure 36. Temperature log data from COST Well 2, Norton Sound, 48.5 hrs after circulation ceased.

[Data from Schlumberger Limited]

to a maximum of 42 percent. From 4570 to 6410 feet, TOC values are generally less than 1 percent with the exception of a few coal-bearing samples. Between 6410 and 9200 feet, coal again causes highly erratic TOC measurements with a maximum value of 61.47 percent. Most sidewall cores in this interval do not exceed 4 percent TOC. While high, they are not nearly as high as cuttings samples, which could indicate that coal sequences are thin and intermittent or that cuttings samples are being contaminated by superadjacent coal layers. Good organic values occur in siltstones from 9773 to 12,035 feet. TOC averages 1.38 percent in this interval. Erratic organic carbon values occur from 12,152 to 14,318 feet, and values are as high as 54 and 55 percent where coal is present. From 14,460 to 14,885.3 feet, TOC values from core samples are less than 0.14 percent. Higher values from cuttings samples reflect contamination from superadjacent sediments.

The $C_{15}+$ total organic extract is reported from conventional cores for depths from 4628 to 14,861 feet in the No. 2 well (Figure 37). $C_{15}+$ extractable bitumen content of kerogen, based upon GeoChem Laboratories, Inc. experience (Bayliss and Smith, 1980), is very good to excellent (2000 ppm to 4000 ppm+) from 7,020 to 8,020 feet and good to very good (1000 ppm to 4000 ppm) from 11,170 to 12,213 feet. Favorable $C_{15}+$ extractable bitumen values also seem to occur more frequently in zones containing coal and carbonaceous material. $C_{15}+$ bitumen to organic carbon ratios are in excess of 0.01, and maximum values are approximately 0.11. Values for this ratio cited by Albrecht, Vandenbroucke, and Mandengué (1976) for extracts from similar kerogen in Cretaceous rocks

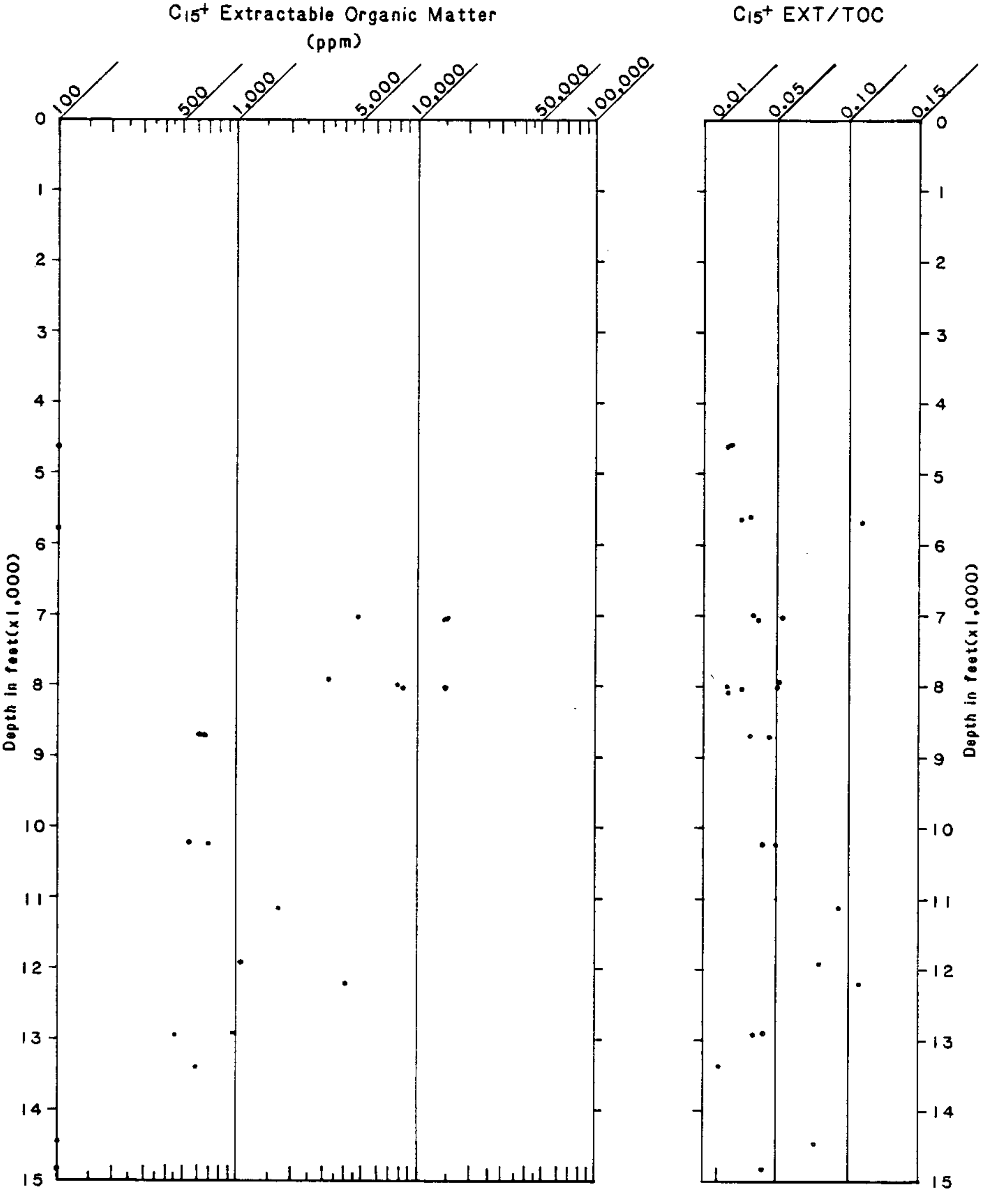


Figure 37. Organic Richness C_{15}^{+} Extractable Organic Matter from Conventional Cores.

found in the Doula Basin, Camaroon, Africa, reach a maximum of 0.11. Tissot and Welte (1978) indicate that when the bitumen to TOC ratio exceeds 0.20, the values are abnormally high and may indicate the presence of nonindigenous bitumens.

Description of Kerogen

Kerogen was examined in reflected and transmitted light. Results of the reflected light petrography and the hydrogen to carbon ratio (H/C) of the kerogen from chemical analyses are depicted in Figure 38.

Three petrographic classes of kerogen plus amorphous material, a subgroup within the exinite or liptinite catagory, are reported in this study as follows:

1. Amorphous (algal or dissolved, colloidal matter)
2. Exinite (herbaceous, lipid-rich relics)
3. Vitrinite (woody and humic components)
4. Inertinite (hard, carbon-rich, nonreactive brittle particles)

Dow (1982) states that it has been the experience of Robertson Research (U.S.), Inc., that samples with less than 35 percent amorphous kerogen will yield primarily dry gas and that oil source beds contain 65 percent or more of the oil-generating components (amorphous + exinite). He adds that intermediate mixtures will expel primarily wet gas and condensate, although a complete transition probably exists. Amorphous kerogen in excess of 35 percent of the total kerogen occurs in a dominantly siltstone unit between 2400 and 3200 feet and between 9200 and

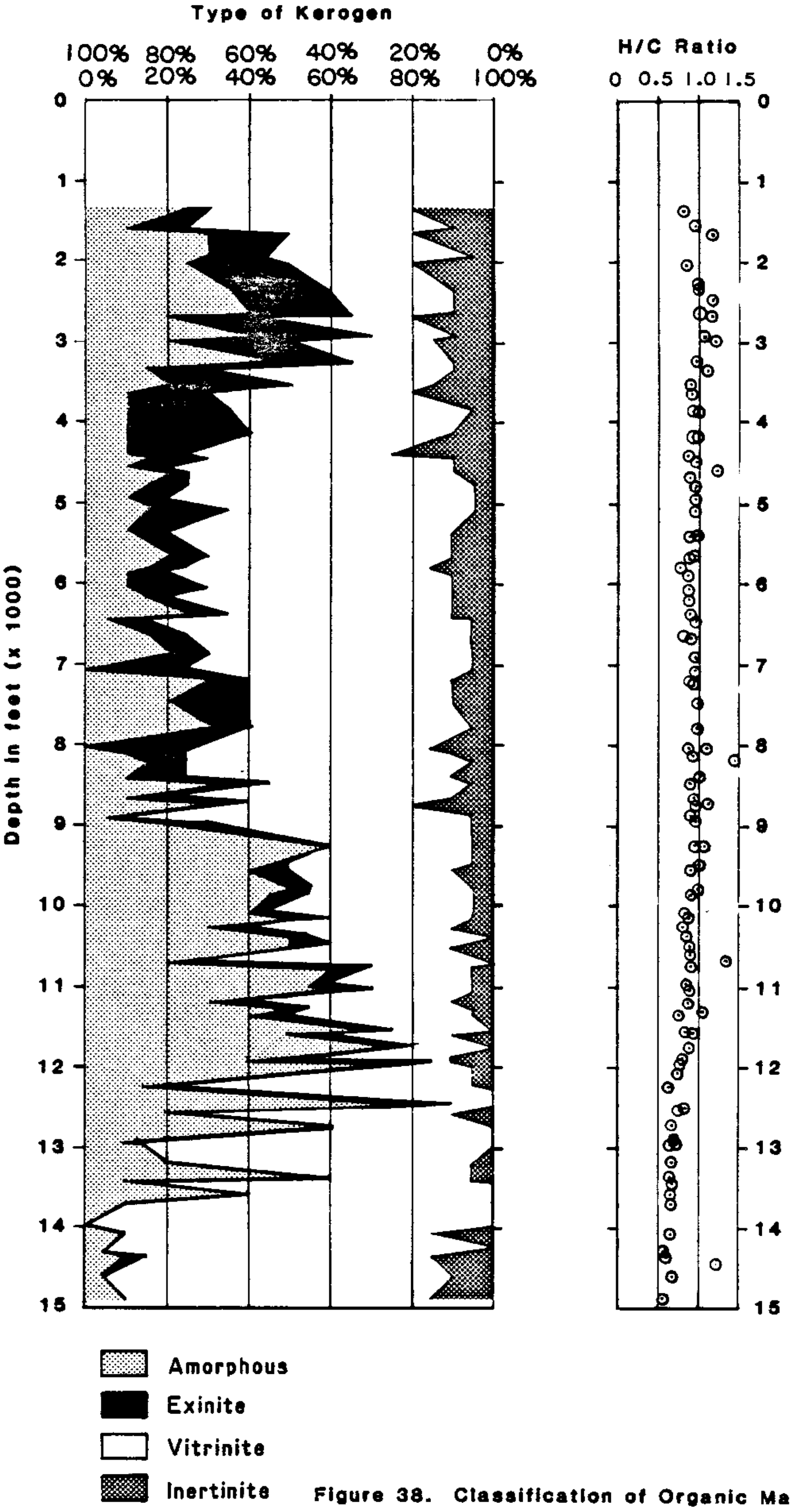


Figure 38. Classification of Organic Matter.

12,200 feet in a shaly siltstone lithology. In this lower unit the amorphous content of the kerogen exceeds 65 percent in several instances. In coaly intervals and at depths greater than 12,200 feet, vitrinite macerals dominated the kerogen with percentages of vitrinite generally in excess of 60 or 65 percent.

Elemental analysis data are in good agreement with the visual identification of kerogen. The H/C ratio ranges from about 1.2 near the surface to a minimum of 0.57 at 14,640 feet. Hunt (1979) indicates that 1.2 is a typical H/C value for herbaceous kerogen and 0.72 characteristic of woody kerogen. These are forms of exinite and vitrinite, respectively. It appears that much of the kerogen in the sediments penetrated by this well is woody, herbaceous material derived from a terrestrial source. This interpretation is supported by pyrolysis.

The hydrogen and oxygen indices from pyrolysis of sidewall core samples are plotted on a modified Van Krevelen diagram, Figure 39. The data plots almost totally along the type III maturation curve. Those samples with hydrogen indices greater than 150 that plot in the vicinity of the type I and type II curves at relatively high levels of thermal maturity are derived completely from the coaly sequences of the lithology. The single highly anomalous data point (HI = 494) is from a sidewall core at 6630 feet. H/C from elemental analyses is 0.88, which is not anomalously high for this kerogen. There is no apparent reason to assume that any of the kerogen analyzed represents either type I or type II.

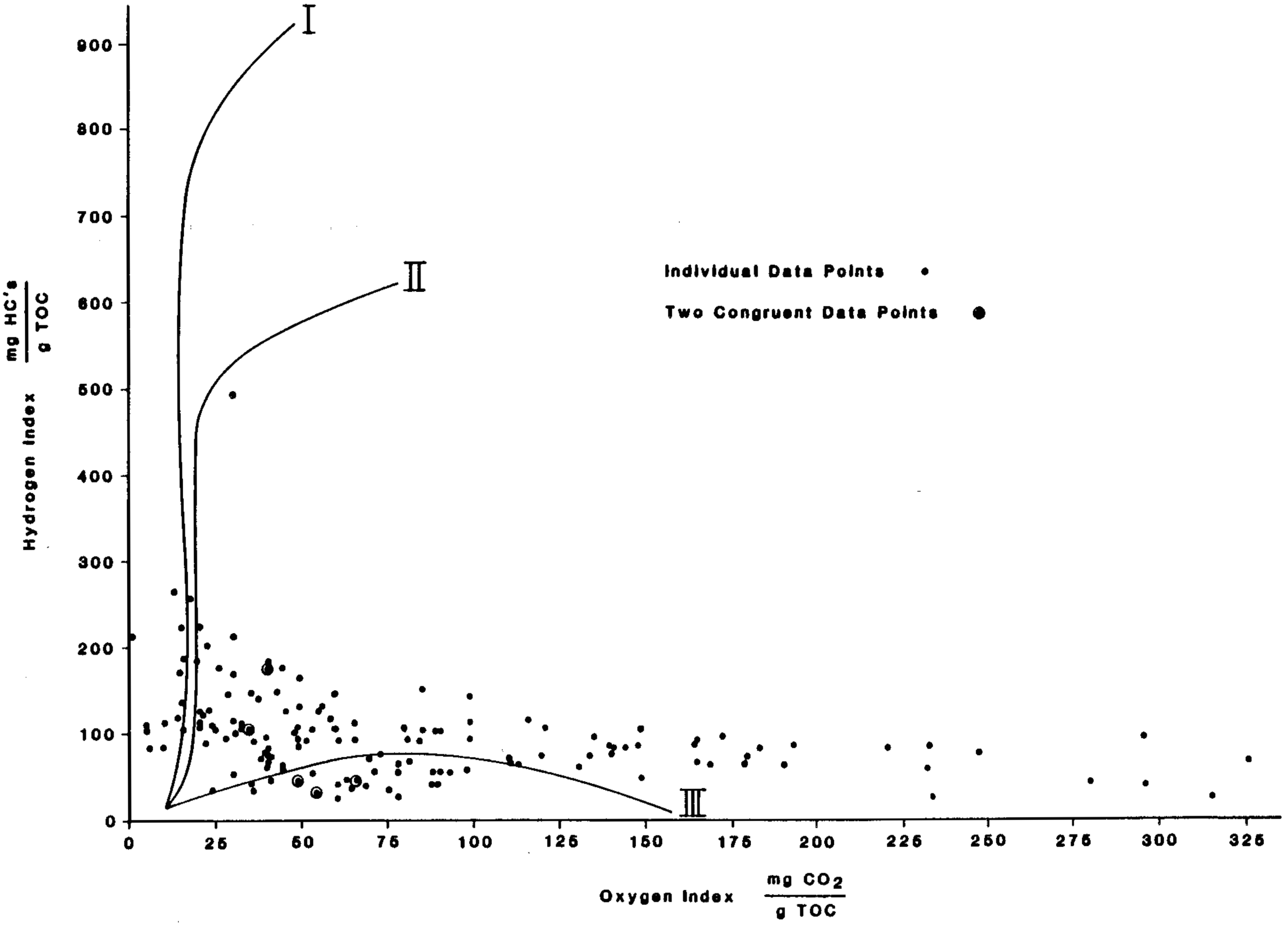


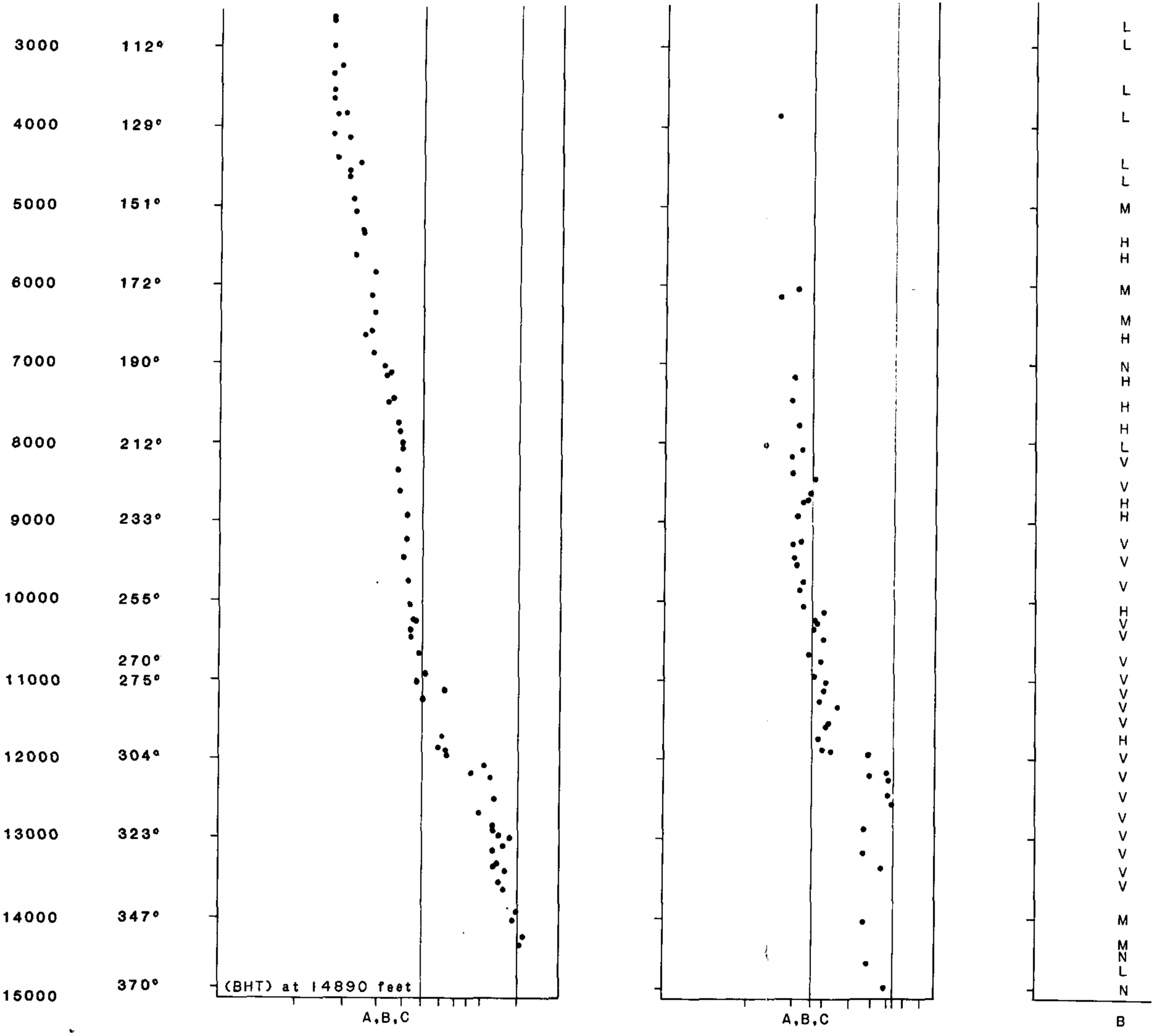
Figure 39. Modified Van Krevelen diagram from analysis of sidewall cores.

Maturation

The level of thermal alteration attained by carbon-bearing sediments can be evaluated in a variety of ways. Figure 40 contains well profiles of the random vitrinite reflectance (Ro), the spore coloration index (SCI), kerogen fluorescence intensity, T_2-max from the second pyrolysis response, and the carbon preference index (CPI).

Robertson Research (U.S.), Inc., (Appendix) reports that the abundance of terrestrial kerogen in most samples analyzed produced very good vitrinite reflectance data with the result that the Ro profile is the most reliable indicator of thermal maturity for the No. 2 well. Histograms of Ro measurements are generally unimodal. The only significant problems reported were high rank, recycled organic matter in some shallow samples, occasional oxidized vitrinite, solid bitumen and pseudovitrinite, and minor caving in a few of the cuttings samples.

Ro values reach 0.6 percent, the lower limit of peak oil generation (Hunt, 1979), at approximately 10,700 feet below the Kelly Bushing. Ro increases continuously to a depth of about 12,100 feet where there is a discontinuous increase in Ro from about 0.7 to 1.0 percent. The Ro values then increase continuously to 14,330 feet where a maximum value of 1.46 percent was observed. Oil could be generated and preserved from 10,700 feet or a little less to at least 14,300 feet, and gas could be generated and preserved from 12,100 feet to total depth of the No. 2 well at this location.


3000
112°
4000
129°
5000
151°
6000
172°
7000
190°
8000
212°
9000
233°
10000
255°
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11000
275°
12000
304°
13000
323°
14000
347°
370°
15000
(BHT) at 14890 feet
A,B,C
A,B,C
L
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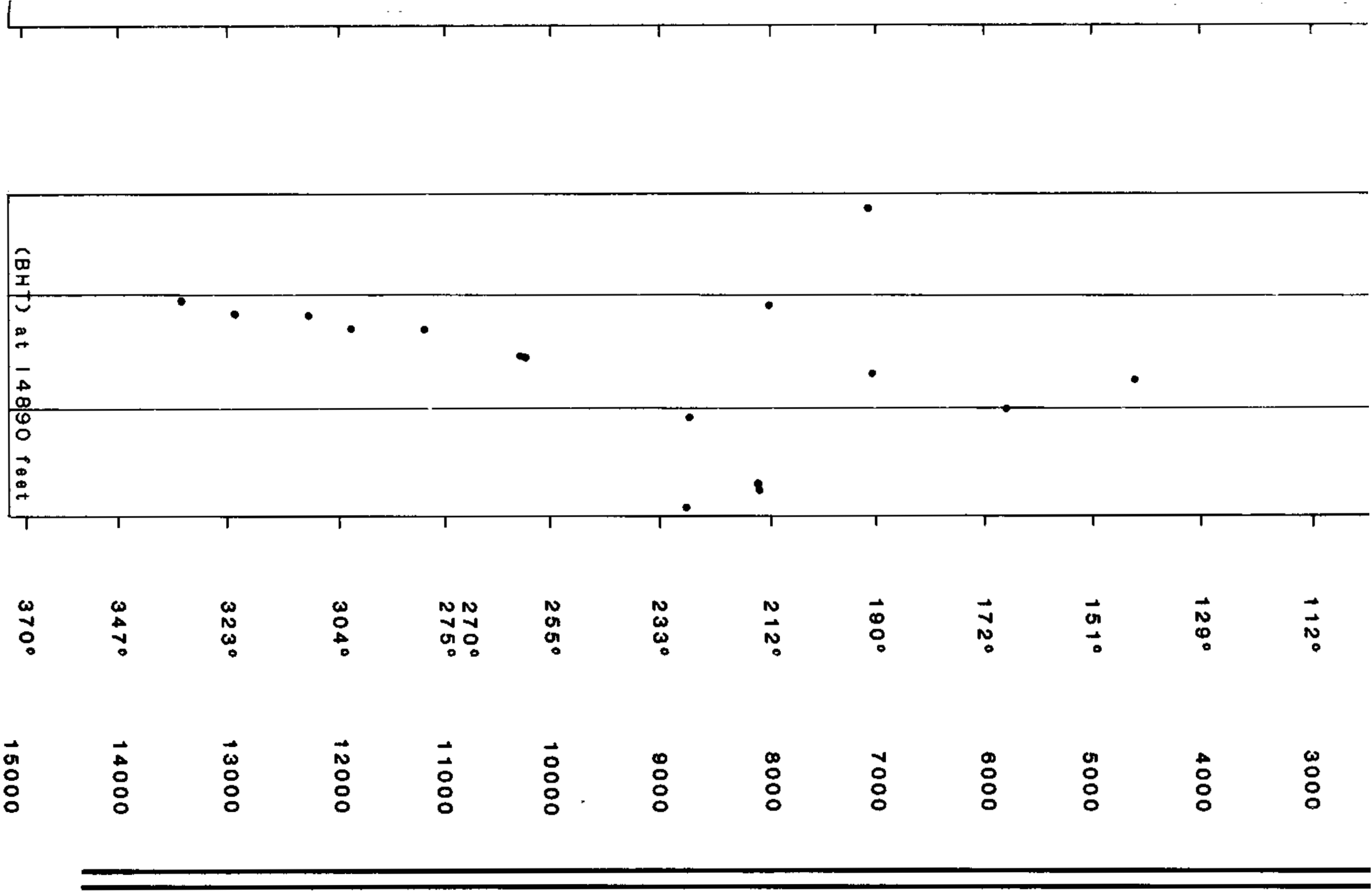


Figure 40. Selected Indicators of Thermal Maturation.

[Sample Sources: A-Cuttings, B-Sidewall Cores, C-Conventional Cores]

Dow (1982) interprets the Ro anomaly at 12,100 feet as being the result of an unconformity. By projecting the lower segment of the Ro profile up hole to about 0.7 percent, it is possible to estimate that several thousand feet of eroded section are unaccounted for in this well (Dow, 1977). The continuous nature of the Ro curve, which projects to nearly 0.2 percent at the present surface, indicates that very little erosion has occurred above the anomaly and that sedimentation was essentially continuous to about 12,000 feet. A correlative anomaly appears to occur at approximately 11,900 feet in the SCI profile.

The spore coloration index is estimated by assigning a value, on a scale of 1 to 10, to the color of spores and pollen observed in transmitted light. This technique is most useful in the lower maturation ranges because, as the spores and pollen become more mature, they become opaque, and it is difficult to evaluate subtle changes in color. A correlation chart provided by Robertson Research (U.S.), Inc., (Dow, 1982) suggests that the lower threshold of peak oil generation for SCI values is approximately 3.5 or 3.6 and the upper value approximately 7.4 or 7.5. These limiting values are approximately equivalent to 0.6 and 1.4 percent respectively on the vitrinite reflectance scale.

Dow (1982) states that SCI data from the No. 2 well are of unusually poor quality owing to an abundance of recycled or oxidized organic matter and apparent discoloration, possibly caused by bituminous material. The discoloration was particularly troublesome above 8000 feet. Nevertheless, the maturation profile developed from SCI values closely resembles the maturation profiles from Ro and T_2-max values. SCI values imply that adequate maturity for generation of hydrocarbons begins between 10,200 and 10,600 feet in the No. 2 well. A discontinuous offset in the maturation profile occurs at about 11,900 feet, and SCI values from this depth to the bottom of the well range between 6 and 7, near maximum values for oil generation.

The intensity of kerogen fluorescence increases with increasing maturity. At 9230 feet the fluorescence intensity associated with the opaque kerogen from sidewall cores is very high and remains very high to a depth of 13,558 feet, at which point it decreases rapidly. This drop in kerogen fluorescence intensity appears to correspond with reduced levels of organic richness and an increase in the content of vitrinitic kerogen at the expense of exinite material. The abruptness in the reduction of the fluorescence intensity suggests that it is related to a change in kerogen composition rather than to the progressive increase in maturity, though increasing thermal maturity is probably a contributing factor.

Barker (1974), Claypool and Reed (1976), and Espitalié and others (1977), have suggested that T_2-max, the temperature at which maximum evolution of thermal hydrocarbons occurs during pyrolysis, can be used to characterize the degree of thermal maturation of kerogen. However, these measurements are influenced by the laboratory's instrumentation and technique, the rate of heating, and by the type of kerogen. Type III kerogen, for example, tends to exhibit lower T_2-max values than types I and II (Tissot and Welte, 1978).

Robertson Research (U.S.), Inc., suggests that the zone of peak oil generation is roughly defined by the limiting T_2-max values 435° and 470° C. These values occur at approximately 10,600 and 13,600 feet respectively in the No. 2 well. The relatively high T_2-max values in the upper part of the lithologic section are caused by recycled organic matter that cannot be screened from pyrolysis analyses, although it frequently can be when Ro measurements are made. In spite of this, the T_2-max data plots as a continuous profile very similar to the Ro profile. The Ro anomaly at 12,100 feet is not apparent in the T_2-max data, possibly owing to the greater statistical variation inherent in this analytical technique.

CPI values for samples from conventional cores were computed using the original Bray and Evans formula (C_{24} through C_{34}). The shallowest observation is 1.79 from a sample at 4528 feet. Values increase to 2.96 at 8727 feet and then decrease to a minimum of 1.07 at 13,405 feet below the Kelly Bushing. CPI values appear to approach 1.3 between 11,000 and 12,000 feet. Values below 12,000 feet project toward an asymptotic limit of about 1.1. Gas chromatograms from conventional core samples at 11,170 and 12,213 feet are reproduced in Figure 41. The change from a bimodal to a unimodal distribution of paraffins with a reduction of longer paraffin and napthene molecules plus the reduction of the CPI values below 12,000 feet all tend to support the hypothesis that a significant increase in thermal maturity has occurred in this interval.

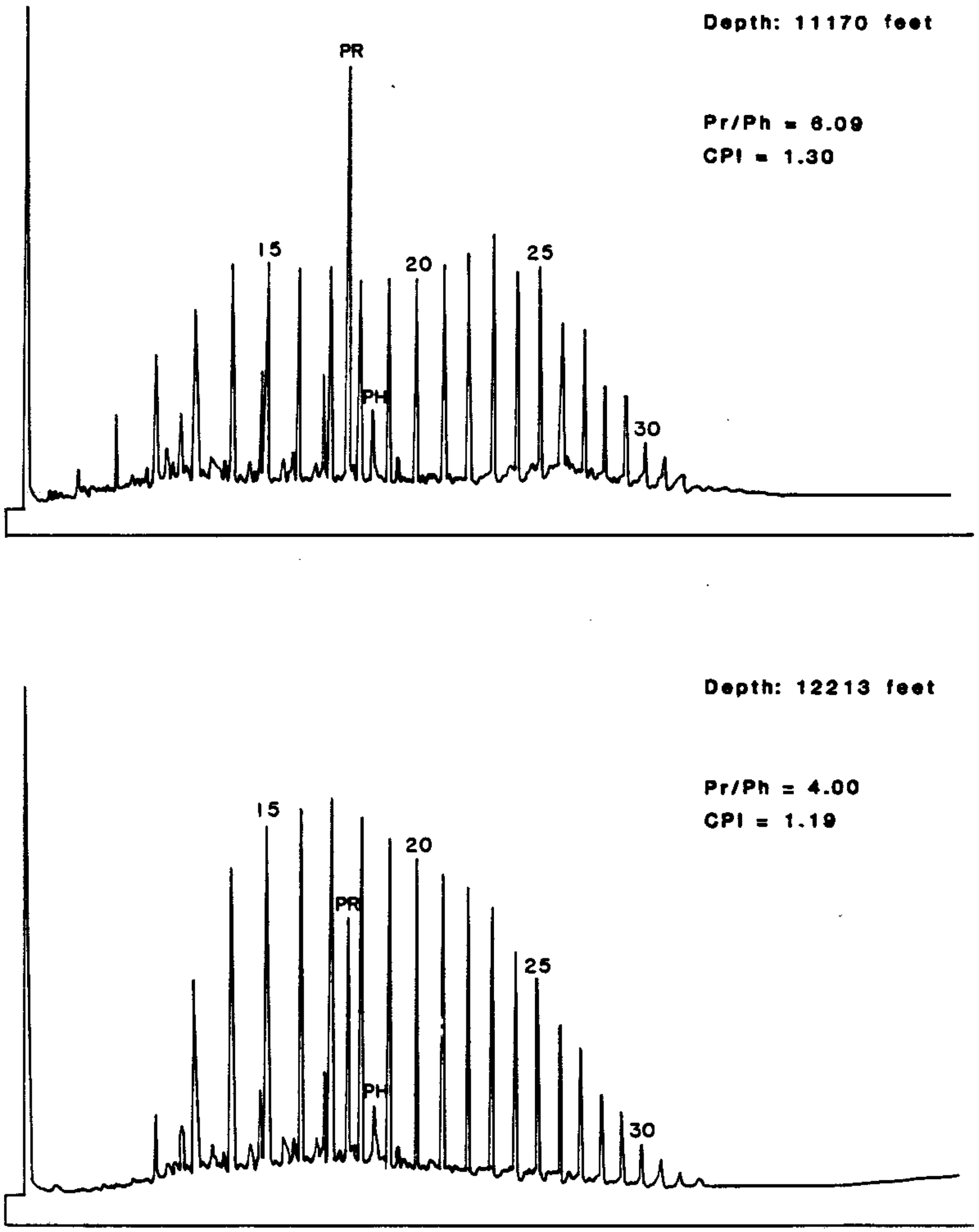


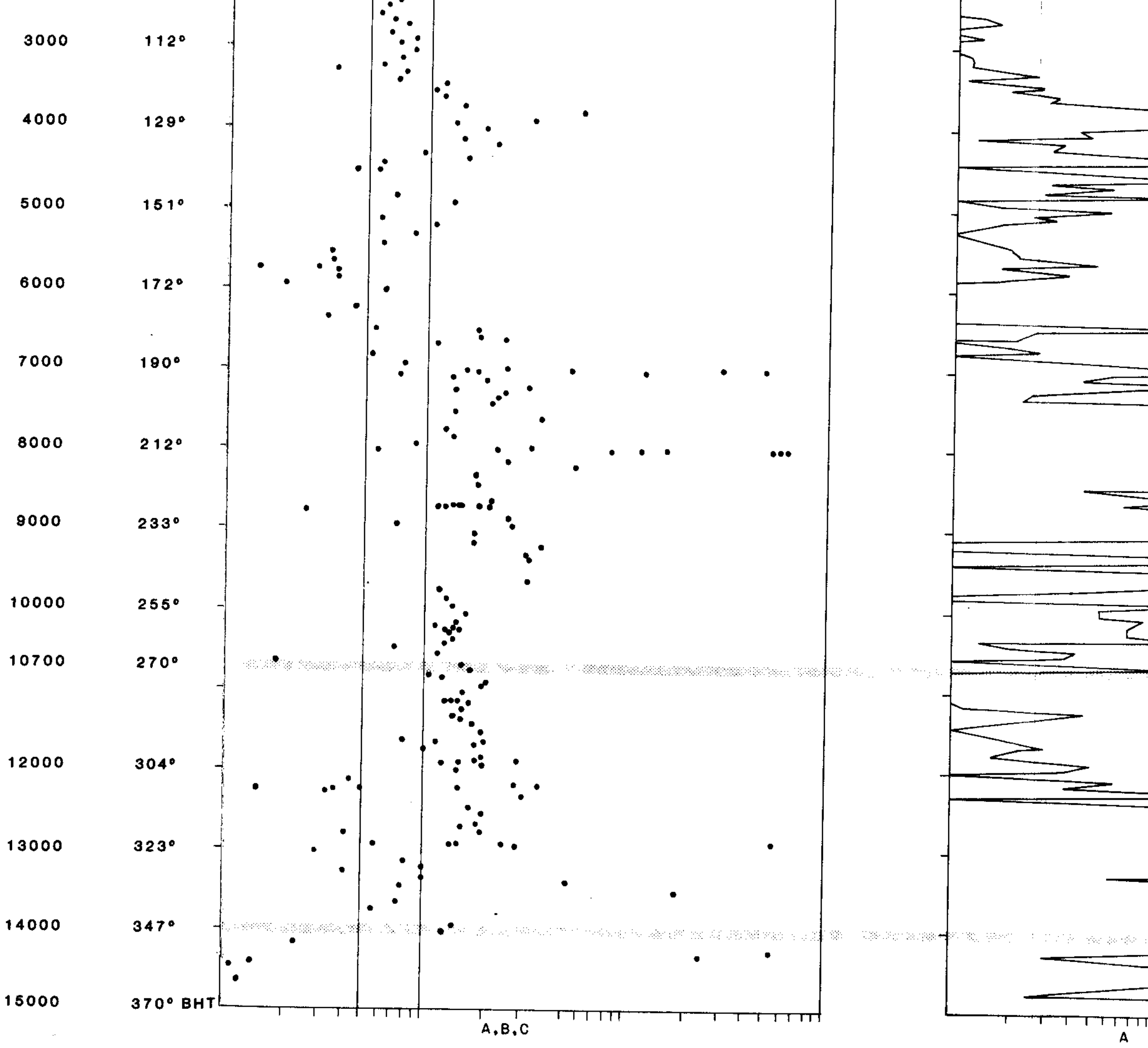
Figure 41. Representative C_{15}+ Gas Chromatograms from conventional core samples showing Alkane distribution.

There is good general agreement among the indicators of thermal maturity that the onset of major oil generation should occur at approximately 10,700 feet at this location and that a significant maturation anomaly exists at about 12,100 feet. The base of the zone of peak oil generation is not as distinct as the upper boundary but it appears to occur at 14,000 to 14,300 feet. Gaseous hydrocarbons could be generated and preserved below 12,100 feet in this well and at considerably shallower depths if generated from coal or by microorganisms.

Hydrocarbon Source Potential

Organic richness, headspace gas and wetness, genetic potential and productivity index from pyrolysis are all displayed on Figure 42. Wetness for this report is defined as $[C_2 + C_3 + C_4] : [C_1 + C_2 + C_3 + C_4]$. The larger headspace gas values are related to anomalous organic carbon levels that generally occur in coaly lithologic sequences. The wetness ratio clearly indicates that until Ro exceeds 0.6 percent, the headspace gas is almost entirely composed of methane. Dow (1982) notes that if primarily oil source beds were present, especially below 10,000 feet, the wetness ratio should be more than 90 percent and that pentane and heavier alkanes should be more abundant than they are.

The sum $S_1 + S_2$ from pyrolysis is termed the genetic potential by Tissot and Welte (1978) because it accounts for both type and abundance of organic matter. They suggest the following threshold values for evaluating the oil and gas potential of source rock.


3000
112°
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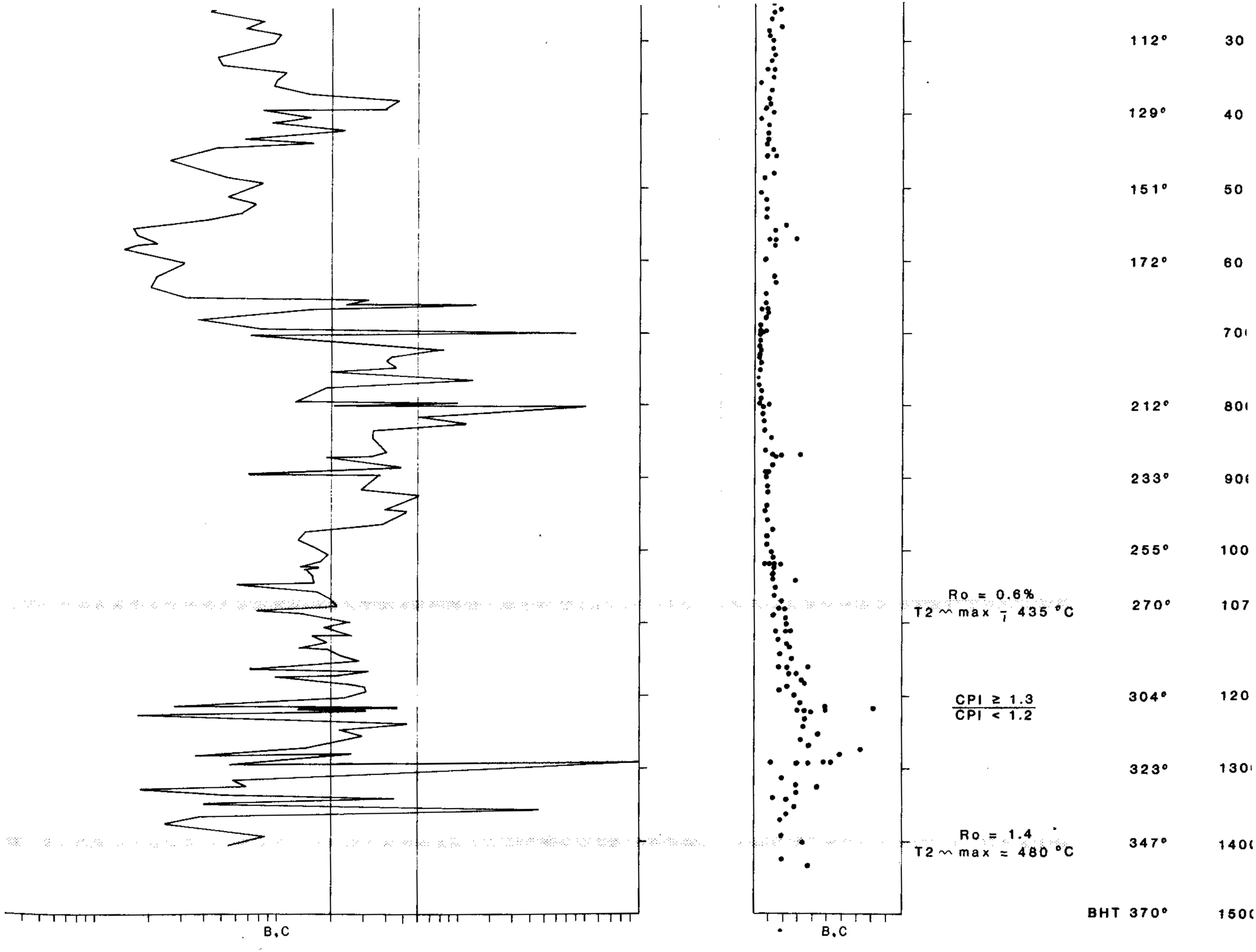
151°
6000
172°
7000
190°
8000
212°
9000
233°
10000
255°
10700
270°
12000
304°
13000
323°
14000
347°
15000
370° BHT
A,B,C
A


B,C
B,C
Ro = 0.6%
T2 ~ max ≅ 435 °C
CPI ≥ 1.3
CPI < 1.2
Ro = 1.4
T2 ~ max = 480 °C
112° 30
129° 40
151° 50
172° 60
70
212° 80
233° 90
255° 100
270° 107
304° 120
323° 130
347° 140
BHT 370° 150

$S_1 + S_2$ (ppm)	Source-Rock Potential
Less than 2000	No oil. Some gas.
2000 to 6000	Moderate source rock.
Greater than 6000	Good source rock.

The quotient $\frac{S_1}{S_1 + S_2}$ is termed the transformation ratio by Tissot and Welte (1978). It indicates the extent to which the genetic potential of a kerogen has been realized provided that volatile hydrocarbons (S_1) evolved from the kerogen are indigenous.

Most of the erratic $S_1 + S_2$ values in excess of 2000 ppm are derived from coaly lithologic sequences. However, the section from about 10,000 to 12,250 feet is largely siltstone and shale with only minor amounts of coal. A single sidewall core sample at 12,230 feet yielded iso and normal pentane contents of 5487 and 7634 ppm, respectively. Below 10,600 feet, the $S_1 + S_2$ values range from 2000 to 8980 ppm and $\frac{S_1}{S_1 + S_2}$ from 0.05 to 0.56. The maximum $\frac{S_1}{S_1 + S_2}$ values were the result of pyrolysis performed upon conventional core 9 at 12,214 feet; a sample composed of a very fine, quartz sandstone with fractures filled with black, shiney, bituminous material, resembling coal.

Robertson Research (U.S.), Inc., identified the solid bituminous material as epi-impsonite on the basis of Ro and elemental analysis. This sample and a sample of gray, quartzitic, and micaceous siltstone from the same core at 12,213 feet contained almost 4000 ppm extractable organic material that produced gas chromatograms closely resembling crude oil. The bituminous material contained some extra n-alkanes in the C_{20} - C_{30} carbon number range that were not present in the pentane-rich siltstone. The $C_{15}+$ extracts from the samples at 12,213 and 12,214 feet yielded pristane to phytane ratios (Pr/Ph) of 4.00 and 4.33 respectively. Pr/Ph ratios between 3.0 and 4.5 from the Carnarvon basin (Jurassic source), Perth basin (central Dandaragan trough), and Papuan basin in Australia are derived from paraffinic-napthenic oils associated with marginal-marine clastic sedimentary rocks or deltaic sequences with some marine influence (Powell and McKirdy, 1975).

The organic extracts from these samples were correlated with extracts from cores 10 and 11 by Robertson Research (U.S.), Inc., on the basis of "gross compositions, saturate fraction gas chromatograms, and key ratios." Robertson Research (U.S.), Inc., (Appendix) concludes that the extractable material in core 9 probably originated in thermally mature clastic sediments as deep as 14,000 feet.

Summary and Conclusions

Geochemical data from the No. 2 well indicate a predominantly type III humic kerogen commonly found in what Demaisson (1981) has termed a "type C" organic facies. This facies is typically the product of a mildly oxic depositional environment and may contain marine and nonmarine sediments, slope and rise deposits, and exinite rich coals. It is characterized geochemically at an Ro of approximately 0.5 percent in the following manner:

H/C: 0.8 to 1.0

Hydrogen Index (HI): 25 to 125 $\frac{\text{mg HC's}}{\text{g TOC}}$

Oxygen Index (OI): 50 to 200 $\frac{\text{mg } CO_2}{\text{g TOC}}$

Average values of these parameters at a depth of 8000 feet where Ro is about 0.5 percent produced the following results:

H/C: 0.93

HI: 165 $\frac{\text{mg HC's}}{\text{g TOC}}$

OI: 71 $\frac{\text{mg } CO_2}{\text{g TOC}}$

The average HI from these cuttings samples is slightly high but it is far less than the minimum value required for an oil-prone facies (HI = 450 $\frac{\text{mg HC's}}{\text{g TOC}}$ for "type B," organic facies, Demaison, 1981). Hydrocarbons formed in a type C organic facies tend to be gas prone, sometimes with condensate. Visual indentification of the kerogen and relatively high Pr/Ph values (see Figure 41) support this hypothesis and suggest that much of the organic matter was derived from terrestrial sources.

Organic matter is abundant throughout most of the sedimentary section encountered in this test well and is especially high in coal-bearing intervals between 3500 to 4600 feet, 6400 to 8600 feet, and 12,200 to 14,400 feet.

Sufficient thermal maturity for peak oil generation exists below 10,600 feet and crude oil could be preserved to at least 14,000 feet. Vitrinite reflectance, supported by other indicators of thermal maturity, suggests that deposition of sediment has been relatively continuous to a depth of about 12,100 feet where a distinct anomaly may represent a hiatus in sedimentation of several thousand feet.

Minor amounts of gas and liquid hydrocarbons are present below 10,000 feet associated with kerogen having a moderate genetic potential for hydrocarbon generation. The best signs of free hydrocarbons plus organic extract and solid bituminous material filling fractures were observed in conventional core number 9, between 12,200 and 12,250 feet.

At depths greater than 14,000 feet, organic carbon content and abundance of sapropelic kerogen are low. Metamorphic rocks are present in a sidewall core at 14,410 feet. It is unlikely that hydrocarbons have been generated at these depths at this location (fig. 42).

ENVIRONMENTAL CONSIDERATIONS

By Paul Lowry

ARCO Exploration Company, as operator for itself and other participants, submitted a letter dated June 18, 1981, for the proposed drilling of a Deep Stratigraphic Test well in the Norton Sound area of the Alaska Outer Continental Shelf. Documents in support of this proposal included a Drilling Plan, an Environmental Report, an Oilspill Contingency Plan, and Coastal Zone Consistency Certification. On the basis of preliminary information on the proposed locations, a site-specific biological survey and a geohazards survey at the primary and alternate sites to detail environmental conditions were required before approval of the Geological and Geophysical (G&G) Permit application for the Deep Stratigraphic Test well. The applicant followed 30 CFR Part 251 in submission of the G&G Permit for this well.

A Deep Stratigraphic Test well is intended to acquire geological and engineering data to determine the potential for hydrocarbon accumulation within a proposed sale area. It is commonly drilled off structure, and it is not intended that any hydrocarbon accumulations be found. Although the revised regulations do not forbid drilling on structure, the Norton Sound No. 2 well was drilled off structure. The information gathered from this test well was used to further evaluate the hydrocarbon potential of OCS Lease Sale No. 57 (Norton Basin) held on March 15, 1983.

As part of the permit application review process, an Environmental Assessment (EA) under the National Environmental Policy Act (NEPA) directive was prepared. An EA serves as a decision-making document to determine if the proposed action is or is not a major Federal action significantly affecting the quality of the human environment in the sense of NEPA, Section 102(2)(C). An EA addresses and includes the following: Description of the proposed action, description of the affected environment, environmental consequences, alternatives to the proposed action, unavoidable adverse environmental effects, and controversial issues.

On the basis of existing data and regulations in effect at the time the proposal was being reviewed, specific environmental aspects were considered MMS before the drilling plan was approved.

Geological Survey

A site-specific shallow drilling hazards survey (Nekton, 1980b), required by MMS, showed the seafloor at the proposed sites to be nearly flat, with extensive evidence of shallow ice gouging. A thin veneer of soft Holocene clayey silt and clay covered both sites. Cyclic loading during storm conditions aids the normal dynamic tidal currents in resuspension and transportation of the upper several feet of sediment. This leads to redeposition and, in some cases, liquefaction of the sea bottom. These conditions permit periodic venting of biogenic gas that might form in pre-Holocene organic-rich peaty sediments. Video and still photographs taken in conjunction with the biological surveys indicated that the substratum at both sites was dominated by sand and silt, with little clay and no gravel. Sediment distribution may be related to the distance of the sites from terrestrial sediment sources and strong currents.

Geologic hazards:

1. Shallow gas in the vicinity of the operations is restricted to biogenic gas near the surface. It is easily vented when the sediments are disturbed and did not affect the drilling operations.

2. No shallow faults were present at the proposed site.

3. Surficial sediments are stable, except for potential liquefaction of the top 1-2 m. This did not interfere with drilling operations.

4. Ice gouges in this area are very shallow and did not affect operations.

5. Sand waves and sediment scour caused by intense current activity did not occur at the well site.

6. Permafrost was not encountered. Engineering procedures were available to control any difficulties that might arise had permafrost been encountered.

7. Abnormal pressures and hydrogen sulfide gas were not expected or encountered.

Geologic hazards did not impose undue restraints on this Deep Stratigraphic Test well program.

Meteorological and Oceanographic Data

Most of the Bering Sea lies in subarctic latitudes and cyclonic atmospheric circulation predominates in the region. Cloudy skies, moderately heavy precipitation, and strong surface winds characterize the marine weather. Storms are more frequent in the fall than in the summer.

There are two dominant current patterns in the Norton Sound area; the northward flowing currents passing east of St. Lawrence Island and the counterclockwise circulation system within Norton Sound. 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. At Nome, the mean dates of sea-ice breakup and freezeup are May 29 and November 12, respectively. Superstructure icing is possible in June and is probable in October.

Sea ice conditions in Norton Sound vary from site to site, and ice movement is caused by a combination of geography and prevailing northeast winter winds. The prevailing northeast winds result in an almost continuous east-northeast to west-southwest evacuation of ice from the Sound throughout the winter. Except for the shorefast ice, the ice in this area is entirely replaced by this process several times during a season. First-year ice usually moves out of the area by the time it is about 18 inches thick. The site is characterized by relatively thin, weak ice in constant motion with extensive rafting.

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. The No. 2 well was drilled during an open-water season.

Because limited meteorological and oceanographic data were available, the MMS issued the Guidelines for Collection of Meteorological, Oceanographic, and Performance Data (January 21, 1982) and required the operator to collect meteorological information to aid in future operations within Norton Sound. During setup and operation, climatic and sea state conditions were monitored to ensure that local conditions did not exceed rig tolerances or jeopardize human safety. Winds, barometric pressure, air and water temperatures, waves, currents, and ice conditions were monitored. All environmental data collected during the drilling of this well are available to the public (800 A Street, Anchorage, Alaska).

Biological Survey

Biological Survey Results

A site-specific marine biological survey was designed by MMS in concert with other Federal and State agencies to provide biological data at the proposed Deep Stratigraphic Test sites. Through the use of underwater video and photographic documentation, plankton tows, infaunal sampling, and trawling; ARCO (Nekton, 1980a) determined the relative abundance and types of organisms present in various habitats. These studies were conducted on August 22-23, 1980, to determine biological resources at the proposed drill sites. The results are summarized as follows:

1. Invertebrates were the dominant component of trawl catches, with the sea star, *Asterias amurensis*, the most abundant taxon.

2. More fish were collected at the alternate site than at the primary site, but the total weight of fish was greater at the primary site. The starry flounder, *Platichthys stellatus*, was the most abundant flat fish at the primary site. Few flat fish were taken at the alternate site. The saffron cod, *Eleginus gracilis*, and the rainbow smelt, *Osmerus mordax dentex*, were the most abundant round fish at both sites.

3. Demersal fish and epibenthic invertebrates observed on video recordings were similar at both sites. Sea stars were the most numerous invertebrates at the alternate site. The epibenthos and substrate were similar at both sites.

4. Taxanomic diversity and density were higher at the alternate site. Polychaete annelids were numerically dominant at both sites, followed by echinoderms, molluscs, and arthropods.

5. The relative abundance, total number of organisms per cubic meter and species composition of the plankton, was similar at the two sites. Copepods were the most abundant planktonic organism at both sides.

Neither site supported unique habitats or species of special interest that required rejection or modification of the Norton Sound No. 2 well program. The Regional Supervisor, Offshore Field Operations, concluded that normal drilling operations at either of the two sites would not adversely affect the environment.

Marine Mammals/Endangered Species

Marine mammal distribution in the northern Bering Sea and Norton Sound is strongly influenced by the presence of sea ice. Seasonal distributions of several species, particularly bowhead and beluga whales, walrus, and ringed, bearded, and spotted seals are closely associated with the advancing and retreating edge of the pack ice. These species winter in the Norton Sound-north Bering Sea region at the southern limit of the pack ice and generally follow its retreat northward during summer. However, not all individuals move north to the Chukchi and Beaufort Seas at that time. A few walrus, spotted and bearded seals, and beluga and killer whales may still be encountered in Norton Sound during summer.

Several endangered whales (the gray, bowhead, fin, and humpback) are known to occur in the Norton Sound area on a regular or an occasional basis. The endangered peregrine falcon occurs along the coast in the Norton Sound area. A formal consultation was requested from the National Marine Fisheries Service (NMFS) pursuant to Section 7 of the Endangered Species Act of 1973, and a response providing a nonjeopardy opinion was issued by NMFS on April 28, 1981.

Using the information received from all interested parties, as well as our own in-house evaluation, it was determined that approval of the proposed action would not affect an endangered species or its critical habitat.

Fisheries

The marine fishery of Norton Sound is not as productive as that in other portions of the Bering Sea; however, there is a limited commercial utilization of local shellfish and demersal fish. Most abundant demersal fish include cod, flatfish, sculpins, herring, and smelt. Shrimp, king and Tanner crab, and clams dominate the shellfish resources.

Birds

The Norton Sound avifauna is dominated by the summer waterfowl and shorebird presence at the Yukon Delta. This area is recognized as one of the most productive nesting areas in Alaska. Estimates of summer populations include 3 million waterfowl and over 100 million shorebirds; 170 different species have been recorded. Coastal salt marshes, which are the key to this area's productivity, provide nesting habitat for birds such as black brant, emperor, cackling, and white-fronted geese; common, spectacled, and Stellar's eiders; whistling swans; and numerous ducks and shorebirds. These birds have a strong affinity for coastal habitats and do not typically occur more than 2 to 3 miles offshore, except during migrations.

Norton Sound also supports several marine bird rookeries, although the number of colonies and their individual sizes (number of birds) do not compare with those in other Bering Sea regions. Murres, kittiwakes, cormorants, and puffins are most common.

Cultural Resources

Cultural resource surveys may be required in order to assure that no disturbance of archeological or cultural resources on the seafloor. After consultation with the resource agencies, MMS determined that such surveys would not be required for the Norton Sound well sites as they were located in low-probability areas for cultural resources. If the TV transects and side-scan sonar taken in conjunction with the biological survey had indicated unexplained anomalies, a review by a qualified marine archeologist would have been required. No such anomalies were detected. No cultural resources were identified during drilling operations.

Discharges into the Marine Environment

Some liquid wastes, including oil from the oil/water separator, were transported from the drilling vessel by supply boats and disposed of in approved onshore locations. Solid wastes were compacted and similarly transported to an approved onshore disposal site. Liquid wastes, including treated sewage, gray water, and some drilling by-products, were discharged on site into marine waters in accordance with regulations set forth by the U.S. Environmental Protection Agency (EPA).

The applicant disposed of drill cuttings and waste drilling mud into the ocean in compliance with existing orders. No oil-based mud was used. Bentonite is a continuous additive to the drilling mud, whereas barite is added as necessary for increasing mud weight. Bentonite and barite are insoluble, nontoxic, and inert. Other additives are used in minor concentrations, and most are used only under special conditions. These other additives are either nontoxic, or would chemically neutralize in the mud or upon contact with seawater (i.e., caustic soda). Excess cement entered and was dispersed into the ocean when the shallow casing strings were set.

Past studies on the fate and effects of routine discharges from offshore oil and gas activities into the marine environment and the known dispersion rates of such discharges, show that such operations do not significantly affect the environment.

Contingency Plans for Oilspills

Plans for preventing, reporting, and cleaning up oilspills were addressed in the Oilspill Contingency Plan (OSCP), which was a part of the drilling plan. The OSCP listed the equipment and material available to the permittee and described the capabilities of such equipment under different sea and weather conditions. The plan also included a discussion of logistical support programs for contingency operations. The probability of encountering hydrocarbons that could cause a blowout at any depth was minimized in this case by locating the well off structure. The operator drilled the well according to the OCS Orders and used standard well control equipment and procedures. The casing and cementing programs and subsequent abandonment requirements (as outlined in OCS Order No. 3) were designed to prevent leakage or contamination of fluids within a permeable zone.

Upon completion of the well, the site was cleared of all pipe and other material on or above the ocean floor.

As a part of the EA process, the proposed program was submitted to the appropriate Federal and State agencies, as well as interested parties, for comments. Responses were included as part of the EA. On the basis of EA No. AK-81-5, it was determined, on October 26, 1981, that ARCO's proposed action constituted a finding of no significant impact (FONSI), and an Environmental Impact Statement was not required. A Notice was issued to that effect. MMS consequently issued a letter to ARCO, dated January 21, 1982, approving their proposed action. The EA and the FONSI documents are in the public file in the office of the Regional Supervisor, Offshore Field Operations, 800 A Street, Anchorage, Alaska, 99501.

SUMMARY AND CONCLUSIONS

By Ronald F. Turner

Prior to the completion of the Norton Sound Deep Stratigraphic Test well program, very little was known about the petroleum potential of this OCS frontier area. The most widely accepted basin evolution model was the comprehensive analysis of Fisher and others (1982). Since the completion of the second and final test well, however, the number of models has apparently increased to near that of the number of participants. With the public release of these data, it is almost certain the number will increase again. Basin evolution models based on subsurface geological, geophysical, and geochemical data are doubly interpretive owing to the very nature of the data. This interpretation is no exception. It is, however, the first published interpretation made with the benefit of well data. Although time constraints imposed by statutory data release dates have, to some extent, limited various aspects of this ongoing investigation, it is substantially complete. Preliminary analysis of the data from the two wells suggests a basin evolution that differs from the predicted models in several aspects of depositional and subsidence history. In general, the basin fill is younger and far more marine than had been anticipated, and the tectono-eustatic history of the basin is more complex.

The sedimentary basin fill appears to be younger than previous estimates. The presence of Cretaceous sedimentary rocks and coal along the eastern shore of Norton Sound (Patton, 1973) led Fisher and others (1982) to postulate that the Norton Basin might contain sedimentary rocks as old as Late Cretaceous.

However, the middle to late Eocene strata present in the No. 2 well (10,160-12,700 feet) are the oldest sediments for which we have a firm age. This definite Eocene section is underlain by a 1760 foot thick sequence of interbedded sandstone, siltstone, mudstone, and coal deposited under fluvial and paludal conditions. Eocene fungal palynomorphs were recovered from sidewall cores taken in this section but not from conventional cores. The preservational state of these palynomorphs matched that of in situ elements of the sparse and poorly preserved spore-pollen assemblage. Because of the somewhat equivocal nature of the evidence, this section, and a much thinner correlative section in the No. 1 well (12,235-12,545 feet), was assigned an age of Eocene or older. In both Norton Sound wells these strata unconformably overlie much older metamorphic basement rocks. On the basis of the present data, it appears likely that they represent the oldest sedimentary rocks in the basin and are no older than Paleocene, probably younger.

Another less direct line of evidence also supports an early Tertiary age for these sediments. The metamorphic terranes of the Seward Peninsula are the source of much of the sediment in the Norton basin, particularly the St. Lawrence subbasin. A potassium-argon date from a muscovite concentrate from one of the lowermost sandstones in the No. 1 well (12,398 feet, Eocene or older section) yielded an age of approximately 146 m.y. This date represents the Late Jurassic to Early Cretaceous metamorphism of the source terrane and is in agreement with potassium-argon ages obtained from white micas from blueschist-facies metamorphic rocks from the Seward Peninsula (A. Till, personal communication). Isolated glaucophane-bearing rocks have long been known from the Seward Peninsula (Smith, 1910; Sainsbury and others, 1978), but more recently Forbes and others (1981), and Till (1982) described an extensive high-temperature blueschist-facies terrane there. These rocks are thought to have formed at 8-10 kb pressure at crustal depths of at least 24 km (A. Till, personal communication). In the late Cretaceous (68-69 m.y., K-Ar date), these rocks were intruded by epizonal granite stocks (the "tin granites") at depths of perhaps 9 km (Hudson, 1979). The overall thickness of the blueschist rocks cannot be ascertained, nor can the amount of section removed at or before the time of granite implacement. Even so, it seems unlikely that micaceous rocks that recrystalized at blueschist-facies depths in the Late Jurassic-Early Cretaceous and were later intruded in the Late Cretaceous while still at great depth, would be available as sedimentary basin fill in the Late Cretaceous. In fact, it appears that the basal unconformity and the onset of basement rifting both may represent early Tertiary events.

The St. Lawrence and Stuart subbasins resulted from multiphasic extensional tectonism expressed as differential, nonsynchronous subsidence along normal faults. There appear to be significant intra-fill unconformities present in both subbasins. Lithologic, dipmeter, geophysical, and geochemical evidence for the lowest unconformity is best developed in the No. 2 well. This surface may have formed contemporaneously with or preceded initial uplifting of the horst. The ambiguous evidence for angularity seen on one nonproprietary seismic line suggests that the unconformity was in part tectonically controlled. Eustatic changes that resulted in lower base level may be invoked as an alternative or ancillary to tectonism. Calculations made from vitrinite reflectance values (following the method of Dow, 1977) suggest that perhaps 1000 feet of section may be missing in the No. 2 well. A more subtle maturity anomaly of less magnitude is present in the No. 1 well for which no missing section could be calculated. If this lower unconformity separates early and middle Eocene rocks, the erosion was relatively rapid. The unconformity could also be interpreted as a marine transgressive event, if the depositional nature of the Oligocene or older section of the No. 1 well was less equivocal and the position of the unconformity in the No. 2 well was moved up to the marine interval at 12,200 feet (the best geochemical fit, rather than the 12,700 feet dipmeter pick). Samples and other data from this interval in both wells are being reprocessed and reevaluated in hopes of clearing up these ambiguities. Aside from the major unconformity between Paleozoic and Cenozoic rocks, and the mid-Eocene (?) unconformity discussed above, two other unconformities were identified, a Plio-Pleistocene unconformity discernible on shallow seismic lines and a mid-Miocene hiatus based on siliceous microfossils.

Perhaps the most intriguing deviation from the predicted basin model concerns the nature of Paleogene deposition. On the basis of scattered outcrops of nonmarine Paleogene rocks around Norton Sound, the presumed nonmarine nature of sediments of this presumed age in the Hope basin, and reference to the Anadyr basin as an analog, Fisher and others (1982) speculated that the Paleogene section of the Norton basin contained only nonmarine rocks. In fact, both wells contain significant thicknesses of Paleogene age marine strata. If, as postulated by Herman and Hopkins (1980), the Bering Sea land bridge separated the Pacific and Arctic oceans until 3.5 m.y. age, this Paleogene marine connection was probably an arm of the Pacific, and the Nunivak arch of Scholl and Hopkins (1969) and Marlow and others (1976) was not the barrier to Paleogene marine incursions postulated by Fisher and others (1982). Alternatively, the seaway between the eastward moving Siberian block (the Chuktosk and Seward peninsulas) and mainland Alaska may not have been entirely closed at the end of the Cretaceous as postulated by Sachs and Strelkov (1961) and Holmes and Creager 1981). It is also conceivable that an Arctic connection could have been reestablished through lows over the Seward Peninsula before major late Cenozoic uplifts. The presence of Paleogene foraminiferal faunas with strong affinities to those of Sakhalin Island and the Kamchatka Peninsula supports a Pacific rather than Arctic connection. In particular, the presence of species of Porosorotalia, a predominantly austral Pacific Paleogene foraminiferal genus, lends further credence to this interpretation.

Of the two wells, the No. 1 is by far the most marine in aspect. Nearly 5000 feet of the 5197 foot thick Oligocene section was deposited in outer neritic to upper bathyal depths. If the apparent turbidites below it (tentatively correlated with the middle to late Eocene section in the No. 2 well) are also marine, then virtually the entire Paleogene section, with the exception of 310 feet of coal-bearing sediments of possible Eocene or older age, is marine. More than half of the 6536 foot Oligocene section in the No. 2 well is made up of shelfal marine sediments; the remainder consists of coal-bearing transitional sediments deposited in marsh and esturine environments under marine influences. The Eocene section also reflects significant transitional conditions, and definite marine fossils are present as deep as 11,200 feet. All in all, there is probably less than 2400 feet cumulative thickness of purely continental Paleogene section present in the No. 2 well. The late Oligocene coal-bearing sequence described in both wells (our D seismic horizon) is in part correlative with coals of the same age reported from near Unalakleet (Patton, 1973; W. Patton, written communication) and from St. Lawrence Island by Csejtey and Patton (1974). These strata appear to define a regional regressive event that may have continued into the earliest Miocene.

The Yukon horst does not appear to have been a major barrier between the two subbasins until after the mid-Eocene (?) erosional event with which it may be causally related. Thereafter the subbasins had somewhat different tectonic and depositional histories until the mid-Oligocene transgressive event that breached the elongate north-south structure. Subsidence after this time appears to have been a basin-wide isostatic reponse to sediment loading, and for the first time deposition extended beyond the independent, structurally delineated subbasins. Although deposition in the St. Lawrence subbasin (No. 1 well) was always more marine than in the more easterly situated Stuart subbasin, the Yukon horst was not an altogether effective physical or faunal barrier as evidenced by the presence of fossiliferous marine stringers intercalated with continental and transitional coals throughout the Eocene and Oligocene section of the No. 2 well.

The most difficult equivalency to establish is that between the problematic Oligocene or older nonfossiliferous turbidites (?) of the No. 1 well and the middle to late Eocene transitional to continental coal-bearing section of the No. 2 well (as was noted in the discussion of the unconformity at the base of both). Small chips of unweathered glaucophane schist in cuttings from this section of the No. 1 well indicate rapid erosion from a nearby source, probably the horst. If these well sections are correlative, as we now believe, then the presence of Eocene marine fossils in the No. 2 well makes a lacustrine origin for the turbidite section of the No. 1 well (9690-12,235 feet) difficult to explain in terms of simple paleogeography. Geochemical evidence for a lacustrine environment is not compelling. The dominant organic material present over the interval is type III kerogen associated with minor amounts of possible type II kerogen. Type I kerogen, especially alganite, is the type of organic material characteristic of large lacustrine depositional systems. Only one sample (from a conventional core at 9758 feet) yielded an analysis that might represent type I kerogen.

On the basis of source, maturity, structure, and potential reservoirs, the Paleogene section of the Norton basin is the most prospective for petroleum. The Neogene section penetrated by the two test wells conformed rather well to expectations of thickness, character, and hydrocarbon potential. Perhaps a thicker Miocene section elsewhere in the basin might have more potential. At first glance it would appear that the Paleozoic section consists of nonprospective metamorphics. Nothing seen in either well strongly contradicts that negative assessment. However, minor amounts of marble were cored in the lower part of the No. 2 well, and a thick sequence of Paleozoic carbonates is present on the Seward Peninsula. It is possible that potential Paleozoic carbonate reservoirs, perhaps enhanced by pre-mid-Oligocene karsting, are present on the horst. The cataclastically sheared slate and marble seen in the No. 1 well might also develop reservoir qualities in some settings. A much more thorough understanding of the age and structural relationships of the rocks of the basement complex is necessary before its potential as an exploration play can be addressed. Although the pattern observed on the Seward Peninsula by Sainsbury and others (1970) of increasing metamorphic grade eastward appears to hold in the Norton Sound wells, it may be more perceived than real. Studies on these rocks currently underway should help elucidate the complex geologic history of the nearby Seward Peninsula, and thus the evolution of the Norton Basin.

ARCO Norton Sound COST No. 2 Summary

The ARCO Norton Sound COST No. 2 well was drilled to a measured depth of 14,889 feet. The KB was 105 feet above sea level and 154 feet above mudline. The water depth was 49 feet. Drilling commenced on June 7, 1982 and was completed in 81 days on August 27, 1982. Drilling rates ranged from 3 to 250 feet/hour. Four strings of casing were set: 30 inch at 416 feet, 20 inch at 1181 feet, 13 3/8 inch at 4673 feet, and 9 5/8 inch at 11,862 feet. The drilling fluid program was: sea water to 1231 feet, 9 pounds/gallon lignosulfate mud to 5100 feet, 10 pounds/gallon to 11,100 feet, 12 pounds/gallon to 14,889 feet. Gas associated with coal beds was encountered from 12,212 to 13,717 feet.

Thirteen conventional cores, 499 sidewall cores, and many well cutting samples were analyzed for porosity, permeability, lithology, hydrocarbon content, and paleontology. Rotary drill bit cuttings were collected from 450 to 14,889 feet.

Logging runs were made at depths of 4700, 11,907, and 14,889 feet. The Dual Induction-Laterolog (DIL), Borehole Compensated Sonic Log (BHC), and Spontaneous Potential (SP), Gamma Ray (GR), Long Spaced Sonic Log (LSS) with Integrated Travel Time (ITT), Repeat Formation Test (RFT), and the Four-arm, High Resolution Continuous Dipmeter (HRD), were recorded on all runs. The Compensated Neutron Log (CNL) with Neutron Gamma Tool (NGT) were recorded on the first and second runs. On the second and third runs a Vertical Seismic Profile (VSP), Lithodensity Neutron Log and Proximity Log-Microlog (MPL) were recorded. Additional logs run were a Compensated Formation Density Log (FDC) and a Velocity Survey, on the first run; and a Cement Bond Log (CBL) and Temperature Log on the last run. A Gamma Ray Casing Collar Locator was run at 11,651 feet.

Two drill stem tests for water analysis were made through perforations in the 9 5/8 inch casing.

The cumulative cost for the well was $32.2 million.

As required by 30 CFR 251, the operator (ARCO) filed a Drilling Plan, Environmental Analysis, Oilspill Contingency Plan, and Coastal Zone Management Certification. In addition, geohazards, geotechnical, and site-specific biological surveys were required. The zooplankton, infauna, epifauna, vagile benthos, and pelagic fauna were collected and analyzed. Particular emphasis was placed on protecting local and migratory marine mammals and avifauna. Waste discharges into the environment were minimal, nontoxic, and in compliance with Federal environmental protection regulations.

Stratigraphic units in the No. 2 well were defined on the basis of microfossil content, lithological and log characteristics, correlation with the No. 1 well, and seismic character. Strata penetrated were Pleistocene from 450 to 1320 feet, Pliocene from 1320 to 2580 feet, Miocene from 2580 to 3524 feet, Oligocene from 3524 to 10,160 feet, Eocene from 10,160 to 12,700 feet, Eocene or older from 12,700 to 14,460 feet, and probable Paleozoic from 14,460 to 14,889 feet.

Sample quality and recovery was poor in much of the Pleistocene section and consisted of fine to medium grained, unconsolidated shelly sand with abundant lithic fragments and organic debris. The Pliocene section is characterized by siltstone, muddy sandstone, and diatomaceous mudstone. The Miocene section consists of diatomaceous mudstones, siltstone, and muddy sandstones. The Oligocene is coal-bearing over most of the section. The coal at the top of the section (3535-4570 feet) is continental (fluvial and paludal), that below 6300 feet is more esturine and deltaic in aspect. Sandstone and siltstone are more common in the deeper marine intervals (4570-6900 feet; 8000-8500 feet). The Eocene section is transitional to inner neritic from 10,160 to 12,200 feet and is characterized by sandstone, siltstone, mudstone, and shale. Coal is present in many samples and may represent either caving or partings as no coal beds were cored or seen on electric logs. The lower part of the interval (12,200-12,700 feet) contains coal, conglomerate, sandstone, mudstone, siltstone, and was deposited in a fluvial environment. The Eocene or older section (12,700-14,460 feet) contains interbedded sandstone, siltstone, mudstone, and abundant, thick coal beds. The interval from 14,460 to 14,889 feet contains quartzite, marble, and phyllite of probable Paleozoic age.

In order to have a permeability of 1 mD, a sandstone in the No. 2 well must have at least 13 percent porosity. On the basis of core data, sandstones with 13 percent or more porosity occur above 9000 feet in the well. Porosity and permeability reduction are a function of compaction, authigenic mineral growth, and cementation.

A thermal gradient of 2.02°F/100 feet was calculated for the section above 11,000 feet; below this depth the mean gradient is 2.50°F/100 feet.

The organic matter is predominantly Type III, humic, gas-prone kerogen. Sufficient maturity for peak oil generation exists below 10,600 feet and crude oil could be preserved to about 14,000 feet. Minor occurrences of gas and liquid hydrocarbons were observed in samples obtained below 10,000 feet. Methane, thought to be of biogenic origin, is present in a few sands above 3000 feet.

Four seismic horizons were mapped and correlated: the basement unconformity (A), mid-Eocene (?) unconformity (B-1), mid-Oligocene transgressive marine facies (C), and late Oligocene regressive facies (D).

Interval velocities calculated from the sonic log are in agreement with those from nearby stacking velocities to a depth of 6100 feet. Below this depth the comparatively higher interval velocities probably are a function of different collection methods. Lithologic differences between the two subbasins probably account for a steeper time-depth curve in the No. 2 well than in the No. 1 well. Depth conversions of seismic data (velocity survey) could not be published or utilized in this study because of its longer proprietary term (USGS, Conservation Division, Policy Paper, January 22, 1982).

REFERENCES

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

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

Barker, C., 1974, Pyrolysis techniques for source-rock evaluation: Bulletin of the American Association of Petroleum Geologists, Vol. 58, p. 2349-2361.

Barron, John; 1980, Lower Miocene to Quaternary diatom biostratigraphy of leg 57, off northeastern Japan Deep Sea Drilling Project, Initial Reports: D.S.D.P. Leg 57, p. 641-686.

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

Biostratigraphics Consulting Micropaleontology, 1982, ARCO Norton Basin COST No. 2 well paleontology reports: 5 parts, 91 p.

Bouma, A. H., 1962, Sedimentary of some flysch deposits: 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, Vol. 22, p. 2-15.

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

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

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: Bulletin of the American Association of Petroleum Geologists, Vol. 60, No. 4, p. 608-626.

Csejtey, Bela, and Patton, W. W., 1974, Petrology of the nepheline syenite of St. Lawrence Island, Alaska: Journal of Research U.S. Geological Survey, Vol. 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.

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.

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

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

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, 1981, 27 p.

Espitalié, 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 leu degre d'evolution: Rev. J l'Institute Francais Petroleum, 32 (1), p. 23-42.

Fisher, M. A., Patton, W. W., and Holmes, M. L., 1982, Geology of Norton Basin and continental shelf beneath northwestern Bering Sea, Alaska: American Association of Petroleum Geologists Bulletin, v. 66, No. 3, p. 255-285.

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, Cordilleron Section, Vol. 13, No. 2, p. 56.

Gladenkov, Y. B., 1977, Stages in the evolution of mollusks and subdivisions of the North Pacific Neogene: First International Congress on Pacific Neogene Stratigraphy, Tokyo, 1976, Proceedings, p. 89-91.

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

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

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 D. W. Hood and J. A. Calder, eds., The eastern Bering Sea shelf and resources, 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.

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

Koizumi, Itaru, 1973, The Late Cenozoic diatoms of sites 183-193, leg 19 Deep Sea Drilling Project, Initial Reports: D.S.D.P. Leg 19, p. 505-856.

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, 32 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.

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, 209 p.

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: AAPG Bulletin, Vol. 60, No. 2, p. 161-183.

Menner, V. V., Baranova, Y. P., and Zhidkova, L. S., 1977, Neogene of the Northeastern U.S.S.R. (Kolyma Region, Kamchatka, and Sakhalin): First International Congress on Pacific Neogene Stratigraphy, Tokyo, 1976, Proceedings, p. 83-88.

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

Minerals Management Service, 1982, Guidelines for collection of meteorological, oceanographic, and performance data: Anchorage, Alaska.

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

Mutti, E., and Ricci, Lucchi, F., 1972, Le torbidii dell' Appennino settentrionale: introduzione all' analisi di facies: Memorie della Societa' Geologica Italiana, v. 11, p. 161-199.

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

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

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.

Patton, W. W., 1973, Reconnaissance geology of the northern Yukon-Koyukuk Province, Alaska: U.S. Geological Survey Professional Paper 774-A, 17 p.

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.

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.

Powell, T. G., and McKirdy, D. M., 1975, Geologic factors controlling crude oil composition in Australia and Papua, New Guinea: Bulletin of the American Association of Petroleum Geologists, Vol. 59, No. 7, p. 1176-1197.

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 G. O. Raasch, ed., Geology of the Arctic, Univ. Toronto Press, p. 48-67.

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.

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

Schrader, Hans, 1973, Cenozoic diatoms from the northeast Pacific, leg 18, Deep Sea Drilling Project, Initial Reports: D.S.D.P. Leg 18, p. 673-798.

Serova, M. Y., 1976, The Caucasina eocenica kamchatica Zone and the Eocene-Oligocene boundary in the northwestern Pacific: Progress in Micropaleontology, p. 314-328, 1 pl., 1 text fig., 3 tbls.

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

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

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.

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.

Stover, L. E., and Evitt, W. R., 1978, Analyses of pre-Pleistocene organic-walled dinoflagellates: Stanford University Publications, 300 p., 6 tbls.

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 Geological Societies Transactions, Vol. XVI, p. 119-130.

Tissot, B. P. and Welte, D. H., 1978, Petroleum Formation and Occurrence: Berlin Heidelberg New York, Springer-Verlag, 538 p.

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

Voloshinova, N. A., Kuznetsova, V. N., and Leonenko, L. S., 1970, Neogene Foraminifera of Sakhalin: Proceedings all Union Petroleum Scientific Research, Geological Exploration Institute (translated from Russian by the National Translation Service, TT 76-53241), 608 p., 51 pl.

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, 5 pl., 9 text-figs.

Wolfe, J. A., 1977, Paleogene floras from the Gulf of Alaska: U.S. Geological Survey Professional Paper 997, 108 p., 30 pl.

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

APPENDIX 1

Well Data and Consultants Reports Available for Public Inspection, Norton Sound COST No. 2 Well

Schlumberger Offshore Services
Anchorage, Alaska

2 in. Borehole Compensated Sonic Log
    Runs 1, 2, 3   1180-14,836 ft

5 in. Borehole Compensated Sonic Log
    Runs 1, 2, 3   1180-14,836 ft

5 in. Cement Bond Log Variable Density
    Run 1

2 in. Compensated Formation Density Log Gamma-Gamma
    Runs 1, 2, 3   1180-14,860 ft

5 in. Compensated Formation Density Log Gamma-Gamma
    Runs 1, 2, 3   1180-11,860 ft

2 in. Compensated Neutron Formation Density Log
    Runs 1, 2   1180-11,872 ft

5 in. Compensated Neutron Formation Density Log
    Runs 1, 2   1180-11,872 ft

5 in. Cyberdip
    Run 1   1180-4634 ft

5 in. Cyberdip
    Run 2   4666-11,875 ft

2 in. Cyberdip
    run 2   4666-11,875 ft

5 in. Dipmeter
    Run 1   1180-4634 ft

5 in. Dipmeter
    Run 2   4666-11,875 ft

5 in. Dipmeter
    Run 3   11,854-14,870 ft

Directional Log 8-30-82
    Run 1   11,854-14,870 ft

Schlumberger - cont.

2 in. Dual Induction - SFL
Run 1, 2, 3 1180-14,870 ft

5 in. Dual Induction - SFL
Run 1, 2, 3 1180-14,870 ft

2 in. Dual Induction - SFL w/Linear Correlation Log
Runs 1, 2, 3 1180-14,870 ft

1 in. Dual Induction - SP-GR Linear
Run 2 4666-11,871 ft

2 in. LDT-CNL-NGT LDT Porosity
Run 3 11,874-14,860 ft

5 in. LDT-CNL-NGT LTD Porosity
Run 3 11,874-14,860 ft

2 in. LDT-CNL-NGT CNL Porosity
Run 3 11,854-14,860 ft

5 in. LDT-CNL-NGT CNL Porosity
Run 3 11,854-14,860 ft

2 in. LDT Bulk Denisty CNL Porosity
Run 3 11,854-14,840 ft

5 in. LDT Bulk Density CNL Porosity
Run 3 11,854-14,840 ft

2 in. Long Spaced Sonic
Runs 1, 2, 3 1180-14,860 ft

5 in. Long Spaced Sonic
Runs 1, 2, 3 1180-14,860 ft

5 in. Long Spaced Sonic Waveforms
Run 1 1180-4634 ft

5 in. Long Spaced Sonic Waveform
Run 2 4666-11,864 ft

5 in. Long Spaced Sonic Waveform
Run 3 11,854-14,860 ft

2 in. Micro-Proximity Log
Run 2 4666-11,875 ft

Schlumberger - cont.

- 5 in. Micro-Proximity Log
  - Run 2 4660-11,875 ft

- 2 in. NGT
  - Run 1 1180-4602 ft

- 2 in. NGT
  - Run 2 4666-11,840 ft

- 2 in. NGT
  - Run 3 11,854-14,830 ft

- 5 in. NGT
  - Run 1 1180-4602 ft

- 5 in. NGT
  - Run 2 4666-11,840 ft

- 5 in. NGT
  - Run 3 11,854-14,860 ft

- Repeat Formation Tester Run 1 6-21-82

- Repeat Formation Tester Run 2 7-28-82

- Repeat Formation Tester Run 3 8-31-82

- Temperature Log
  - Run 1 380-14,870 ft

- Geodip Pattern Recognition
  - 6 Folders Printout
  - 6 Folders Charts Sepia
  - 1 3500-5800 ft
  - 2 5800-7100 ft
  - 3 7100-8450 ft
  - 4 10,400-11,500 ft
  - 5 11,900-13,800 ft
  - 6 13,800-14,600 ft

- Directional Survey Run No. 2
  - Plot and Print Out 4666-11,868 ft

- Directional Survey Run No. 3
  - Plot and Print Out 11,854-14,870 ft

- Logging Quality Control Survey
  - Runs 1, 2, and 3

Schlumberger - cont.

High Resolution Dipmeter Cluster Listings
- Run 1, 1202-4628 ft
- Run 2, 4702-11,868 ft
- Run 3, 11,857-12,160 ft

Exploration Logging Inc. (Exlog)
Anchorage, Alaska

Downhole Logging While Drilling Log
450-11,220 ft, Sepia

Final Geochemical Well Report
Vol. 1

Organic Carbon and Pyrolysis Data
1230-14,491 ft, 33 p.

Organic Carbon and Pyrolysis Data
Cores 4, 5, 6, 7, and 9, 4 p.

Head Space Gas Analysis
1230-4590, 4 p.

Temperature Data Log Raw Data
Sepia 154-14,889 ft

Temperature Data Log End To End
Sepia 154-14,889 ft

Pressure Evaluation Log
Sepia 154-14,889 ft

Drilling Data Pressure Log
Sepia 154-14,889 ft

Mud Resistivity Log
Sepia 154-14,889 ft

Wireline Data Pressure Log
Sepia 154-14,889 ft

Formation Evaluation Log
Sepia 154-14,889 ft

Geochemical Evaluation Log
Sepia 1236-14,889 ft

End of Well Report
1 Vol.

Birdwell Division
Seismograph Service Corporation
Tulsa, Oklahoma

Airgun Seismic Velocity Survey

6-21-82	1180-4634	A-U
7-26-82	4666-11,875	A-Z
7-26-82	4666-11,875	AA-AD
7-28-82	4673-11,875	A-Z
7-28-82	4637-11,875	AA-DD

Vertical Seismic Profile

Final Seismic Velocity Survey
and Log Calibration

ARCO Alaska Inc.
Anchorage, Alaska

Drill Stem Test No. 1 Procedures

Drill Stem Test No. 2 Procedures

Wellsite Core Descriptions
Cores 1-13, 13 reports

Sidewall Core Descriptions
1324-15,856 ft, 12 p.

Lithology Log
Sepia RKB-14,900 ft

ADP Sundry Notices Well Completion Report

Core Laboratories, Inc.
Dallas, Texas

Correlation Core Graphs Sepia
4600-7100, 7950-10,300, 11,150-13,000, 13,340-14,900 ft

Core Photos
1-23 Ultraviolet light
1-23 White light

Core Gamma Preliminary Data
Cores 1-6, 6 p.

Final Permeability and Porosity
Report on Cores, 3 p.

Core Laboratories, Inc. - cont.

Final Permeability and Porosity
Report on Sidewall Cores, 4 p.

Biostratigraphics, Inc.
San Diego, California

Final Biostratigraphic Report

Biostratigraphic Charts Sepia
Foraminifera: 1230-13,850 ft
Spores, Pollen, Microplankton: 1230-13,850 ft
Diatoms: 1230-7070 ft

Paleobotany Report
5 p.

Global Geochemistry Corporation
Canoga Park, California

Cation, Anion, and Isotope Data
7370, 10,300, 14,850 ft

Geochemical Analysis of D.S.T. Samples 1 and 2
10-8-82

Teledyne Isotopes
Westwood, New Jersey

K-AR Age Determination
Sample KA 82-595, 596, 597

AGAT Consultants Inc.
Denver, Colorado

AGAT Report, 5 vol.

Robertson Research
Houston, Texas

Geochemical Analysis Final Report
1 vol.

Chemical and Geological Laboratories of Alaska, Inc.
Anchorage, Alaska

Water Analysis Reports
RFT Samples, 2 p.

Water Analysis Reports
14 p.

Minerals Management Service
Anchorage, Alaska

Environmental Assessment

PBI, Inc.
Golden, Colorado

Core Velocity Data