UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGICAL and OPERATIONAL SUMMARY, COST NO. B-3 WELL, BALTIMORE CANYON TROUGH AREA, MID-ATLANTIC OCS

Roger V. Amato and Edvardas K. Simonis, Editors

Open-File Report 79-1159

1979

CONTENTS

ILLUSTRATIONS
(Plates in pocket)

Page

TABLES Page

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 centimeter
1 gallon = 3.78 liters (cubic decimeters)
1 barrel (42 US 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

GEOLOGIC AND OPERATIONAL SUMMARY, COST NO. B-3 WELL,
BALTIMORE CANYON TROUGH AREA, MID-ATLANTIC OCS

INTRODUCTION

The Continental Offshore Stratigraphic Test (COST) No. B-3 well was drilled to a depth of 15,820 feet by Chevron USA Inc., who acted as well operator for 10 other participating companies. The well was begun on October 9, 1978, and completed on January 25, 1979, at a location approximately 93 statute miles southeast of Atlantic City, N. J. (fig. 1). Drilled in 2,686 feet of water by the dynamically positioned drill ship ship Ben Ocean Lancer, this is the first deep well to penetrate the U. S. Atlantic slope, that part of the continental margin between the shelf and rise. The B-3 penetrated 2,240 feet of Tertiary calcareous mudstone, claystone, and argillaceous limestone, 2,650 feet of Upper Cretaceous sandstone, siltstone, and calcareous mudstone, 3,710 feet of Lower Cretaceous sandstone interbedded with shale and minor carbonate rocks, and 3,420 feet of Upper Jurassic shale, limestone, and sandstone. The well had a show of gas in the interval from 15,744 to 15,752 feet; the show was judged to be significant by the U. S. Geological Survey and was announced to the public on January 18, 1979.

Geological and engineering data obtained from this deep stratigraphic test were used by participating companies and the U.S. Geological Survey (USGS) for evaluating the petroleum potential, as well as possible drilling problems in the deep-water shelf and slope areas of the Baltimore Canyon Trough area in preparation for Lease Sale No. 49 held on February 28, 1979. Information obtained on the operations, lithology, potential source rocks, temperature and pressure gradients, biostratigraphy, etc., is summarized in this report. As with previous COST wells, the COST No. B-3 well was drilled away from any potential petroleum-bearing feature, but near several tracts that were included in the sale area. The public disclosure provision of the regulations on geological and geophysical explorations of the OCS (30 CFR 251.14) specifies that geological data from deep stratigraphic tests, including analyzed and interpreted information, shall be released 60 days after the issuance of the first Federal lease within 50 nautical miles of the test site, or 5 years after the well completion if no lease is issued. Block 21, about half a mile northwest of the B-3 well, was leased on May 1, 1979, to Murphy Oil Company following OCS Lease Sale 49.

Part of the information included in this summary is based on contract reports by service companies, sample analyses by oil companies, and USGS interpretations of electric logs, drill cuttings, and cores. These data may be inspected at the Public Information Room of the USGS, 1725 K Street, N. W., Washington, D. C. All depths referred to in this report are given in feet below the Kelly Bushing (K. B.) elevation which was 42 feet above mean sea level. Because mainly English units of measurement are used in the report, a table of equivalent metric units follows the Contents.

OPERATIONAL DATA

By Jan Libby-French

Chevron USA Inc., acting as operator for the well program, drilled the COST No. B-3 well under an OCS permit No. E-9-78 issued by the U. S. Geological Survey (USGS). Expenses were shared by the following 11 participants:

Atlantic Richfield Company
Chevron USA Inc.
Continental Oil Company
Exxon Company USA
Getty Oil Company
Mobil Exploration and Production Services Inc.
Ocean Production Company
Phillips Petroleum Company
Shell Oil Company
Tenneco Oil Company
Union Oil of California

Drilling stipulations required that the operator provide the USGS with copies of all well logs, washed and unwashed samples, core slabs, and operational and technical reports. These were received by the USGS at the same time as they were by the industry participants.

The surface location of the COST No. B-3 well was lat. 38°55'00.655" N.; long. 72°46'22.578" W. or at U.T.M. coordinates x = 693,086 meters and y = 4,309,699 meters, in Block 66 in the OCS Official Protraction Diagram NJ 18-6 (fig. 2). The B-3 well was drilled as a vertical hole with the course inclination no greater than 2 3/4°.

Chevron used ODECO's dynamically positioned drill ship Ben Ocean Lancer to drill the well. The ship's length is 490 feet, beam, 77 feet, depth, 41 feet, and design draft, 26 feet. Its minimum operating water depth is 300 feet and its maximum is 3,000 feet. The ship arrived

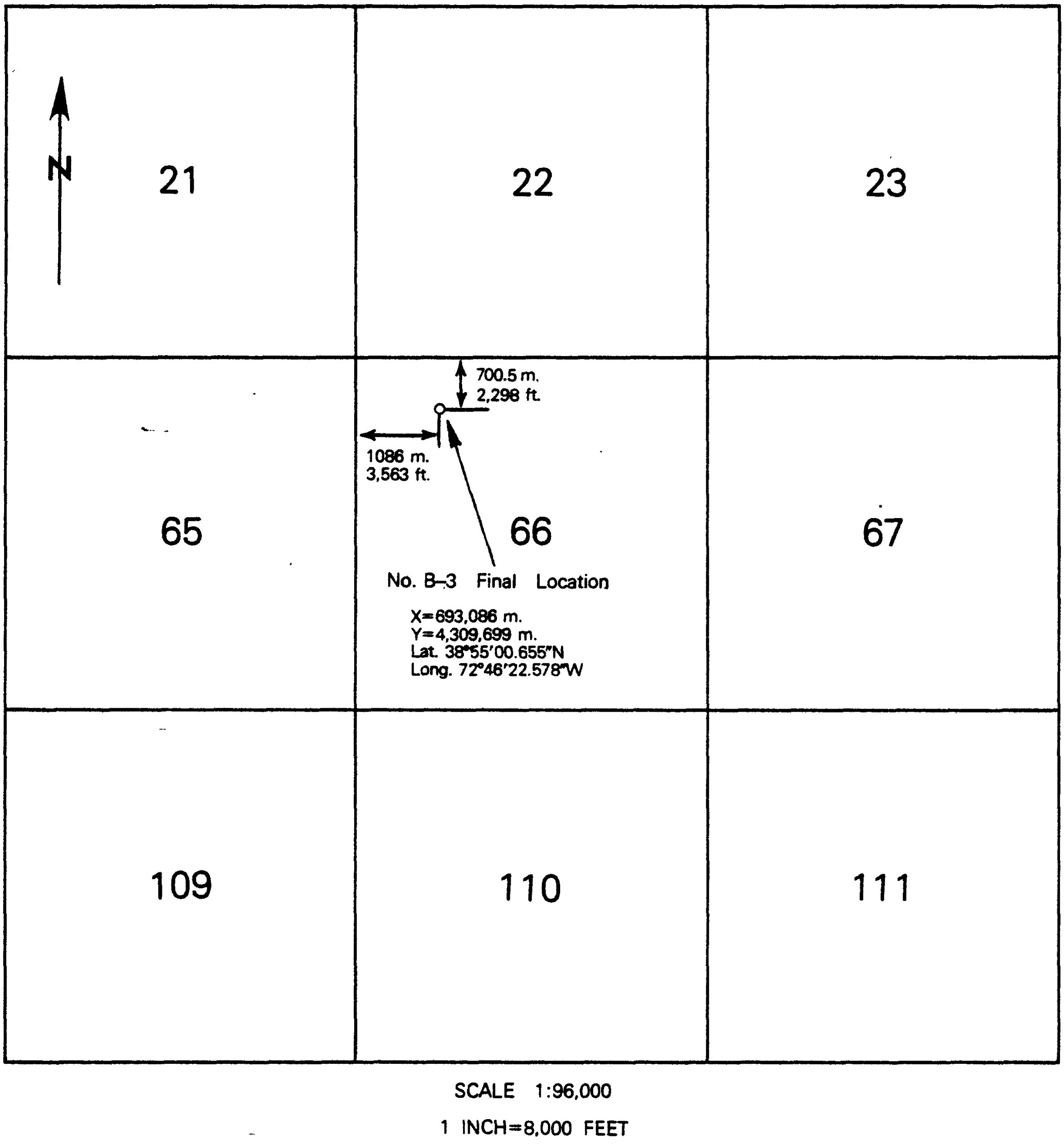

Figure 2.--Final location plat showing the surface position of the COST No. B-3 well in OCS Protraction Diagram NJ 18-6.

on location and was positioned in 2,686 feet of water on October 8, 1978. The well was spudded on October 9th and drilled to a total depth of 15,820 feet which was reached on January 18, 1979. Final wireline logging and seismic velocity surveys were completed and sidewall cores were obtained. The well was then plugged and the rig was released on January 25, 1979, 109 days after spud date.

Variances in Operating Procedures

The U. S. Geological Survey permitted several variances in operational procedures during the drilling of the COST No. B-3 well: Stipulation No. 6, issued in conjunction with the permit to drill the well, required that the drill cuttings be down-shunted at a depth of 40-50 feet below the ocean surface. This requirement was waived because the discharge of drill cuttings below the ship would have interfered with the ship's acoustic positioning system. The USGS agreed that the discharge above, instead of below the ocean surface would cause only a minor and temporary effect on the area's marine biology.

Exception was also granted to the Mid-Atlantic OCS order No. 2 requiring the use of a riser system in drilling the structural and conductor holes for the 30-inch and 20-inch casing. The Ben Ocean Lancer was not equipped to connect a riser to the 30-inch casing, so permission was granted to let the drilling returns spill to the sea floor until the 20-inch conductor casing was set at 1,025 feet below the sea floor. Sea water was used as the main drilling fluid down to this depth; therefore chemical pollution of the ocean was minimal.

Contrary to normal operating procedures, the casing strings were not cut below the sea floor after plugging the well. The required plugs were set during the plugging operations and an attempt was then made to recover the guide base assembly. However, the assembly had settled approximately 8 feet while the 20-inch casing was being set, and a cone of soft silt had formed around the base of the blow-out preventer (BOP) during subsequent drilling operations. When the BOP was raised, the silt settled and covered the guide base. A search with a television camera showed that the guide base was totally covered. As the wellhead was not protruding above the sea bed, permission was granted to abandon the well without cutting the casing strings below the sea floor.

Drilling Program

The COST No. B-3 well was drilled using one 26-inch drill bit to a depth of 3,785 feet, twenty-one 12 1/4-inch bits to 12,695 feet and twelve 8 1/2-inch bits to reach total depth of 15,820 feet. Seven additional bits were used for reaming out the hole before setting the casing strings, drilling out cement at the bottom of casing, and cutting the conventional diamond cores. Figure 3 shows the daily drilling progress and logging and casing depths for the well. The drilling rate ranged from 4 to 800 feet/ hour. The average drilling rate to 5,766 feet was 105 feet/hour, decreasing to 60 feet/hour from 5,766 to 7,400 feet, 30 feet/hour from 7,400 to 9,700 feet, and 8 feet/hour from 9,700 feet to total depth.

Four casing strings were set and cemented with Class G cement (fig. 4). The 30-inch casing was set at 2,894 feet, the 20-inch casing

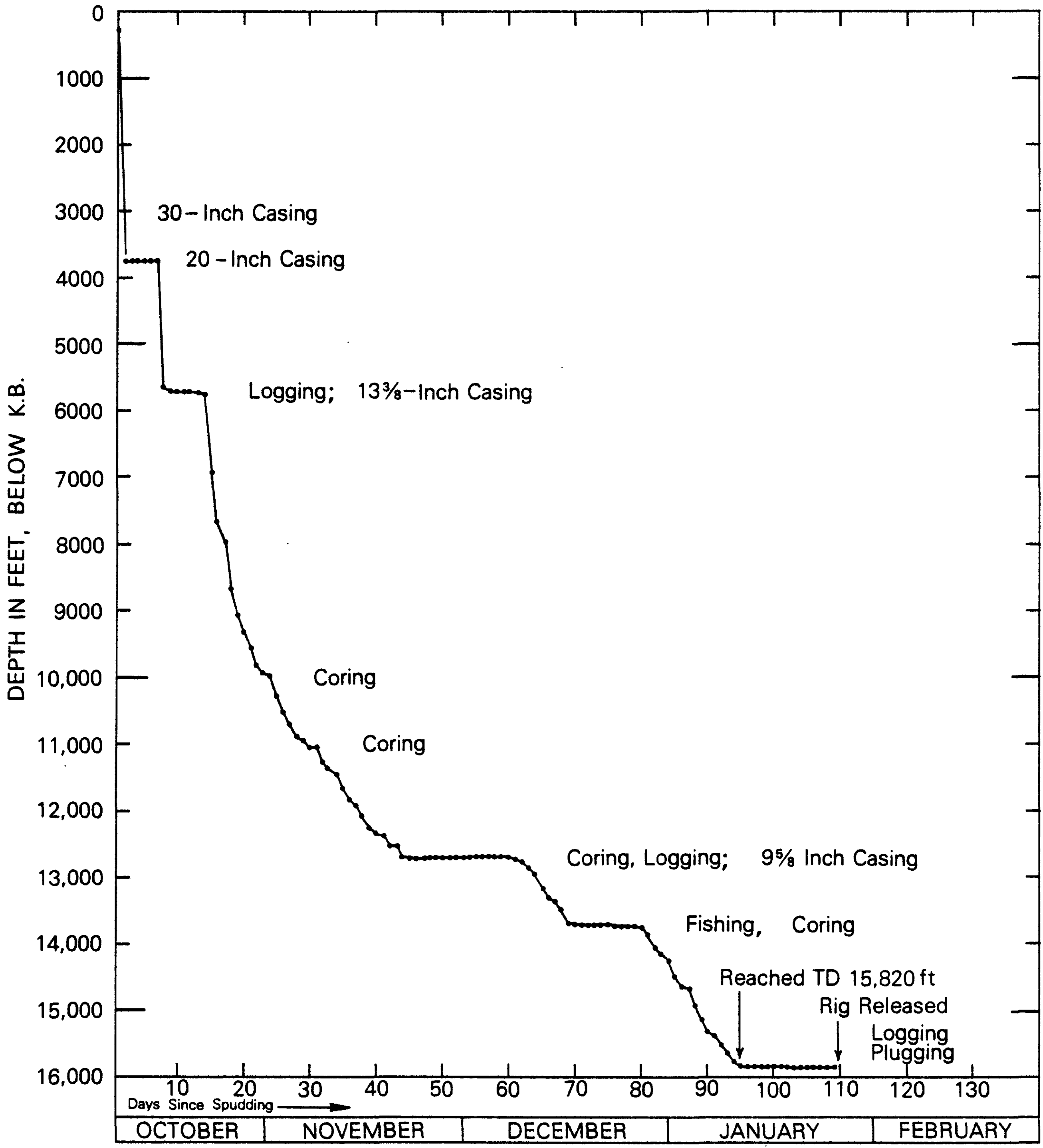

Figure 3.--Daily drilling progress for the COST No. B-3 well, 1978-79.

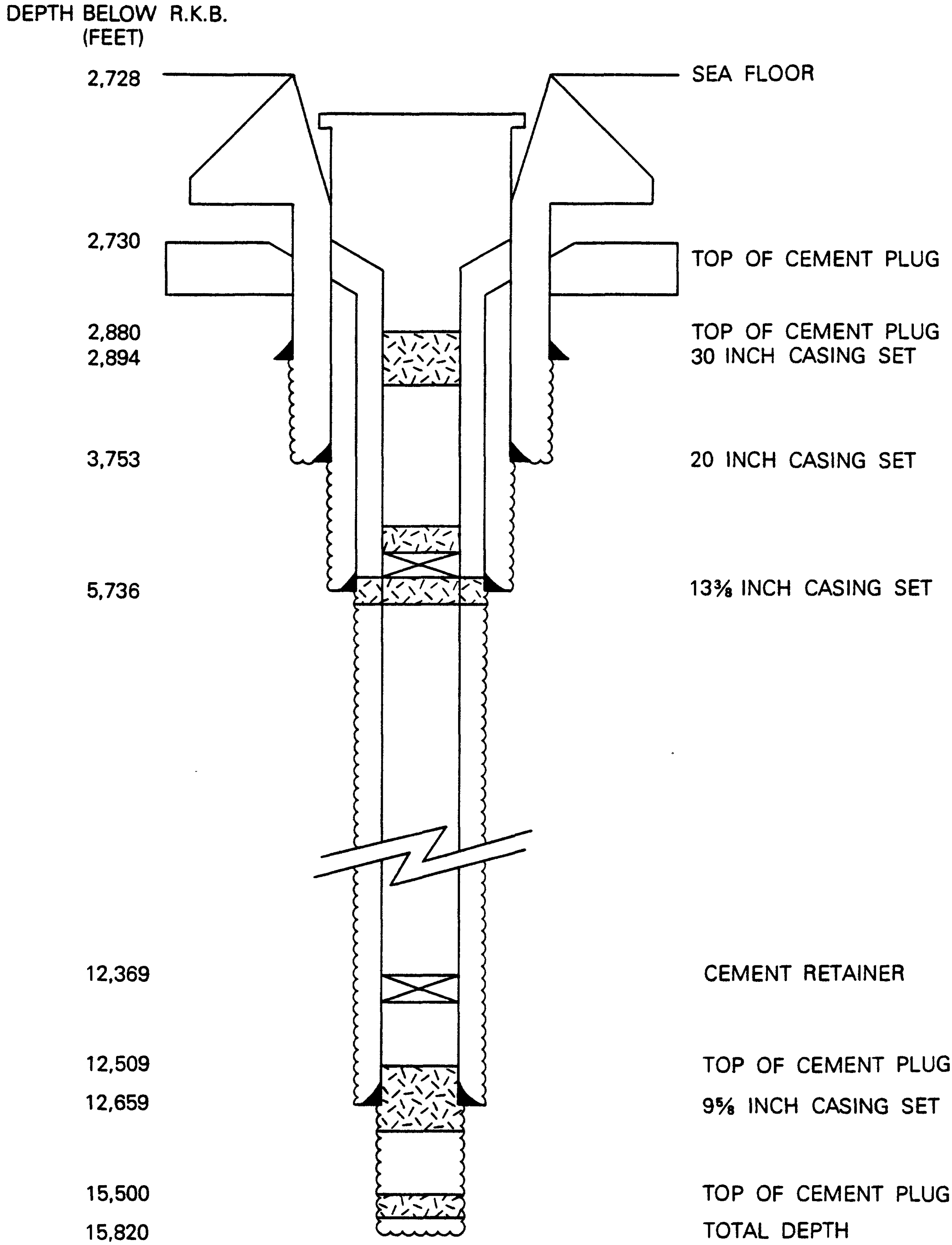

Figure 4.--Diagram showing relative position of casing strings and plugging and abandonment program.

was set and cemented at 3,753 feet with 1,250 sacks of cement, the 13 3/8-inch casing at 5,736 feet with 1,328 sacks of cement, and the 9 5/8-inch casing at 12,659 feet with 2,587 sacks of cement.

Sea water was used to drill from 2,894 to 3,785 feet, a sea water-gel system was used from 3,785 to 5,766 feet and a gel-lignosulfonate mud was used to drill the remainder of the well. The mud weight was increased gradually from 9.0 to 10.0 pounds per gallon (ppg) for the first 12,659 feet. It was then decreased to an average of 9.6 ppg to a depth of 15,640 feet. While drilling between 15,750 and 15,780 feet with 10.1 ppg mud, the mud was cut by gas to 8.2 ppg. The mud weight was then increased to 11.7 ppg for the remainder of the well. Mud viscosity ranged from 38 to 50 seconds but generally remained between 42 to 46 seconds. The pH ranged from 8.0 to 11.8 and averaged 11.3 below 6,400 feet.

Exploration Logging Inc. provided the mud logging service for the B-3 well and collected the cuttings samples. A physical formation log was run as drilling proceeded, in order to monitor the mud system and drilling progress. Included in this log are the rate of drill penetration, a lithologic description of the cuttings and the total hot wire gas units and chromatographic analysis.

The final estimated cost for the well was approximately $12 million. This amount included approximately $604,000 for the preliminary site surveys, $545,000 for the geoscience and logging costs, $156,000 for drill bits and other downhole equipment, $197,000 for mud costs and $558,000 for the casing program. The time spent on the various activities in the drilling operation was as follows:

	Hours	Percent of Total
Drilling	734.0	29.4
Tripping	459.0	18.4
Fishing	322.5	12.9
Circulating and Reaming	136.0	5.5
Abandonment	50.0	2.0
Coring	69.5	2.8
Wireline Logging	230.5	9.2
Rigging Up and Running Casing	53.5	2.1
Rig Repair	72.0	2.9
Cementing	15.5	0.6
Repeat Formation Testing	16.5	0.7
Surveys	15.0	0.6
Waiting on Weather	152.5	6.0
Other	168.75	6.9
Total	2495.25	100.0

Samples, Tests, and Logs

Samples of well cuttings were obtained from the B-3 well at 30-foot intervals from 3,790 to 5,770 feet and at 10-foot intervals from 5,770 feet to total depth. These samples were used for both lithologic and paleontologic study. Sidewall and conventional cores were also obtained and provided data such as porosity, permeability, grain density, and lithologic and paleontologic descriptions. A total of 1,466 sidewall cores were attempted, of which 689 were recovered. Four conventional cores were cut; the cored intervals and recoveries are as follows:

Core No.	Depth (feet)	Feet Cut	Recovery (feet)
1	9,921 - 9,940	19	14
2	11,009.5-11,069.5	60	51.25
3	12,572 -12,588	16	15.3
4	13,773 -13,798	25	21.5

Geophysical logs and seismic velocity surveys were conducted at three different times and intervals during drilling of the well. Log run 1 was conducted October 17-19 for the 3,753-5,726 foot interval and included a dual induction-spherically focused log , a compensated neutron log/compensated formation density log, a long-spaced sonic log, a high-resolution dipmeter, and a seismic reference survey. Log run 2 was conducted November 22-December 1 for the 5,726-12,654 foot interval and included continuations of the same suite of logs from log run no. 1 with the addition of a proximity microlog. Log run no. 3 was conducted January 12-16 for the 12,654-15,810 foot interval and included continuations of log runs 1 and 2 and an additional dual laterolog. Wireline formation tests were performed once at 15,748 feet, and 15,749 feet and twice at 15,750 feet with a repeat formation tester.

Conclusion

No major problems were encountered in drilling operations and geologic evaluation of the COST No. B-3 well. The operation confirmed the functional state of technology for exploratory drilling in the relatively deep waters of continental slopes.

LITHOLOGY

By David J. Lachance

Drill cutting samples from the COST No. B-3 well were obtained at 30-foot intervals from 3,790 to 5,770 feet, and at 10-feet intervals from 5,770 to 15,820 feet. A lithologic log was prepared for the B-3 well participants by the Amoruso Group of Houston, Texas, and is available for inspection along with other logs, samples, and cores at the Public Information Office of the USGS, 1725 K Street N. W., Suite 204, Washington, D. C. 20006.

The following summary of the strata penetrated by the COST No. B-3 well is based on my detailed lithologic studies of its drill cuttings. The lithologic column is summarized on plate 1. All depths are measured depths below Kelly Bushing which was 42 feet above mean sea level.

The stratigraphic sequence penetrated by the COST No. B-3 well has been divided into four major lithologic units. Section IA and IB, from 3,790 to 6,080 feet, is of Tertiary age and consists of calcareous mudstone, claystone, and minor amounts of argillaceous limestone and siltstone. Section II, from 6,080 to 8,200 feet, consists dominantly of mudstone and siltstone of Late Cretaceous age. Sections IIIA to IIID, from 8,200 to 12,400 feet, is composed of sandstones interbedded with shale and minor amounts of carbonates; this section ranges in age from Early Cretaceous to early Late Cretaceous. Section IVA and IVB, from 12,400 to 15,820 feet, consists of Upper Jurassic shales, carbonates and lesser amounts of sandstone.

These sections are further divided into subsections. All contacts are gradational except for the sharp contacts at the top and bottom of Section IIIA.

Section IA 3,790-5,160 feet

This section consists of light-gray and green-gray to brown-gray calcareous mudstones with traces of muscovite, foraminifera, and quartz sand grains and pebbles. Other minor constituents include sparse to trace amounts of shell fragments, pyrite, microcrystalline limestone, buff chert, coal, and rare to abundant glauconite grains.

Section IB 5,160-6,080 feet

Above 5,780 feet this section consists of very calcareous, light-gray to off-white and greenish gray, subfissile claystone and minor amounts of medium-gray shale. Trace constituents include: nodular pyrite; fibrous calcite spar; light-gray to light-brown, and orange-brown chert; light-brown to light-orange microcystalline, glauconitic limestone; quartz sand grains and pebbles; and a few glauconite grains. Foraminifera occur in trace to locally abundant amounts. Below 5,780 feet, in addition to the claystone and shale, thin laminae of very calcareous, light-to brownish-gray siltstone are present, and contain traces of pyrite, glauconite, and forams.

Section II 6,080-8,200 feet

The contact with Section IB is gradational, and the upper part of Section II is marked by a relative increase of the gray siltstone present in Section IB; however, this siltstone gradually grades into mudstone at approximately 6,290 feet. Below this depth the section consists of interbedded calcareous, light-to medium-gray, amorphous to subfissile, silty mudstone with minor amounts of thin laminae and beds of light-to medium-gray shale, minor amounts of very thin, soft, earthy, white limestone, and soft to hard, dense, earthy to microcrystalline, gray to buff limestone and dolomite. From approximately 6,600 to 7,060 feet minor amounts of quartz sand grains and pebbles are present. Most of the grains appear to be floating in the mudstone, and are fine to very coarse, subangular to rounded, and opaque. A second minor zone of fine sand extends from 7,610 to 7,810 feet.

Glauconite grains, nodular pyrite, muscovite, coal, shell fragments, foraminifera and fibrous calcite spar are scattered in sparse amounts throughout this section. Near and in the sandy intervals glauconite becomes common to abundant.

Section IIIA 8,200-8,710 feet

This section consists of interbedded sandstone, shale, amorphous to subfissile mudstone, and minor amounts of carbonate, and has relatively sharp upper and lower contacts. The sandstone is light gray, moderately indurated, and slightly calcareous. The quartz grains in the sandstone are angular to subangular, moderately sorted, clear to opaque gray, and medium to coarse grained and locally pebbly. Sparse constituents include glauconite grains, pyrite, shell fragments, muscovite, and forams. The shale and mudstone are light to medium gray, slightly to moderately calcareous, and contain a few coal laminae, traces of fibrous calcite spar, and disseminated siderite. The carbonates occur as thin laminae in the mudstone and shale, and predominantly consist of soft, earthy, white to off-white, locally sandy limestone with scattered glauconite grains and shell fragments.

Also present are minor amounts of light-gray to buff, hard, microcrystalline limestone and dolomite with traces of glauconite and pyrite. A third type of carbonate--a soft, earthy, buff dolomite--occurs as scattered laminae.

Section IIIB 8,710-9,860 feet

This section consists of shale and amorphous to subfissile mudstone, and minor amounts of thin laminae and beds of sandstone and carbonate. The mudstone and shale are slightly sandy, calcareous, and predominantly light to medium gray; minor amounts of greenish-gray and off-white laminae are present. Sparse constituents include pyrite, fibrous calcite spar, and glauconite grains. Between the top of the section and 9,370 feet are trace to locally abundant limestone nodules. Most of these nodules are 1 to 2 mm in size, and roughly spheroidal to ellipsoidal, with numerous shape variations (including discoidal and composite spheres).

The sandstones occur as thin laminae and beds, and are light gray to brownish gray, moderately consolidated, and calcareous, with traces of pyrite and glauconite. The quartz grains are very fine to medium grained, angular to subangular, moderately sorted, and predominantly clear to gray opaque.

The carbonates occur as thin laminae, and resemble those in Section IIIA. However, each type of carbonate is present in approximately equal amounts.

A few thin laminae of coal occur in the mudstone and shale.

Section IIIC 9,860-11,630 feet

This section consists of interbedded sandstone, shale, limestone, and minor siltstone. At approximately 10,755 feet, the section can be divided into upper and lower intervals, according to the relative proportions of sand to shale plus carbonate. The upper interval contains slightly more shale.

The sandstone and siltstone are micaceous, calcareous, locally argillaceous, poorly indurated, and contain very rare to trace amounts of glauconite grains, forams, pyrite, and shell fragments. Above approximately 11,260 feet the sand and siltstone are predominantly light gray with a few buff laminae. The quartz grains in the sandstone are angular to subangular, poorly to moderately sorted, clear to gray opaque, medium to coarse grained, and locally pebble sized. Below 11,260 feet the sandstone and siltstone are predominantly light buff, and the quartz grains in the sandstone are very fine to fine grained.

The shale is noncalcareous to calcareous, slightly micaceous, locally silty, and medium to dark gray and locally black. Sparse constituents include glauconite grains, shell fragments, and ovoid siderite pellets. Mudstone similar to that in Section IIIB occurs in a thin transitional interval near the top of the section.

The limestone occurs as thin laminae to relatively thick beds, and is dense, soft, white to off-white, and locally pale pink, slightly argillaceous, silty, and sandy. Texture ranges from earthy to fine crystalline. Sparse to trace constituents include glauconite grains, pyrite, and shell fragments. Also present are minor amounts of coal, and thin buff hard microcrystalline limestone.

Section IIID 11,630-12,400 ft

This section consists of interlaminated shale, thin sandstone, and minor amounts of siltstone and carbonate. The contact with Section IIIC is gradational, and with increasing depth the sand/shale ratio decreases.

The sandstone and siltstone are calcareous, micaceous, argillaceous, and light gray to faintly buff, with a few grains of glauconite, pyrite, and shell fragments. The quartz grains in the sandstone are angular to subrounded, poorly to moderately sorted, very fine to medium grained, and clear to gray opaque. The siltstone, in occasional thin laminae, is dark buff, argillaceous, and calcareous.

The shale is calcareous, micaceous, and light to dark gray and brownish gray, with traces of glauconite and pyrite. Thin laminae of pale-greenish -gray, calcareous shale are also present.

The few carbonates present consist of very thin, hard, microcrystalline, light-gray to buff limestone and dolomite.

Coal is present as scattered thin stringers in the sands and shales.

Section IVA 12,400-12,710 feet

This section consists of interbedded sandstone, and shale, and relatively thin beds of limestone, some of which are oolitic; upper and lower contacts are gradational.

The sandstone is calcareous, white to light gray, and well indurated, and contains sparse grains of pyrite, muscovite, glauconite, and fossil fragments. The quartz grains in the sandstone are fine to coarse grained, angular to subangular, poorly sorted and clear to gray opaque.

The shale is predominantly medium to dark gray. A few thin laminae of dark brown and chloritic green shale are present.

The limestone is predominantly light gray to off-white, and ranges in texture from soft to hard, and dense and earthy; to hard, dense and microcrystalline. Oolites, pellets and algal lumps are common in some of these limestones. Also present are thin laminae of buff, microcrystalline, argillaceous limestone.

Section IVB 12,710-15,820 feet

This section consists of interlaminated shale and limestone, and minor amounts of thin sandstone beds. Despite numerous local variations, several general lithologic trends are noticeable. With increasing depth, the shale/carbonate ratio gradually increases, and both the total sandstone content and the muscovite content of the sandstone and shale increase slightly.

The shale is slightly micaeous, silty, light to dark gray and dark brownish gray, and is calcareous to very calcareous.

The carbonates are slightly argillaceous, predominantly light gray to white and faintly buff, and vary in texture from soft, dense, and earthy and microcrystalline to hard, dense, and microcrystalline to fine crystalline. With numerous local variations, degree of crystallinity increases with depth. Throughout the section are trace to locally abundant algal lumps, pellets, several oolite zones, and scattered pyrite grains.

A second type of limestone, common only in parts of the upper third of this section, is extremely argillaceous, waxy and subfissile, soft, and medium gray.

Present, in minor amounts, are scattered thin laminae of dense, dark buff limestone and dolomite.

The sandstone is light gray to white, very calcareous, well consolidated (15,750-15,780 feet is an exception), fairly micaceous, with very small amounts of pyrite, and occurs as thin, sporadic laminae and beds in the shale. The quartz grains in the sandstones are angular, moderately sorted, fine to medium grained, and clear to gray opaque.

Also present are a few very thin laminae of light-brown chert in the shales and limestones, and below 13,750 feet several very thin zones of coal, and possible gilsonite.

BIOSTRATIGRAPHY

By William E. Steinkraus

Paleontological investigations for the COST No. B-3 well were conducted largely by International Biostratigraphers Inc. (written communication, 1979). The biostratigraphic analyses were also supplemented by John W. Bebout (USGS) and myself. Microfossils studied included foraminifers, calcareous nannoplankton, spores, pollen, and dinoflagellates.

The biostratigraphic investigations were made from sidewall cores, conventional cores, junk basket core chips, and well cuttings samples. Foraminiferal analyses were conducted from 401 well cuttings samples composited at 30-foot intervals collected between 3,790 and 15,820 feet, and from 105 sidewall cores. Nannofossil age determinations resulted from the examination of 193 sidewall cores between 4,100 and 15,785 feet, from conventional cores and from 30-foot composite well cuttings samples. Palynological studies were made from 90-foot composite well cuttings samples, from 127 sidewall and conventional cores and from junk basket samples at 13,746-13,747 feet.

It was concluded that the B-3 well penetrated about 2,240 feet of Tertiary strata, 2,650 feet of Upper Cretaceous section and 3,710 feet of Lower Cretaceous beds. The well also penetrated 3,420 feet of Upper Jurassic rocks. Kimmeridgian-age palynomorphs have been identified at the total depth of 15,820 feet. The following data represent a composite paleontological summary of the well showing the depth to the tops of geologic series or stages:

Depth (feet)	Geologic Series, parts of Series, or Stage
3,800	In Middle Miocene
4,410	Lower Miocene
4,710	Upper Oligocene
4,860	Lower Oligocene
4,950	Upper Eocene
5,160	Middle Eocene
5,520	Lower Eocene
6,040	Lower Maestrichtian - Upper Cretaceous
6,200	Campanian
6,500	Santonian
6,920	Coniacian
7,910	Turonian
8,180	Cenomanian
8,690	Albian - Lower Cretaceous
9,530	Aptian
10,070	Barremian
10,610	Hauterivian
11,920	Berriasian
12,400	Tithonian - Upper Jurassic
13,220	Kimmeridgian
15,820	(T.D.)

Age Determinations

Biostratigraphic determinations in the Tertiary and Upper Cretaceous sections were based on foraminifers, calcareous nannofossils and palynomorphs. Early Cretaceous and Late Jurassic ages were delineated mainly from palynomorphs and to a lesser extent from nannofossils and foraminifers. Age diagnostic foraminifers were generally lacking in the interval between 8,690 and 15,820 feet.

Tertiary

Middle Miocene (3,800-4,410 feet)

Foraminifera: Planktonic species, Globorotalia peripheroacuta, Globorotalia fohsi fohsi and Globorotalia siakensis indicate a middle Miocene age. The diverse faunal assemblages also include Globorotalia praemenardii, Globorotalia scitula scitula, Bulimina gracilis, and Robulus Americanus spinosus. Radiolarians are common in the interval between 3,800 and 4,710 feet.

Palynomorphs: Dinoflagellates are rather abundant. Palaeocystodinium golzowense is present in the highest sample examined at 3,810 feet, indicating an age not younger than middle Miocene.

Nannofossils: The nannoflora is characterized mostly by long-ranging species. A middle Miocene age is suggested, though not confirmed, from the study of the sidewall cores.

Early Miocene (4,410-4,710 feet)

Palynomorphs: The interval between 4,410 and 4,710 feet has been defined as early Miocene largely based on the highest occurrence of Faguspollenites cf. granulatus and Chiropteridium aspinatum at this level. Comparable palynological assemblages of early Miocene age were recognized in the COST No. B-2 well.

Late Oligocene (4,710-4,860 feet)

Foraminifera: Globorotalia opima nana, Globigerina tripartita, and Catapsydrax unicavus have their highest occurrence in sidewall cores at 4,710 feet.

Palynomorphs: The highest occurrence of the dinoflagellate species Deflandrea phosphoritica indicates a late Oligocene age. Additional palynomorphs occurring in this relatively thin interval are Homotryblium floripes, Pentadinium laticinctum, Chiropteridium dispersum, Cordosphaeridium cantharellum, and Stephodinium spiniferum. Nannofossils: The occurrence of Triquetrorhabdulus carinatus together with Helicopontosphaera recta in the sidewall core at 4,710 feet indicates a latest Oligocene age.

Early Oligocene (4,860-4,950 feet)

Palynomorphs: The early Oligocene section is defined from the occurrence of the dinoflagellates Areosphaeridium diktyoplokus and Cordosphaeridium funiculatum.

Nannofossils: The presence of Sphenolithus ciperoensis in this interval suggests the absence of sediments of earliest Oligocene age in the COST No. B-3 well. The Oligocene Epoch is divided into early and late only.

Late Eocene (4,950-5,160 feet)

The entire Eocene section is characterized by rich and diverse faunal and floral assemblages of foraminifers, dinoflagellates, and calcareous nannofossils.

Foraminifera: The top of the Eocene is determined from the highest occurrence of Globorotalia cerroazulensis cocoaensis, Globigerinatheka semiinvoluta, Hantkenina longispina, Globorotalia cerroazulensis cerroazulensis, and Bulimina jacksonensis.

Palynomorphs: Late Eocene age is defined by Diphyes colligerum and

Batiacasphaera compta.

Nannofossils: The sidewall core at 4,965 feet contains the highest occurrence of *Discoaster barbadiensis*, *Discoaster saipanensis*, and *Isthmolithus recurvus*.

Middle Eocene (5,160-5,520 feet)

Foraminifera: The middle Eocene section is identified by the presence of *Globorotalia lehneri*, *Globorotalia spinulosa*, *Truncorotaloides rohri*, and *Hantkenina liebusi* occurring in the lower part of the interval. Additional planktonic foraminifers are *Globigerina frontosa*, *Globorotalia aragonensis*, and *Globoratalia pentacamerata*.

Nannofossils: Diverse assemblages observed in the sidewall cores include *Chiasmolithus grandis*, *Helicopontosphaera lophota*, *Helicopontosphaeara seminulum*, *Chiasmolithus solitus*, *Chiasmolithus consuetus*, and *Sphenolithus radians*.

Early Eocene (5,520-6,040 feet)

Foraminifera: An early Eocene age is based on the highest occurence of *Globigerina soldadoensis soldadoensis*, *Globorotalia caucasica*, and *Globorotalia quetra*. The presence of *Globorotalia formosa formosa*, *Globorotalia marginodentata*, and *Globorotalia subbotinae* at 5,910 feet indicates a middle early Eocene age. Assemblages characteristic of the lower part of the early Eocene have not been recognized in the B-3 well.

Palynomorphs: The assemblages in this interval are characterized palynologically by the species *Wetzeliella articulata*, *Wetzeliella clathrata*, *Samlandia reticulifera*, *Duosphaeridium nudum*, and *Homotryblium tenuispinosum*.

The lower part of the interval also contains Wetzeliella edwardsii.

Nannofossils: The highest occurrence of early Eocene species has been observed at 5,525 feet. The assemblages within the interval include Discoaster lodoensis, Chiasmolithus californicus, Discoasteroides kupperi, and Tribrachiatus orthostylus. Additional species are present in the lower part of the section between 5,940 and 6,030 feet, including Discoaster multiradiatus and Lophodolithus nascens.

No microfossil assemblages characterizing the Paleocene or the latest Maestrichtian ages have been recognized in the COST B-3 well.

Cretaceous

Early Maestrichtian (6,040-6,200 feet)

Foraminifera: Globotruncana gansseri, Globotruncana conica, Globotruncana contusa, and Globotruncana stuarti have their highest occurrences at 6,040 feet.

Palynomorphs: Early Maestrichtian age has been defined from the occurrence of Hystrichodinium pulchrum in the sidewall core at 6,086 feet. The sample yielded a diverse assemblage including Isabelidinium cretaceum, Alterbia minor, and Exochosphaeridium bifidum.

Nannofossils: In the sparse assemblage between 6,040 and 6,070 feet, Arkhangelskiella cymbiformis, Tetralithus aculeus, and Micula staurophora have been identified from well cuttings samples. Broinsonia parca is present at 6,070 feet and Tetralithus nitidus at 6,086 feet.

Campanian (6,200-6,500 feet)

Foraminifera: This interval contains a rich and diverse assemblage and is characterized by Globotruncana calcarata, Globotruncana elevata, Globotruncana fornicata, Globotruncana lapparenti, and Kyphopyxa christneri.

Palynomorphs: The top of the Campanian has been based on the highest occurrence of Odontochitina costata and Cyclonephelium distinctum at 6,200 feet. Odontochitina porifera has been identified at 6,380 feet.

Nannofossils: A characteristic Campanian assemblage is present in the sidewall core at 6,280 feet, including Eiffellithus eximius and Bukryaster hayi.

Santonian (6,500-6,920 feet)

Foraminifera: The top of this stage is placed at the highest occurrence of Globotruncana concavata, Globotruncana carinata, and Globotruncana coronata at 6,500 feet. It should be noted, however, that the highest occurrence of the nannofossil indicator has been observed 30 feet above this interval.

Palynomorphs: The Santonian has been identified by the occurrence of Dinopterygium cladoides and Tanyosphaeridium variecalamum at 6,560 feet and Callaiosphaeridium asymmetricum at 6,740 feet.

Nannofossils: The stage is recognized by the presence of Marthasterites furcatus which has its highest occurrence at 6,470 feet.

Coniacian (6,920-7,910 feet)

Palynomorphs: The top of the Coniacian has been determined from the highest occurrence of Schizosporis reticulatus and Cicatricosisporites perforatus at 6,920 feet. Heliosporites sp. and Appendicisporites cf. A. segmentus is present at 7,280 feet.

Foraminifera: Age-diagnostic foraminifers appear to be absent in the uppermost part of the interval and the fauna is indicative of an inner shelf environment of deposition. The planktonic species Globotruncana schneegansi and Globotruncana sigali occur at 7,110 feet.

Turonian (7,910-8,180 feet)

Foraminifera: The foraminifers present at 8,040 feet include Praeglobotruncana stephani, Praeglobotruncana turbinata, and Lingulogavelinella turonica. The highest occurrence of Globorotalia helvetica is slightly lower in the interval.

Palynomorphs: The top of the Turonian is based on the highest occurrence of Coronifera oceanica and Proteacidites sp. Exeisipollenites tumulus is present at 8,095 feet.

Cenomanian (8,180-8,690 feet)

Foraminifera: The Cenomanian top is based on the highest occurrence of Rotalipora cushmani at 8,180 feet. Other foraminifers including Rotalipora greenhornensis, Rotalipora reicheli, and Globigerinelloides bentonensis are also present in the upper part of this interval.

Palynomorphs: The Turonian is delineated by the highest occurrence of Perinopollenites elatoides.

Nannofossils: A sparse nannoflora characterizes this interval. Cenomanian-age species include Cruciellipsis chiasta at 8,200 feet and Corollithion sp. "A" at 8,230 feet.

Albian (8,690-9,530 feet)

Palynomorphs: The top of the Early Cretaceous section has been defined by the common occurrence of the dinoflagellate species Spinidinium vestitum in the sidewall core sample at 8,690 feet. The top of the Albian may, however, be slightly higher as evidenced by the rare occurrence of the pollen species Corolina torosus at 8,630 feet.

Nannofossils: The Albian section is recognized from rare specimens of Braarudosphaera africana and Nannoconus bucheri at 8,770 feet.

Foraminifera: This interval yielded poor faunal assemblages. Favusella washitensis occurs at 9,470 feet. The benthonic species in the interval are characterized by Epistomina spinulifera colomi, Robulus muensteri, and Tritaxis pyramidalis.

Aptian (9,530-10,070 feet)

Palynomorphs: The Aptian has been determined by the highest occurrence of "Cyclonephelium" tabulatum, Pilosisporites trichopapilosus, and Pilosisporites verus at 9,530 feet. Systemmatophora schindewolfii is present at 9,890 feet.

Nannofossils: Rare specimens of Nannoconus globulus occur at 9,640 feet. Conusphaera mexicana is present lower in the interval at 9,850 feet.

Barremian (10,070-10,610 feet)

Palynomorphs: The top of the Barremian is placed at 10,070 feet, based on the highest occurrence of Muderongia simplex and Muderongia staurota. Pseudoceratium pelliferum is present at 10,100 feet.

Hauterivian (10,610-11,920 feet)

Palynomorphs: The mutual association, at 10,610 feet,of "Ctenidodinium" elegantulum, "Broomia" jaegari and Pseudoceratium pelliferum is indicative of Williams' (1975) "Ctenidodinium elegantulum zone" (provisionally dated as Hauterivian).

Berriasian (11,920-12,400 feet)

Nannofossils: The top of the Berriasian has been placed at 11,920 feet based on the rare occurrence of *Polycostella senaria* and the presence of *Nannoconus bronnimanni*. Delineation of the Berriasian section in other wells in the offshore Atlantic has generally been based on the highest occurrence of *Polycostella senaria*. The species was identified at a depth of 11,500 feet in the COST No. B-2 well.

Jurassic

Tithonian (12,400-13,220 feet)

Palynomorphs: The exact placement of the Jurassic-Cretaceous boundary has been somewhat problematic among paleontologists working wells in the Baltimore Canyon area. For the sake of consistency, the top of the Tithonian is here interpreted on the basis of the highest occurrence of "*Ctenidodinium*" *panneum* together with "*Ctenidodinium*" *culmulum* at 12,400 feet. The joint occurrence of these species conforms with Williams' (1975) "*Ctenidodinium panneum* zone" which he provisionally dated as Tithonian. It should be noted that in many of the Atlantic OCS wells the dinoflagellate species "*Ctenidodinium*" *panneum* has its highest occurrence at or near that of the nannofossil species *Hexalithus noelae*. This nannofossil species is not known to occur above the Tithonian.

Kimmeridgian (13,220-5,820 feet)

Palynomorphs: The top of the Kimmeridgian is placed at 13,220 feet based on the highest occurrence of the dinoflagellate species *Gonyaulacysta jurassica*. *Senoniasphaera jurassica* has also been identified in the cuttings sample at 13,220 feet. No palynomorphs indicating an age older than Kimmeridgian have been observed in the samples down to the total depth of 15,820 feet.

Foraminifera: The presence of the foraminifer *Pseudocyclammina jaccardi* at 13,960 feet indicates a Kimmeridgian age.

Nannofossils: The nannoflora in the sidewall samples is extremely sparse. The rare occurrence of *Polypodorhabdus escaigi* at 13,280 feet provides additional evidence of a Kimmeridgian age.

GEOLOGIC CORRELATION WITH OTHER WELLS

By Frederick Adinolfi and Sara S. Jacobson

The COST No. B-3 well has been correlated to the COST No. B-2 well, which was drilled 32 statute miles north of the B-3 site in 1976. The stratigraphic column of the COST No. B-3 well (pl. 1) summarizes the lithologic, geochemical, petrophysical and paleontological data described elsewhere in this report. The stratigraphy of the COST No. B-2 well has been described by Smith and others (1976), Scholle (1977), and Poag (1978). Plate 2 is a time-stratigraphic and rock-stratigraphic correlation of the two Mid-Atlantic COST wells based on paleontologic data, geophysical logs and lithologic descriptions. The five correlative lithologic units shown on plate 2 are summarized from bottom to top as follows: 1) non-marine to marginal marine deposits of Late Jurassic (Kimmeridgian) age consisting of interbedded shale, coal, sandstone and, in the B-3 well, limestone; 2) limestone, sandstone, and shale deposited during a major Late Jurassic to Early Cretaceous (Tithonian and Berriasian) marine transgression; 3) a Lower Cretaceous progradational sequence dominated by thick-bedded sandstones; 4) calcareous shale, mudstone, and glauconitic sandstone deposited during a Late Cretaceous marine transgression-- a Lower Maestrichtian unconformity represents the culmination of this transgression; 5) a Tertiary section which grades upward from Eocene limestone to Miocene shale and sandstone.

The COST No. B-2 and B-3 time-stratigraphic correlations have been extended to the ESSO No. 1 Hatteras Light and COST No. GE-1 wells to the south and to the Shell No. B-93 Mohawk, Shell No. 0-25 Oneida and Mobil No. C-67 Sable Island wells on the Scotian Shelf to the north (pl. 3). Correlations were also extended to the USGS No. 1 Island Beach and Anchor Gas No. 1 Dickinson wells located on the New Jersey coastal plain (pl. 4). Biostratigraphic and lithologic data are taken from published reports.

Data from additional wells and submarine outcrop samples were also considered to complete the stratigraphy from Nova Scotia to Florida. Because correlations have been drawn over great distances between the wells, interpretations should be considered tentative.

Pre-Mesozoic Basement Rocks

Cambrian-Ordovician metamorphic rocks have been encountered beneath the Scotian Shelf, and Devonian granites are present in the Gulf of Maine as well as on the Scotian Shelf (Ballard and Uchupi, 1975; Jansa and Wade, 1975). Precambrian granite and Paleozoic sedimentary rocks ranging in age from Early Ordovician to Devonian are present as basement underlying the Mesozoic and Cenozoic sediments of northern Florida, Georgia, and the Southeast Georgia Embayment (Maher, 1971; Simonis, 1979).

Older Mesozoic Rocks

Subsurface Triassic and Lower to Middle Jurassic sedimentary rocks have only been reported in the northern Atlantic along the Scotian shelf. Continental red beds with anhydrite (Eurydice Formation of Canada) and salt (Argo Formation of Canada) were deposited in restricted basins contained in rift valleys (McIver, 1972; Jansa and Wade, 1975; Given, 1977). These beds are overlain by a dolomite-evaporite sequence (Iroquois

Formation of Canada), thought to represent a marine transgression prior to opening of the Atlantic (Given, 1977; Jansa and Wade, 1975). On the basis of seismic stratigraphy, the presence of these older Mesozoic rocks has been inferred in the Georges Bank Basin and Baltimore Canyon Trough (Poag, 1978).

Middle to Late Jurassic

Both the COST No. B-2 and COST No. B-3 wells bottomed in an Upper Jurassic clastic interval consisting of interbedded sandstone, siltstone, shale, and coal (pl. 2). The shales in the B-2 well are variegated gray, brown, and red, whereas in the B-3 well they are mainly gray. Limestone is present in the B-3 well but not in the B-2 well. The deepest sediments penetrated in the Shell No. B-93 Mohawk and Shell No. 0-25 Oneida wells consisted of a similar clastic interval of Middle Jurassic age (pl. 3). These sediments (Mohican Formation) overlie the Lower-Middle Jurassic carbonates on the Scotian shelf and may represent the first period of continental clastic deposition following the initial opening of the North Atlantic Ocean (Given, 1977; Jansa and Wade, 1975; McIver, 1972).

Late Jurassic to Early Cretaceous

A major marine transgression apparently characterized Late Jurassic time along the Atlantic continental margin. Limestone and sandstone constitute the Upper Jurassic to Lower Cretaceous interval in the COST No. B-2 well. The COST No. B-3 well penetrated more than 1,500 feet of Upper Jurassic oolitic grainstone and sandstone (pls. 1 and 2).

On the Scotian Shelf of Canada, four different facies have been described from sediments of this age: (1) fluvial and near-shore sandstones (Mohawk and

Lower Missisauga Formations); (2) near-shore calcareous shales with interbedded calcareous sandstones and limestones (Mic Mac Formation); (3) a shallow marine limestone-shale sequence (Abenaki Formation); (4) a deep-shelf facies mostly composed of calcareous shale (Verrill Canyon Formation) (Given, 1977; Jansa and Wade, 1975; McIver, 1972). Submarine outcrop samples from Heezen Canyon on Georges Bank contain a Neocomian (Early Cretaceous) fossil assemblage. These bioclastic limestones and calcareous sandstones were deposited along a reef tract on a carbonate platform (Ryan and others, 1978).

In southern Florida, the Amerada No. 2 Cowles Magazine well penetrated about 2,200 ft of Upper Jurassic (?) or Lower Cretaceous (?) oolitic limestone, anhydrite and shale with a basal arkosic sandstone (Applin and Applin, 1965). Basal arkosic sandstone and conglomerate of Late Jurassic or Early Cretaceous (Neocomian) age are present in the ESSO No. 1 Hatteras Light well (Maher, 1971). No Jurassic rocks have been identified in the COST No. GE-1 well.

Early Cretaceous

An influx of clastics in the form of prograding delta wedges characterize the Early Cretaceous northern Atlantic continental margin. In the COST No. B-2 well, thick sandstones interbedded with shales, and thin layers of coal and limestone were deposited under dominantly nonmarine conditions (Poag, 1977). The deltaic sand section in the B-3 well contains thicker shale intervals and more numerous limestone beds than that section in the B-2 well. In the B-2 well, the top of the Lower Cretaceous (Albian) is marked by a progradational sandstone. This prominent shale/sandstone contact occurs at the same depth (8,200 ft) in the B-3 well, where it marks the top of the Cenomanian (lower Upper Cretaceous).

Onshore, the Lower Cretaceous and locally Cenomanian Potomac Group, exposed in the Salisbury Embayment and penetrated in the USGS No. 1 Island Beach and Anchor Gas No. 1 Dickinson wells, consists of fluvial-deltaic gravels, sand, and varicolored silt and clays (pl. 4). Generally, correlative onshore intervals are thinner and coarser grained than offshore.

On the Scotian Shelf, thick, massive sandstone units of the Missisauga Formation grade vertically and laterally into prodelta shales of the Verrill Canyon Formation. Above this is the nonmarine to marine Nakasapi Shale which is overlain by the siltstones and sandstones of the Logan Canyon Formation and the laterally equivalent marine shales of the Dawson Canyon Formation. The upper units are indicative of a slow regional transgression which continued into the Late Cretaceous (McIver, 1972; Jansa and Wade, 1975; Given, 1977). This is well illustrated in the 8,000-foot-thick Lower Cretaceous interval in the Mobil No. C-67 Sable Island well (pl. 3).

In the COST No. GE-1 well, Lower Cretaceous terrestrial to shallow marine sandstone and shale redbeds are overlain by shallow marine carbonate rocks and associated evaporites. Above the carbonates is an Albian to Turonian regressive sandstone, which includes an unconformity between the Upper and Lower Cretaceous (Poag, 1979). A shallow, tropical sea covered south Florida during the Early Cretaceous and resulted in deposition of interbedded carbonate rocks, evaporites, and thin lenses of dark shale (Maher, 1971).

Late Cretaceous

A marine transgression resulting in deposition of a deeper-water facies occurred during the Late Cretaceous along the Atlantic continental margin. On the Scotian shelf, sandstones and siltstones of the Logan Canyon Formation, the marine shales of the Dawson Canyon Formation, and the Wyandot Chalk were deposited in increasingly deeper water (Jansa and Wade, 1975; Given, 1977). Two Upper Cretaceous outcrop samples from submarine canyons on Georges Bank consisted of brown and black sandy mudstones deposited in upper-slope water depths (Ryan and others, 1978).

Calcareous shale, mudstone, and glauconitic sandstone deposited during the Late Cretaceous in both the COST No. B-2 and B-3 wells indicate open shelf marine deposition. Owens and Sohl (1969) recognized two transgressive cycles of sedimentation during deposition of the Upper Cretaceous Raritan and Magothy Formations of the New Jersey coastal plain (pl. 4). In outcrop, the Raritan Formation (Cenomanian to Turonian) consists of light colored sand and dark clay and is separated from the overlying Magothy Formation by an unconformity. The Magothy Formation (Santonian-Campanian) contains cross-stratified quartz sand, clay, and carbonized wood fragments deposited in a marginal marine (beach) environment (Perry and others, 1975). Coniacian regressive sandstone intervals have been identified in the USGS No. 1 Island Beach, the Anchor Gas No. 1 Dickinson, and the COST No. B-2 and B-3 wells (pl. 4). This Late Cretaceous regression is not recognized on the Scotian Shelf.

According to Petters (1976), a second Late Cretaceous transgression began during the early Santonian on the New Jersey coastal plain. The transgression was followed by oscillation of the shoreline during the late Campanian and Maestrichtian producing alternating greensands and regressive sand units (Petters, 1976). The final regressive sandstone was penetrated at 5,000 feet in the B-2 well and is missing in the B-3 well (pl. 4). Chalk and mudstone characterize the Upper Cretaceous interval in the COST No. GE-1 well (Amato and Bebout, 1978); a glauconitic clastic section was penetrated in the ESSO No. 1 Hatteras Light well.

Tertiary

An unconformity at the top of the Cretaceous has been identified in the three Atlantic COST wells and on the Scotian Shelf. Paleocene sediments are generally very thin or missing in all these offshore wells (pl. 3). However, exposures of green glauconite sand of Paleocene age on the coastal plain of New Jersey have been reported (Owens and others, 1977). A conspicuous feature of the middle and south Atlantic wells is the occurence of a lower Tertiary carbonate facies; these chalks were deposited at depths equivalent to those found on the continental slope (Smith and others, 1976; Scholle, 1979). In the COST No. B-2 and B-3 wells, Eocene chalk is overlain by Oligocene clay. Evidence of a late Oligocene regression is present in both those COST wells, based on foraminiferal biostratigraphy (W. E. Steinkraus, USGS, oral commun., 1979). This brief regression was followed by a rise in sea level, and deposition of a prograding shelf sequence of Miocene clay and, in the COST No. B-2 well, sand.

Eocene outcrop samples were collected from the walls of Heezen submarine canyon on Georges Bank. They consist of deep-water canyon-fill deposits of brown, silty mudstone overlain by pelagic white chalk (Ryan and others, 1978).

To the north in Canada, carbonates are absent in the early Tertiary section in the Scotian Basin; these sediments are predominantly clays (Jansa and others, 1978) (pl. 3). The clay occurs in the Banquereau Formation with subordinate amounts of sandstone and marl (Jansa and Wade, 1975). Several hiatuses in deposition are recorded in this sequence. As in the Mid-Atlantic, a late Oligocene regression is noted on the Scotian Shelf, during which coarser clastics were deposited. However, on the Scotian Shelf, this regression continued into the Pliocene (Jansa and Wade, 1975). In the COST No. GE-1 well, Paleocene, Eocene, and lower Oligocene limestones were deposited on a marine carbonate shelf (Valentine, 1979). This was followed by a rise in sea level and deposition of upper Oligocene and Miocene silty mud and limestone. Light-colored limestones characterize the Tertiary deposits of Florida (Maher, 1971).

In summary, the late Mesozoic and Cenozoic geologic history of the Baltimore Canyon area appears to have been dominated by a major marine transgression. This transgression was interrupted by a extensive deltaic progradation in the Early Cretaceous. In addition, regressions have been identified during the Coniacian (Late Cretaceous) and late Oligocene (Tertiary). This generalized geologic history can be correlated to equivalent rock sequences in basins both north and south of the Mid-Atlantic area.

DEPOSITIONAL ENVIRONMENTS

By John W. Bebout and David J. Lachance

Both paleontologic and lithologic analyses of the COST NO. B-3 sediments have been applied to the determination of the environments of deposition represented in the well. Paleobathymetric interpretations, however, are based largely on the distribution of benthonic foraminifers as reported by International Biostratigraphers Inc. (written communication, 1979). The paleobathymetric interpretations become progressively less precise with increasing geologic age, because they are derived by comparing fossil benthonic assemblages with Holocene assemblages known to favor certain environments.

Palynologic and lithologic studies of the B-3 well supplemented the foraminiferal data, and they provided additional insight into the depositional environments. The results of these studies are discussed in this chapter.

From a detailed study of the distribution of benthonic foraminifers, International Biostratigraphers Inc. determined the following general environments of deposition for the COST No. B-3 well:

Depth (feet)	Environment
3,800 - 4,710	Outer neritic-upper bathyal
4,710 - 4,950	Outer neritic
4,950 - 5,160	Upper bathyal
5,160 - 6,040	Middle bathyal
6,040 - 6,540	Outer neritic
6,540 - 8,040	Outer neritic to marginal marine
8,040 - 8,180	Outer neritic
8,180 - 8,690	Outer neritic to marginal marine
8,690 - 9,600	Marginal marine - shallow shelf? *
9,600 - 10,100	Shallow marine to inner shelf
10,100 - 10,600	Nonmarine to marginal marine
10,600 - 12,300	Marginal marine to outer shelf
12,300 - 13,500	Outer to inner shelf
13,500 - 13,700	Outer shelf
13,700 - 15,820 (T.D.)	Inner shelf to nonmarine?

*In the Lower Cretaceous and Upper Jurassic sediments of the Atlantic offshore few species are present which may be compared directly to living forms; consequently, less precise paleobathymetric terms have been applied.

This chapter compares these foraminiferal data with changes in the ratio of terrestrial to marine palynomorphs recovered from B-3 sediments and discusses pertinent lithologic data.

As a group, palynomorphs are not generally regarded as sensitive paleobathymetric indicators, although some progress is being made through the use of select dinoflagellate genera. It has long been recognized, however, that the distribution of terrestrial species (spores and pollen) in marine sediments can be useful in reconstructing paleohydrologic conditions (for example, Muller, 1959, and Stanley, 1965).

Generally, the amount of spores and pollen in modern marine sediments decreases seaward, owing to a lateral and vertical mixing with marine water of lower sedimentary-particle concentrations. This is not necessarily a simple linear relationship, because their abundance is also affected by surface currents.

Palynologic data for the COST No. B-3 well were plotted (fig. 5) as the percent of terrestrial forms versus depth, and this curve is compared to a paleobathymetric curve based on foraminifers which was generated by International Biostratigraphers, Inc. (written communication, 1979). The "ages" used in this chapter, and on figure 5, are assigned according to the USGS interpretation presented in this report. They represent a composite based on foraminifers, palynomorphs, and nannofossils (see Steinkraus, this report).

The two curves were subdivided into nine intervals (A-I). Within most of these intervals, the two curves simply substantiate each other; in other intervals, however, a comparison of the two curves has provided some additional information on the environments of deposition for sediments in the COST No. B-3 well.

Interval A, depth 15,820-14,000 feet (Kimmeridgian). Foraminifer recovery from this interval was poor, and the limited data indicate a marginal marine environment. The percentage of terrestrial palynomorphs in any sample within this interval, however, does not exceed 40 percent; in other parts of the well, this percentage is generally associated with deeper water. Lithologically, numerous thin coals interbedded with shale and oolitic, algal and pelletal limestone indicate intermittent changes in environment of deposition from nonmarine to shallow marine, possibly tidal flats. Transport of marine palynomorphs shoreward by tidal currents

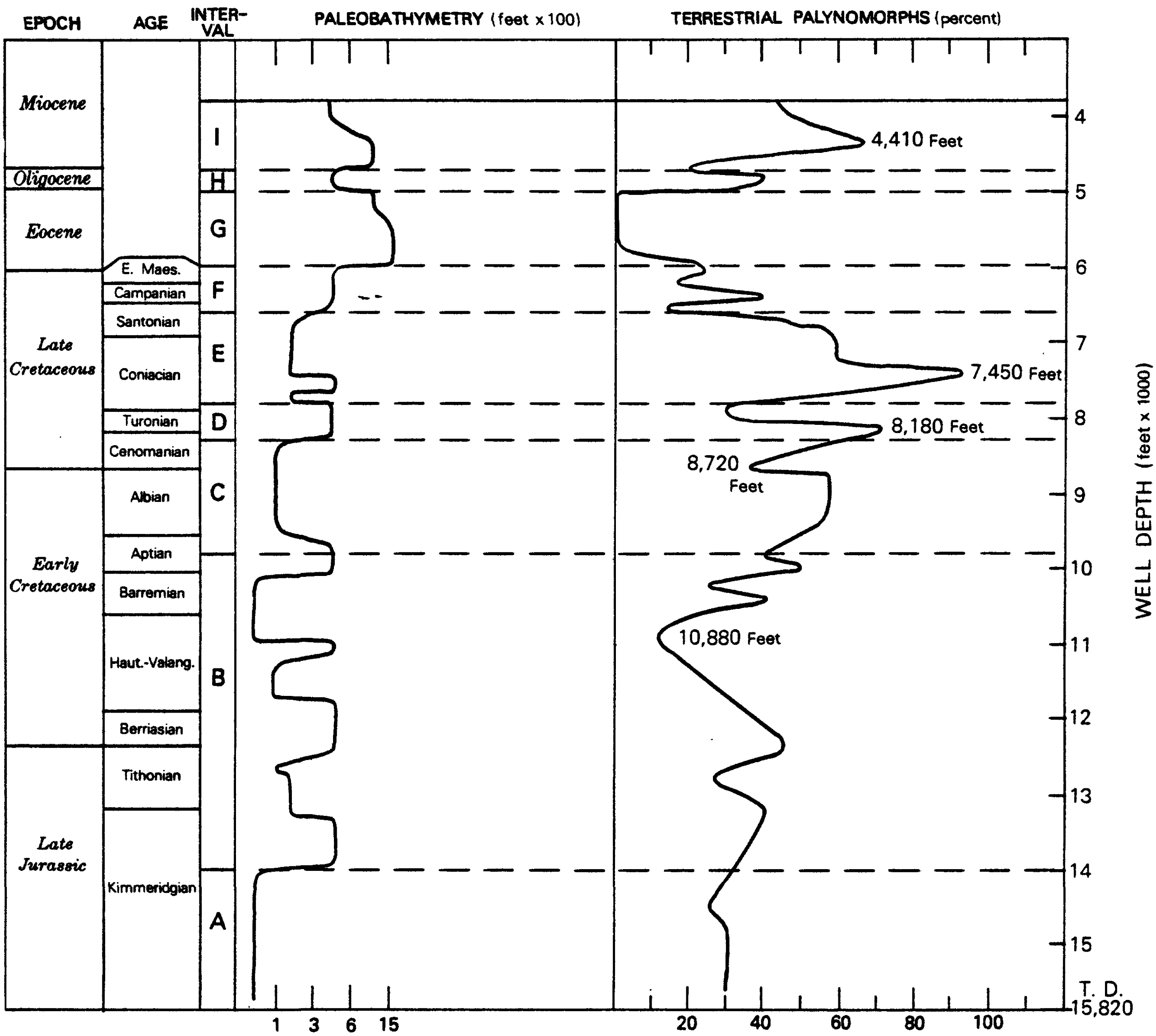

Figure 5.--Abundance of terrestrial palynomorphs compared with paleobathymetry of foraminifera.

is a possible cause for the apparently anomalous palynomorph content.

Interval B, depth 14,000-9,800 feet (Kimmeridgian-Aptian). As de- determined from the foraminiferal water-depth data, this interval represents alternating marine transgressions and regressions. This interpretation is supported by the palynomorph curve which also shows several "peaks and valleys," although the two curves do not match well. The lack of correlation presumably reflects the generally poor palynomorph recovery from this interval (many cuttings samples were barren of all but caved fossils).

Lithologically, the Jurassic section between 14,000 and 12,400 feet is similar to that of the underlying interval A, except that limestone is more abundant and coal is absent. Although many of the limestones are micrites and pelletal wackestones indicating deposition below wave base, fossiliferous oolitic grainstones near 12,600 feet reflect high-energy, very shallow marine environment. Lithology of the section between 14,000 and 12,400 feet points to deposition in water depths somewhat shallower than those interpreted from foraminiferal assemblages. A Lower Cretaceous (lower Neocomian) shale sequence between 12,400 and 11,630 feet contains a few thin beds of argillaceous limestone in its lower part and is progressively siltier and sandier toward the top. This lithologic unit is interpreted to represent a rapid marine transgression followed by a gradual shallowing. The foraminifer curve generally supports this interpretation.

A major deltaic progradation during late Neocomian to early Aptian time is represented between 11,630 and 9,900 feet by thick-bedded sandstone interbedded with shale, limestone, and a few thin coals. Texturally, the sandstones vary from very coarse to fine-grained, and from very poorly to moderately well sorted, and are interpreted to represent deposition in channels, delta front, and offshore bars. A shale and limestone zone between 10,950 and 10,750 feet coincides with the low percentage of terrestrial polynonmorphs at 10,880 feet and possibly indicates a brief marine transgression. On the foraminifer curve this transgression is shown to occur slightly lower (earlier) probably due to cavings.

Interval C, depth 9,800-8,300 feet (Aptian-Cenomanian). As inferred from the foraminiferal data, most of the sediments in this interval were deposited in a fairly uniform marginal marine environment. The palynomorph curve, however, indicates at least one deeper water incursion represented between 8,700 and 8,400 feet.

Between approximately 9,800 and 8,700 feet a thick shale interval indicates either a marine transgression or a lateral shift of deltaic supply of sands. The time-equivalent section in the B-2 well contains thick bedded sandstones showing that sands were being deposited shoreward (?) of the B-3 location. Thin coal beds at 9,500 feet support the paleontologic evidence for shallow-water environments. Thin-bedded sandstones increase in number in the upper part of the shale section, heralding another major phase of sand deposition.

From 8,700 to 8,200 feet, thick Cenomanian sandstones are interpreted to have been deposited in a delta front setting. Interbedded micritic limestones were probably deposited near an area of active clastic deposition. There is no lithologic evidence for the palynologically interpreted deepening of water during deposition of the sediments between 8,400 and 8,700 feet. It is possible, however, that different types of palynomorphs may have been mixed by tidal currents.

Interval D, depth 8,300-7,800 feet (Cenomanian-Turonian). During deposition of these sediments, an increase to outer shelf water depths is indicated by foraminiferal assemblages. Correspondingly, the percentage of terrestrial palynomorphs decreases from a high of 70 percent in the interval below to less than 30 percent. Lithologically, the transgression is reflected by a sharp change at 8,200 feet from sandstones below to a thick section of shale and claystone above.

Interval E, depth 7,800-6,600 feet (Coniacian-Santonian). According to foraminiferal data, this interval indicates a general shallowing. It is interesting that although the foraminifers indicate marine (neritic) environments, terrestrial species constitute more than 90 percent in some samples. This disproportionately high percentage may be due to the proximity of a major drainage source; glauconitic sandstones are common in this section.

Interval F, depth 6,600-6,000 feet (Santonian-early Maestrichtian). This interval consists of gray claystone and brown siltstone. Foraminiferal data suggest a fairly uniform water depth of 300-600 feet for most of this interval. The percentage of terrestrial palynomorph forms is correspondingly less. The palynomorph curve does suggest at least one deeper water incursion during this interval, peaking near 6,200 feet. The palynomorph peak near 6,200 feet coincides with a zone of calcareous, slightly glauconitic siltstone.

Interval G, depth 6,000-5,000 feet (Eocene). Within this interval, foraminifers indicate upper bathyal (600 to 3,000 feet) conditions, apparently the greatest water depth at which B-3 sediments were deposited. The interpretation is dramatically substantiated by the palynomorph curve, which shows a virtual absence of terrestrial forms. Both curves strongly suggest hiatuses bounding the Eocene Epoch. The lithology, consisting of light-gray calcareous claystone ranging to clayey chalk, is consistent with the bathyal depositional depths indicated by the paleontologic data.

Interval H, depth 5,000-4,700 feet (Oligocene). Outer neritic water depths (300-600 feet) are suggested by foraminiferal data for deposition of these sediments, mainly gray clay and glauconitic sandstone. As expected, terrestrial palynomorphs are correspondingly more abundant. Both curves strongly suggest hiatuses bounding the interval.

Interval I, depth 4,700-3,800 feet (Miocene). Foraminiferal assemblages indicate that during deposition of this sequence water depths decreased from 600-1,500 feet to 300-600 feet. Somewhat suprisingly, the percentage of terrestrial palynomorphs within this interval increases to a maximum 66 percent of the total palynoflorule. Judging from the data for the rest of the well, this is a much higher proportion than expected for that water depth.

Lithologically, this interval consists mainly of light-gray clays and dark-green glauconite sands. The glauconite sands appear to be concentrated in the lower part of the interval between 4,400 and 4,700 feet, and are interpreted to represent a period of low terrigenous influx during an early Miocene transgression after a major Oligocene regression. Later Miocene(?) progradation of the shelf can be seen in regional seismic records as large-scale foreset beds. The high terrestrial palynomorph content at 4,410 feet may be due to high terrigenous influx during early stages of this major progradation.

SEISMIC VELOCITY DATA AND CORRELATION

By George R. Carlson

Detailed seismic velocity data for the COST No. B-3 well were obtained by correcting the integrated sonic log with the uphole velocity survey. The corrected velocities were compared at shotpoint 2906 on seismic reflection line 25, a 48-fold common-depth-point (CDP) stacked data line acquired by Geophysical Service Incorporated in 1978.

The B-3 well was drilled in an area of sparse seismic coverage, the closest seismic line being approximately 8 statute miles downdip to the southeast (fig. 6). It was necessary to project the B-3 well on strike to seismic line 25, shotpoint 2906, approximately 10 miles to the southwest, to carry out the velocity correlations and analyses. Velocity analyses were run every 1 3/4 miles along line 25, and on the average, 6-8 events were picked between 0 and 4.0 seconds on the velocity displays for calculations at shotpoint 2906. Corrected velocities from the geophysical log were also compared with geologic data from the well.

Despite the limited seismic data coverage, it was possible to correlate the B-2 well with the B-3 well, approximately 32 miles to the south, by meams of seismic lines (fig. 6). Both wells were projected along seismic lines to a common dip line, USGS line 2, for comparison. Interval velocity curves were prepared along with time-depth curves, to compare the two wells.

Time-depth curves constructed from both the corrected geophysical log and shotpoint 2906 on line 25 were plotted on the same coordinates and show a notable discrepancy (fig. 7). Two factors may be responsible for this discrepancy: (1), The seismic line lies approximately 10 miles from the well and a lateral velocity change may exist between the line

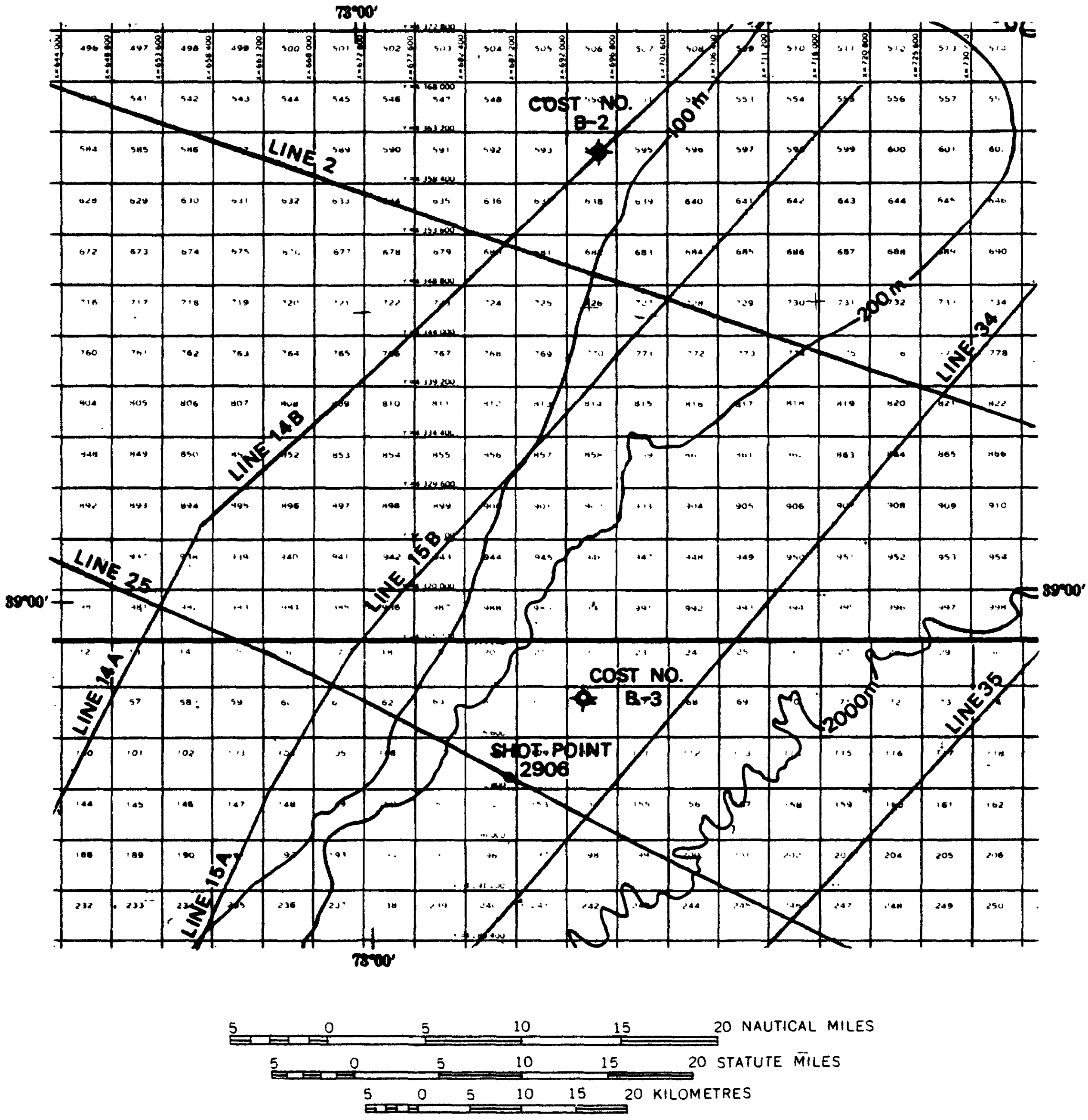

Figure 6.--Location of seismic lines in the vicinity of the COST No. B-2 and B-3 wells. Bathymetry in meters.

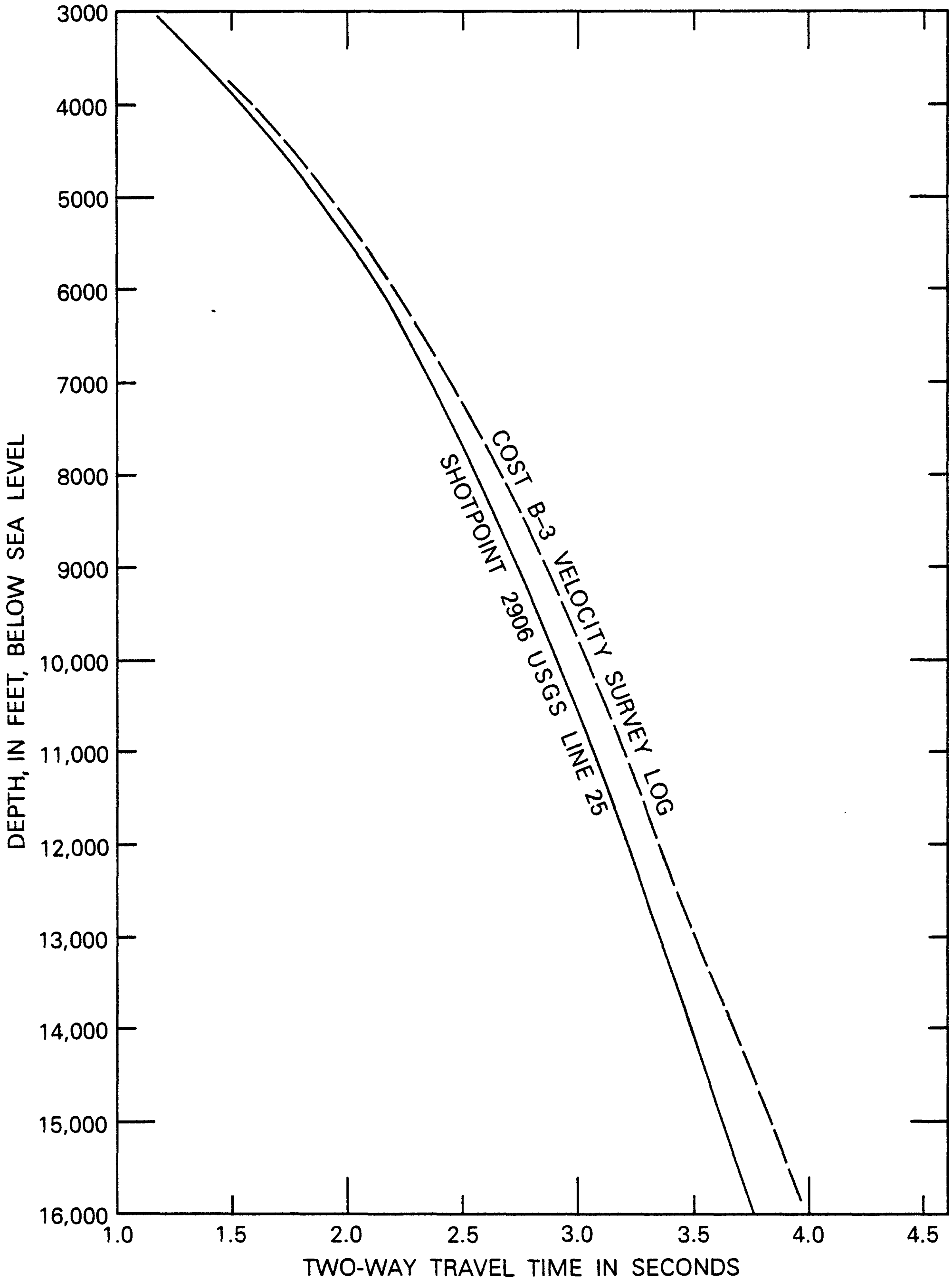

Figure 7.--Comparison of time-depth curves from COST No. B-3 velocity survey log and CDP data from USGS seismic line 25, shotpoint 2906.

and well (velocities at shotpoint 2906 appear to be 5-8 percent higher than at the B-3 well); and (2), in calculating the time-depth curve for line 25, shotpoint 2906, the root-mean-square velocities were used, which are 3-5 percent faster than the average velocities used in geophysical log calculations. Thus, the combination of slightly faster velocities used in the calculations, plus the possibility of a lateral velocity change, could produce the discrepancy shown in figure 7. The apparent enlarged discrepancy at greater depths is due to the linear depth scale used.

Interval velocities derived from the velocity survey log and from line 25 are shown in figure 8. Though not immediately apparent from this graph, overall agreement of velocities is good. Only 6 intervals were calculated for line 25 because of the lack of recognizable events on the velocity display, causing the reflection data to be averaged over large intervals. The interval velocities agree very well; the reflection data, when averaged, and log data agree within 2 percent.

The velocity surveys conducted in both wells indicated a considerable lateral variation in velocity. The time-depth curves in figure 9 show the general velocity relationship between the two wells. Most of the difference in average velocities is due to much deeper water at the B-3 location. A thicker section of sediments (shallower water) in the B-2 well than at the B-3 location is interpreted to be the main cause for the higher interval velocities in the B-2 well down to approximately 10,000 feet (fig. 10). Below this depth, the greater amount of limestone in the B-3 well causes the higher velocities in the B-3 well in most intervals.

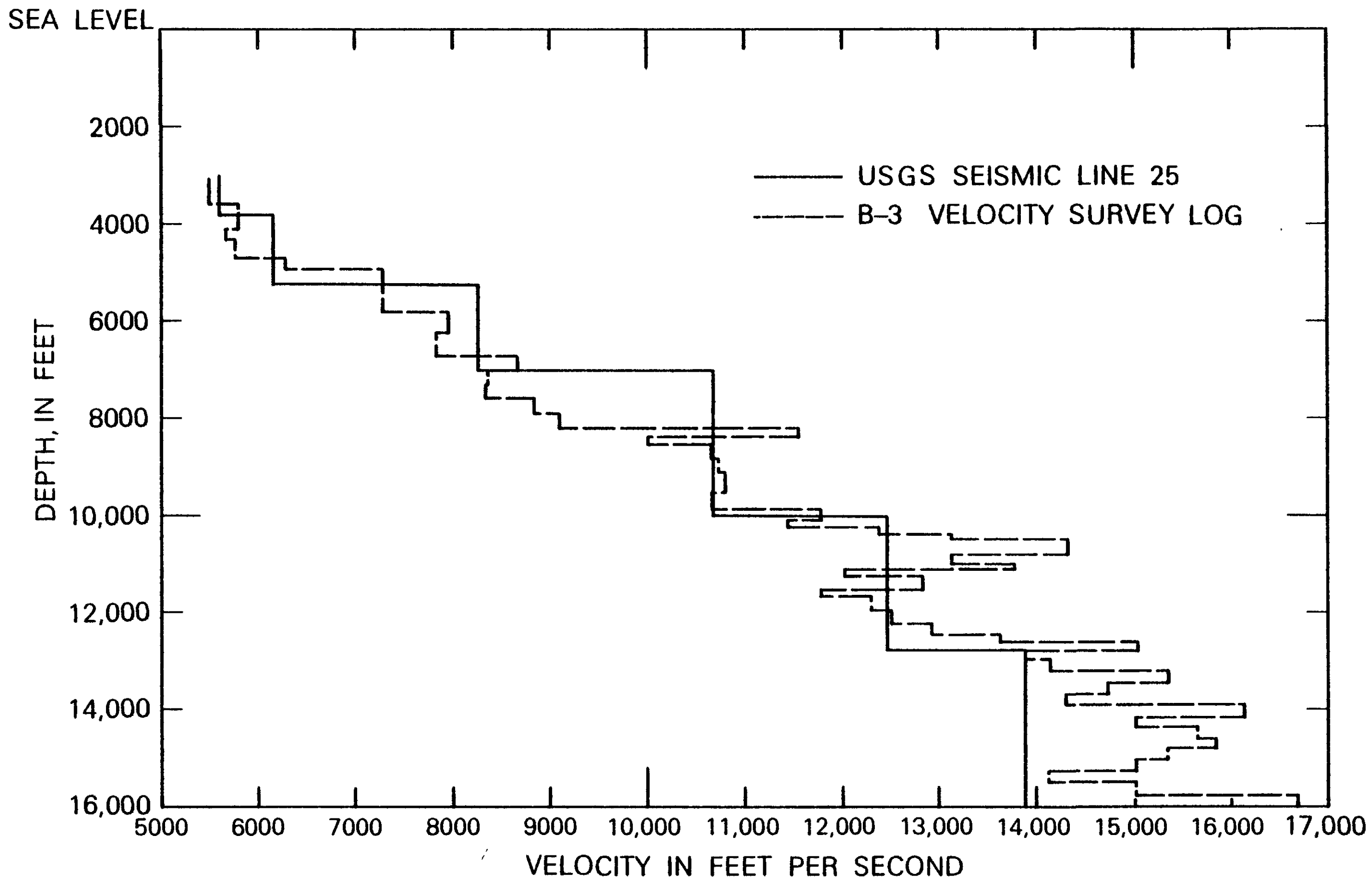

Figure 8.--Comparison of interval velocities from COST No. B-3 velocity survey log and USGS line 25.

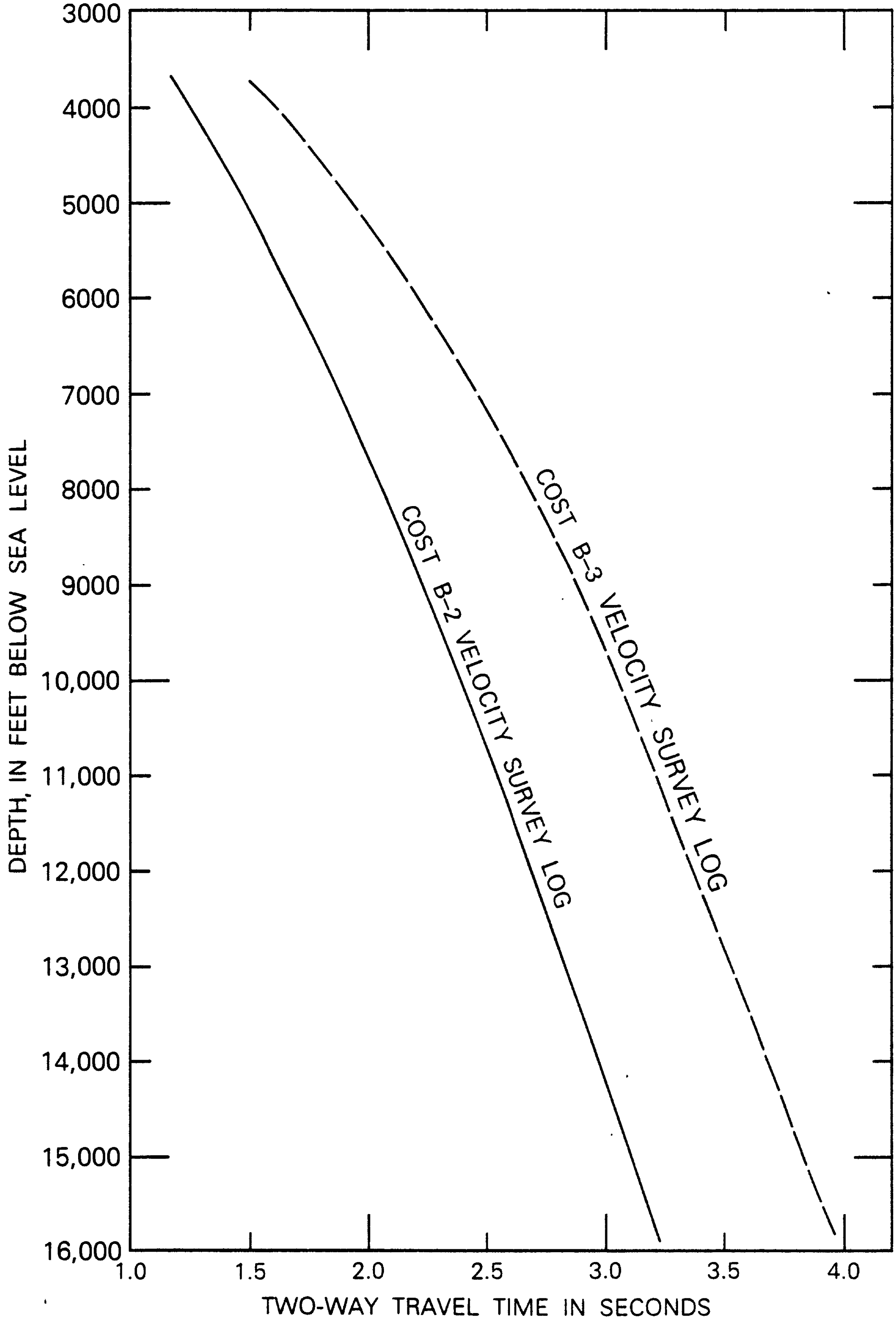

Figure 9.--Comparison of time-depth curves for velocity survey logs of the COST No. B-2 and B-3 wells.

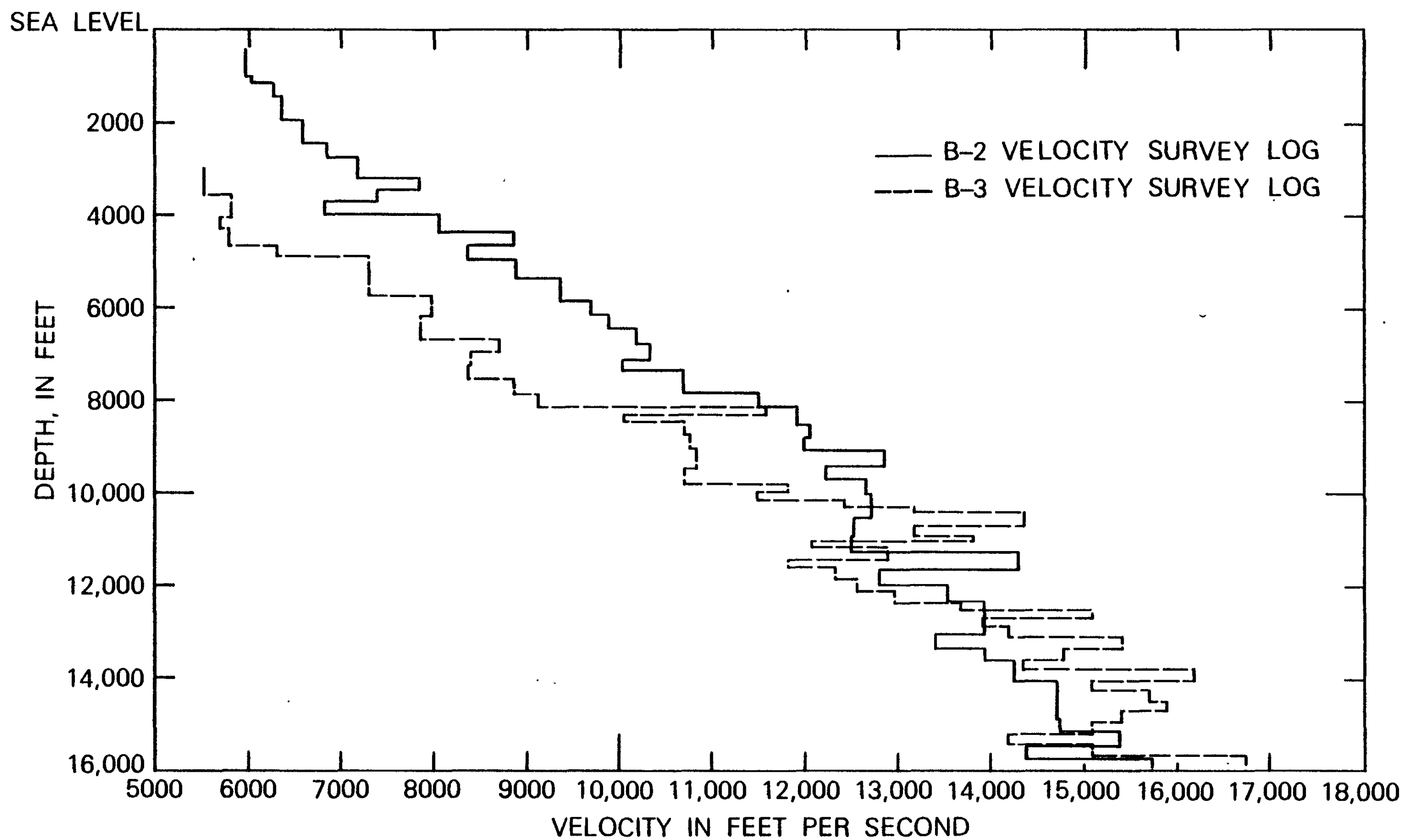

Figure 10.--Comparison of interval velocities for the COST No. B-2 and B-3 wells.

Sonic-derived velocities from the B-2 and B-3 wells were correlated with seismic reflection profiles and projected to a common dip line, USGS line 2 (pl. 5). The two wells were projected to line 2 also, and tied seismically using the four correlatable seismic reflection horizons.

Plate 5 shows a segment of line 2 with the two wells plotted, showing their generalized lithologies and geologic correlations of the section. In projecting the wells to a common line it was necessary to disregard the sea level datum and tie the horizons by seismic character. This does not affect the calculations in any way; it is only a graphical representation problem. The seismic events are strong between the two wells. The abrupt changes from the shale-limestone-sandstone interfaces produce good reflectors that can be traced over the area. Despite lithologic and facies changes between the two wells, the primary seismic reflectors seem to be continuous. According to interval velocities lithologic units in both wells correlate closely, especially at greater depths.

INTERPRETATION OF GEOPHYSICAL LOGS

By Renny R. Nichols

Schlumberger Limited ran the following geophysical ("electric") logs in the COST No. B-3 well to provide information for stratigraphic correlation and evaluation of lithology, porosity, and formation fluids:

	Depth interval (ft) below K.B.
Dual induction-spherically focused log (DISFL)	3,753-15,810
Long-spaced sonic log (LSS)	3,753-15,810
Compensated neutron log/compensated formation density log (CNL/FDC)	3,753-15,810
Compensated formation density (FDC)	3,753-15,810
High-resolution dipmeter (HDT)	3,753-15,810
Proximity microlog (PML)	5,726-15,813
Dual laterolog (DLL)	12,654-15,803
Repeat formation tester (RFT), Tests 1, 2, 3, 4	15,748-15,750

Exploration Logging Inc. provided a mud log, a drilling data pressure log, a wireline data pressure log and a pressure analysis log.

The geophysical logs were analyzed in detail to determine the thickness (in feet) of effective porosity (at least 8 percent) and hydrocarbon present, as well as average porosities. Reservoir rocks with porosities less than 8 percent were disregarded. A combination of all logs was used to help distinguish shale and siltstone streaks, but a detailed lithologic determination from samples, cores, and sidewall cores is necessary to substantiate the following preliminary estimates.

Depth (feet)	Thickness (ft) of beds with effective porosity	Average Porosity (percent)	Water Saturation (percent)	Thickness (ft) of beds with Hydrocarbons
6,000 - 6,500	8	23	NC*	0
6,500 - 7,000	91	24	NC	0
7,000 - 7,500	-	-	NC	0
7,500 - 8,000	107	19	NC	0
8,000 - 8,500	187	21	NC	0
8,500 - 9,000	202	16	NC	0
9,000 - 9,500	56	16	NC	0
9,500 - 10,000	37	16	NC	0
10,000 - 10,500	267	22	NC	0
10,500 - 11,000	98	18	NC	0
11,000 - 11,450	259	16	NC	0
11,450 - 12,000	142	21	NC	0
12,000 - 12,500	33	19	NC	0
12,500 - 13,000	33	15	NC	0
13,000 - 13,500	16	12	NC	0
13,500 - 14,000	6	10	NC	0
14,000 - 14,500	3	11	NC	0
14,500 - 15,000	34	9	NC	0
15,000 - 15,500	38	11	NC	0
15,500 - 15,773	8	12	32	8

*not calculated

Conventional Core Porosity

Conventional core porosity values agree closely with the density log values to approximately 12,000 feet. From 12,000 to 13,700 feet, the conventional core values compare more favorably with the sonic log values. Below 13,700 feet, the core and density log values again agree. In a zone near 15,750 feet, where no conventional core was taken, the sonic and density log porosity values each average 12 percent. The sidewall cores, however, show significantly higher porosities, about 20 percent.

Core	Interval (ft)	Lithology	Porosity (percent) Core avg.	Sonic log	Density log	Neutron log
1	9,921 - 9,935	Sandstone	16	24	18	29
2	11,009.5-11,-60.75	Sandstone and shale	10	17	4	36
3	12,572 -12,587.3	Limestone	6	8	3	9
4	13,773 -13,794.5	Shale and sandstone	4	35(upper zone)	5(upper zone)	19

Permeability

Permeability (K) determinations for the conventional cores were as follows:

Core No.	Interval (ft)	K range (md.)
1	9,921- 9,935	0.03-3970
2	11,008-11,060.75	.01- 236
3	12,572-12,587.3	.01- 47
4	13,773-13,794.5	.02- 6.6

These results generally agree with the logs which show substantial invasion in the reservoir intervals above 12,500 feet.

Dipmeter

Results of the HDT survey were recorded on a dipmeter arrow plot from 3,850 feet to total depth, except for the interval between 5,750 and 8,200 feet. Above 5,150 feet, angle and direction of dip readings are highly variable. At 5,150-5,750 feet, dip angle appears to be 0°-1°; dip direction readings are variable except near 5,300 feet where a westward dip is apparent. In a sandstone section from 8,200 to approximately 8,900 feet, dip direction readings appear to be nearly random with a slight westerly tendency and most readings of the dip angle range from 1° to 10°. In the remainder of the well, gentle (average 2°) westward dips are recorded, except in some sandy sections where dip readings tend to be scattered. No definite structural anomalies were recognized on the arrow plot. Minor dip pattern anomalies which may be either structural or sedimentary were noted at 12,200, 12,900, 13,150, 15,200, 15,300, and at 15,750 foot depths.

Significant Show

While drilling through the interval 15,745 to 15,785 feet, the *Ben Ocean Lancer* encountered a drilling break in which significant amounts of gas were detected by the mud logging unit. The rate of penetration of the drilling increased from 6 to 8 feet per hour from 15,700 to 15,745 feet, to 15 feet per hour from 15,745 to 15,755 feet, to 25 feet per hour from 15,755 to 15,760 feet; the rate then decreased to 15 feet per hour from 15,760 to 15,785 feet, and to 7 feet per hour from 15,785 to 15,820 feet.

Figure 11 shows parts of the curves of the DISFL and the mud log. On the left are the spontaneous potential curve which indicates porous sandstone when deflecting left and a gamma-ray curve which helps to differentiate sandstone, and limestone (both of which deflect to the left) from shale. The relatively high reading (50 ohms) of the deep induction resistivity curve points to the presence of hydrocarbon which is more resistive than formation water. The lithologic log and total gas curve from the mud log are 15 feet lower than the sandstone at 15,744-15,752 feet where the show was encountered. This depth difference probably is due to time lag required for the drill cuttings and gas in the mud to be circulated up the hole to the mud-logging unit.

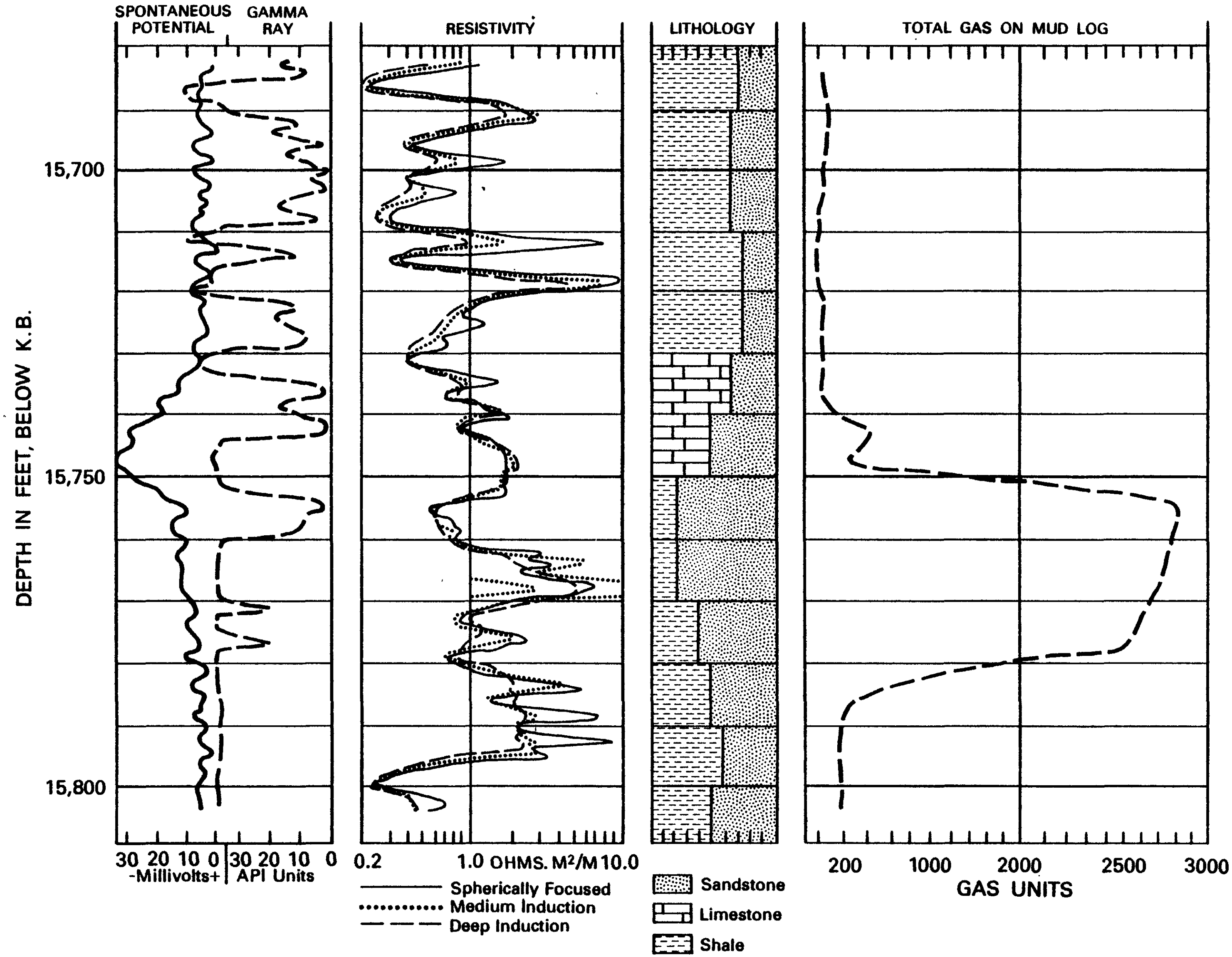

Figure 11.--Portions of geophysical logs showing relationship of various parameters in the interval of the publicly announced hydrocarbon show.

The mud gas hot-wire readings (fig. 11) increased from 5 units at 15,700-15,740 feet, to 22 units from 15,740-15,750 feet, to over 2500 units at 15,750-15,790 feet, and dropped back to 8 units from 15,790 to 15,820 feet. Chromatographic analysis of the hydrocarbons in the interval 15,750-15,790 feet was:

C 1	(methane):	194,940 ppm
C 2	(ethane):	17,980 ppm
C 3	(propane):	6,500 ppm
C 4	(butane):	806 ppm
C 5	(pentane):	1,200 ppm

The mud weights changed as follows:

15,700 - 15,750 ft: 10.1 lbs/gal.

15,750 - 15,787 ft: 8.2 lbs/gal. when circulated up.

(Increased to 11 lbs./gal. before drilling resumed).

The following lithologies in the interval of the gas show were determined from examination of drill cuttings:

Brown, pelletal limestone with abundant clay and silt from 15,730-15,750 feet; white friable, medium to coarse-grained, subrounded well-sorted sandstone with good visible porosity with minor amounts of cacite cement at 15,750-15,780 feet; dark-gray to black, splintery, micaceous shale at 15,780 to 15,800 feet; white, medium-grained, well-sorted, subrounded, friable sandstone at 15,800-15,810 feet; and dark-gray, micaceous, splintery shale at 15,810-15,820 feet.

Geophysical log calculations indicate 8 feet of hydrocarbon-bearing sandstone between 15,744 and 15,752 feet with an average porosity of 12 percent and a water saturation of 32 percent. Sidewall core porosity in this interval averages nearly 20 percent, but permeability is low, 0.1-2.2 millidarcies. Pale fluorescence and a slight cut in sidewall cores between 15,745 and 15,799 feet were reported by the well-site geologist. A wireline RFT was run four times between 15,748 and 15,750 feet and small volumes of methane-rich gas were recovered. Measurements of initial formation pressure averaged approximately 9,100 psi (pounds per square inch), but low permeability was indicated by the very slow pressure build-up in the test chambers. Admittedly, a wireline formation testing tool tests only one small spot of a rock at a time, and therefore, zones more permeable than indicated by the limited number of tests may be present.

This show is considered to be significant, because it indicates the presence of hydrocarbons adjacent to areas tentatively scheduled for future leasing. Accordingly, the U.S. Geological Survey announced the show on January 12, 1979, in keeping with regulations governing stratigraphic test drilling which require that the USGS Director "shall immediately issue a public notice identifying any hydrocarbon shows or environmental hazards on unleased lands discovered during drilling operations when the shows or hazards are judged to be significant by the Director." Although the well was intentionally located away from any geologic feature which might form a hydrocarbon trap, the B-3 apparently encountered a small stratigraphic trap which could not be predicted from seismic data over the drill site.

GEOTHERMAL GRADIENT

By Charles E. Fry

Since temperature logs were not run in the COST No. B-3 well, temperature gradient readings were taken from thermometer data on other geophysical logs. Eight such logs were run in the B-3 well, but only five have temperature values listed for all three runs. The maximum temperature for each run of these logs was plotted against the logging depth (fig. 12). The plotted points are joined together so that each line on the graph represents a single log. The logs represented on the graph are: dual induction-spherically focused, compensated neutron-formation density, compensated formation density, sonic, and continuous dipmeter.

The COST No. B-3 well was drilled in 2,686 feet of water and any difference in temperature between the surface and the ocean bottom would cause an exaggerated error in the slope calculation. The temperature readings increase in the order in which the logs were run. The dual induction-spherically focused log was run first, and the continuous dipmeter last. The temperature readings for the dual induction-spherically focused log were the coolest, whereas the warmest temperatures were recorded on the continuous dipmeter log. The slope of the second run for all the logs averaged 0.88°/100 feet. Temperatures for the third run increased faster than for the second, averaging 2.16°/100 feet. Computing all the slope determinations with their proportional distances gives an average gradient of 1.26°/100 feet. Notwithstanding the sparsity of temperature-gradient data, the average gradient agrees closely with the gradient in other east coast wells, including the COST No. B-2 which has a gradient of 1.30°/100 feet (Scholle, 1977).

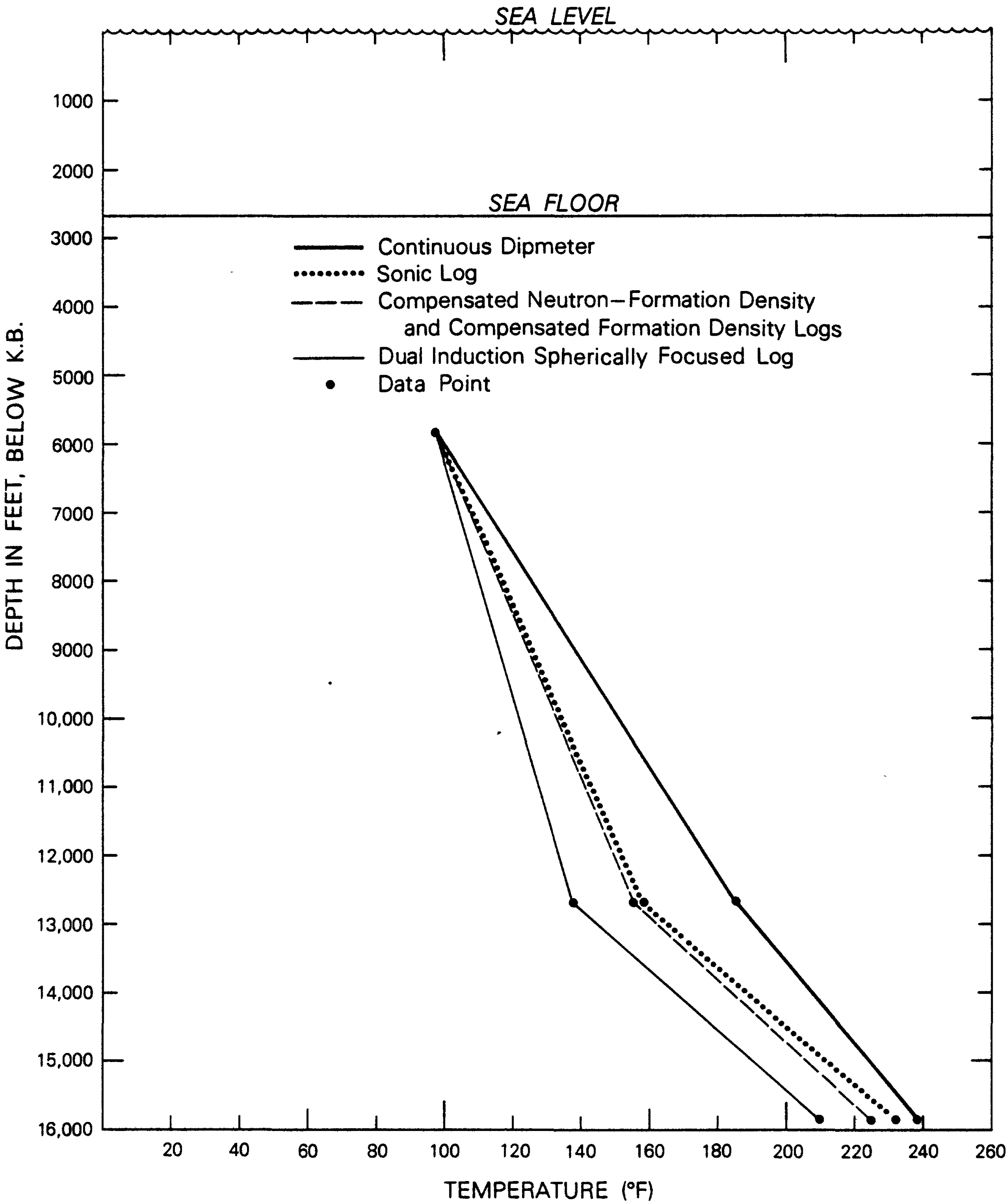

Figure 12.--Geothermal gradients from COST No. B-3 geophysical logs.

CORE DESCRIPTIONS AND ANALYSES

By Marion J. Malinowski

Four conventional diamond cores and 689 sidewall cores were recovered from the COST No. B-3 well. The conventional cores and 61 sidewall cores were analyzed by Core Laboratories, Inc (1979a). Table 1 lists the conventional cores, including their dominant lithologies and ranges of porosity and permeability. Table 2 lists the porosities and permeabilities of analyzed sidewall cores. Figures 13 and 14 show the wide range of porosity and permeability values of the conventional cores and sidewall cores in the COST No. B-3 well. Figure 15 shows core porosities plotted against core permeabilities. In general, porosity decreases with depth; however, if only the values for the sidewall cores are considered, there is no apparent trend (fig. 13). Porosity values for the sidewall cores between 14,500 and 15,820 feet are quite high, ranging from 15 to 27 percent. These values possibly reflect development of secondary porosity. However, permeability in that interval is low, ranging from 1 to 13 md (fig. 14). Permeability is generally low (less than 10 md.) throughout the well, except for some high values between 7,500 and 11,500 feet. Figure 15 shows that when core porosities are plotted against core permeabilities, the majority of the samples having porosity values of 15-30 percent have permeability values less than 10 md.

The lithologic summaries of the four conventional cores are based on lithologic and thin section descriptions provided by Core Laboratories, Inc. (1979a).

Table 1.--Record of conventional cores, their dominant lithologies and ranges of porosity and permeability

CORE NUMBER	CORED INTERVAL			CORE RECOVERY (feet)	POROSITY (Percent)			PERMEABILITY (md)			DOMINANT LITHOLOGY
	Top	Bottom	Feet Cut		High	Low	Mean	High	Low	Mean	
1	9,921	9,940	19	14	26.3	3.4	16.1	3970	0.03	1,356.4	Sandstone
2	11,009.5	11,069.5	60	51.25	25.9	3.8	9.9	236	.01	18.8	Shale and Sandstone
3	12,572	12,588	16	15.3	9.7	3.8	6.0	47	.01	3.2	limestone
4	13,773	13,798	25	21.5	10.7	1.6	4.1	6.6	.02	1.0	Shale and Sandstone

Table 2.--Porosities, permeabilities, and dominant lithologies of sidewall cores from COST B-3 Well. Siltstone is dominant lithology for depth 9,425 feet, sandstone for all others [Data from Core Laboratories, Inc., 1979a].

Depth (feet)	Porosity (percent)	Permeability (millidarcies)
6,869	30.3	5.7
6,960	27.9	.3
7,817	32.5	69.
7,966	27.0	36.
8,074	21.2	.1
8,210	30.6	100.
8,230	30.4	300.
8,270	20.8	1.6
8,370	18.6	.3
8,450	22.3	1.5
8,472	20.6	27.
8,506	22.6	7.3
8,572	22.6	.1
8,667	29.8	.9
8,785	17.8	.2
8,880	16.5	.1
9,104	23.1	1.2
9,425	15.8	.1
9,918	19.8	2.3
9,936	24.6	2.0
10,053	19.9	3.5
10,094	24.2	45.
10,153	21.9	7.2
10,217	26.1	81.
10,294	17.1	.1
10,530	17.3	.1
10,594	21.1	7.3
10,890	17.0	4.5
11,054	22.4	20.
11,176	20.9	16.
11,290	18.2	1.7
11,320	19.6	.6
11,476	23.6	19.0
11,600	20.0	5.1
12,625	17.6	.4

Table 2.--Porosities, permeabilities, and dominant lithologies of sidewall cores from COST B-3 Well.--Continued

Depth (feet)	Porosity (Percent)	Permeability (millidarcies)
12,844	18.1	0.6
12,844	23.3	6.1
14,532	24.2	9.3
14,733	25.0	12.0
14,875	21.2	1.0
14,785	22.3	6.5
14,822	22.6	4.7
14,822	27.1	13.0
14,863	24.7	3.4
14,863	23.6	2.5
14,958	21.5	.4
14,958	20.6	.5
15,025	16.0	.1
15,134	23.4	2.5
15,384	23.9	11.
15,384	23.7	6.2
15,409	23.0	1.7
15,745	17.6	.1
15,746	19.3	.5
15,747	21.6	1.6
15,748	18.1	.1
15,749	22.3	2.2
15,751	15.8	.1
15,752	19.1	.9
15,752	19.2	.1
15,754	21.6	1.4

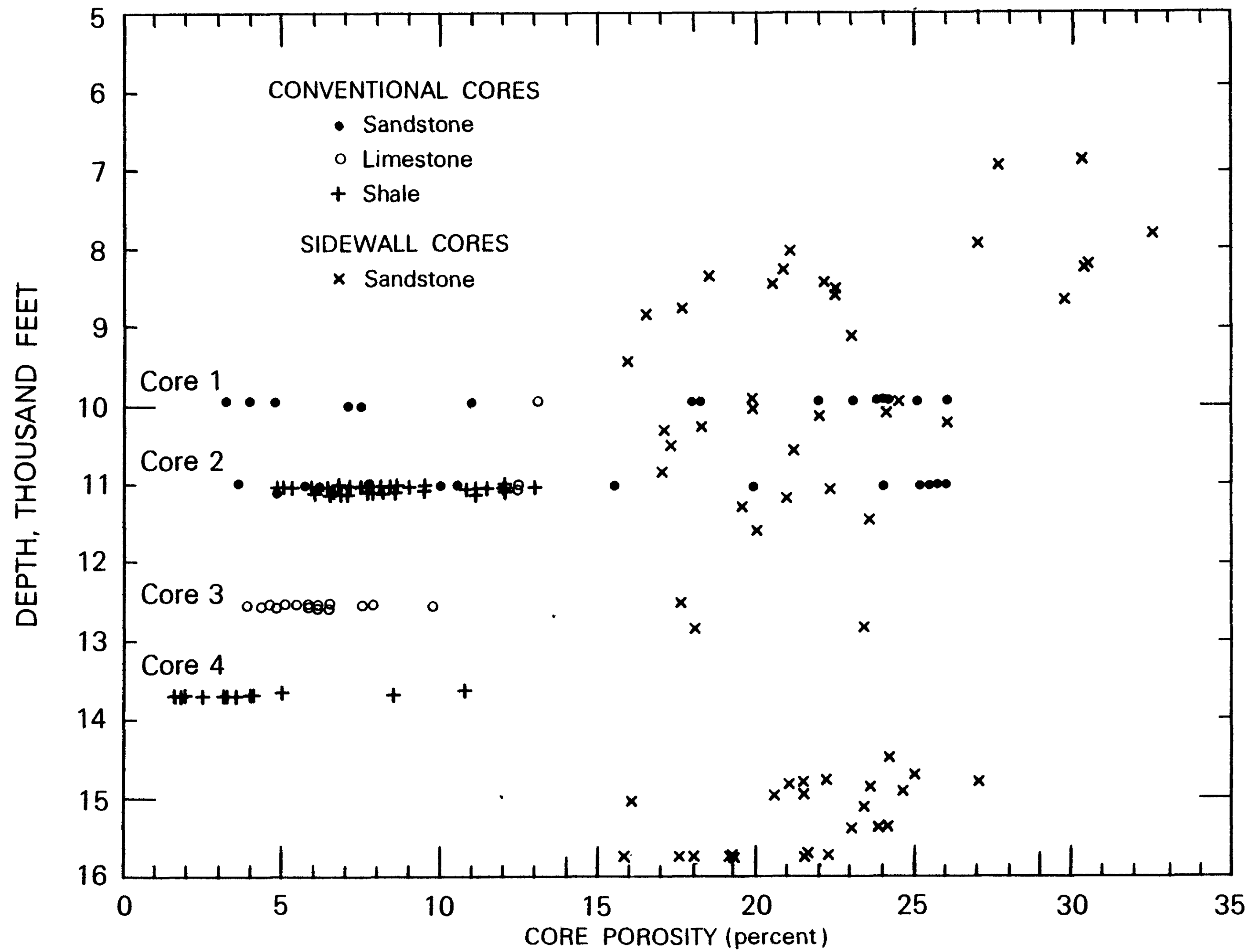

Figure 13.--Porosity of conventional and sidewall cores, COST No. B-3 well.

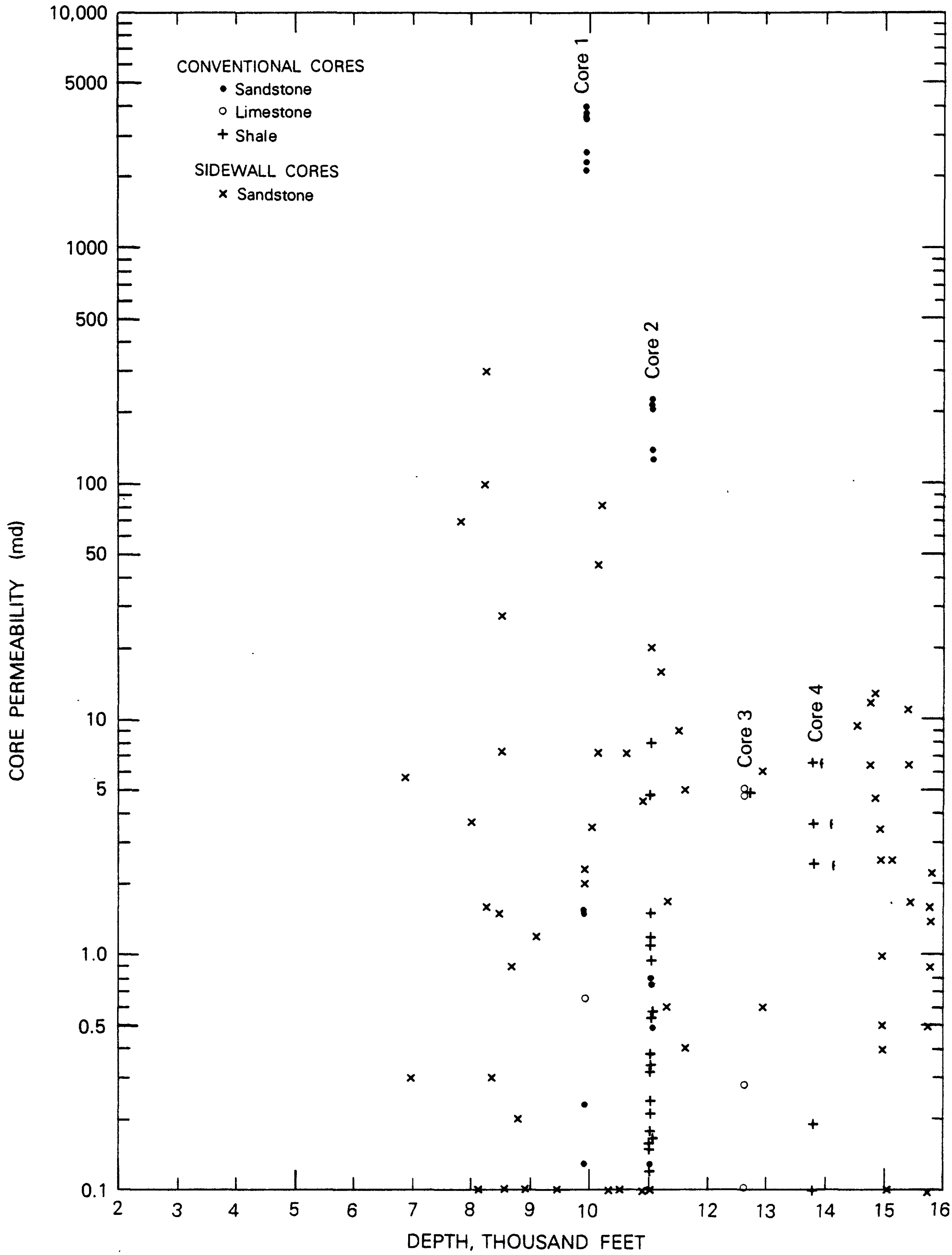

Figure 14.--Permeability of conventional and sidewall cores, COST No. B-3 well.

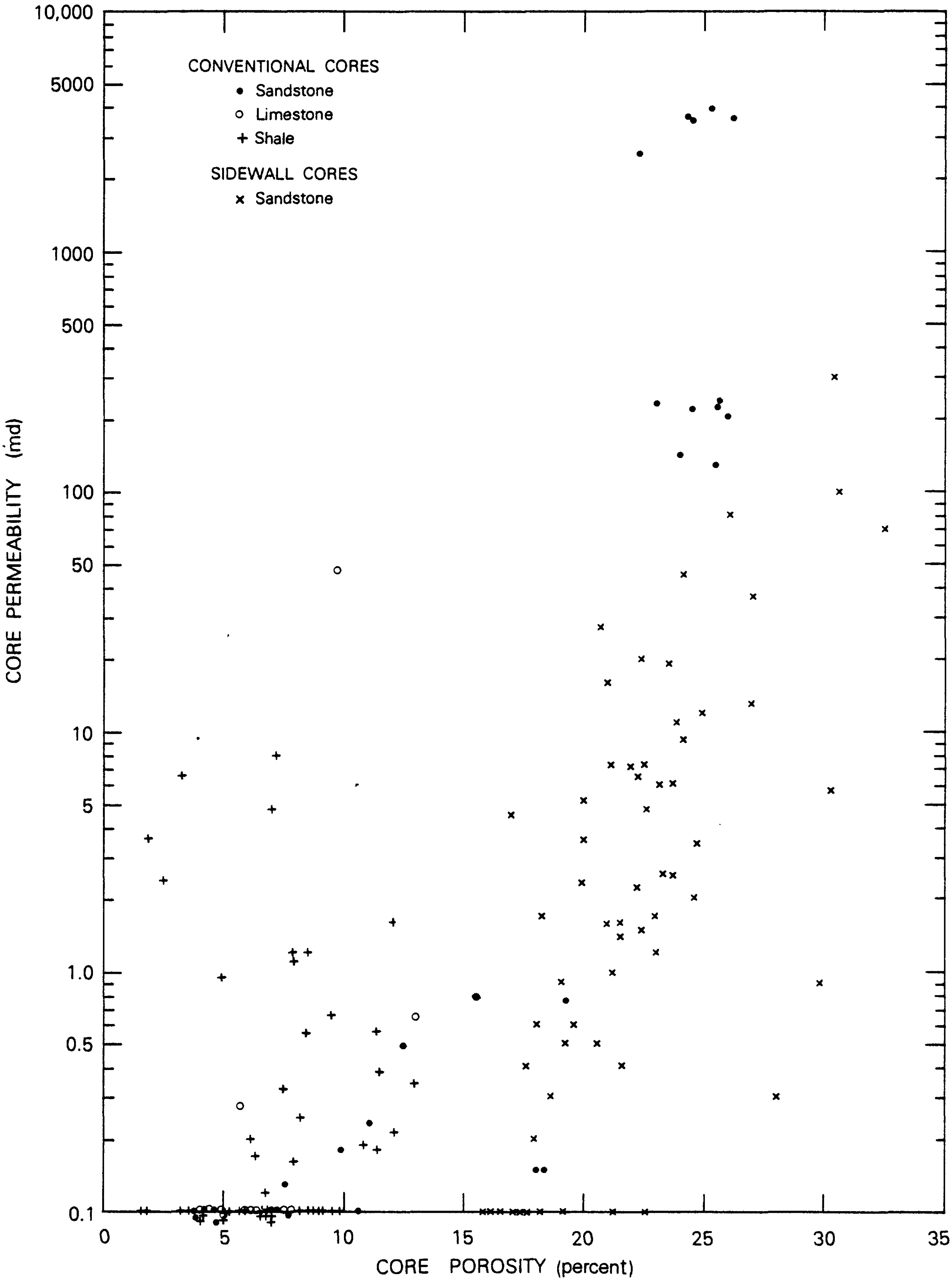

Figure 15.--Core porosity plotted against permeability, COST No. B-3 well.

Core 1 (9921-9935 feet). Core 1 is composed of sandstone with one limestone interval at 9933.5-9933.9 feet. The sandstone varies from light to dark gray, is medium- to very coarse-grained quartz with calcareous cement, has moderate to poor sorting, and is slightly to well indurated. Although the intervals 9921-9923.5 and 9923.6-9929.9 are porous, the interval 9929.9-9931.6 is compact and well indurated. The 9932.9-9933.5 foot interval is unconsolidated. Organic matter and fossil shell fragments (molluscan debris, foraminifera, echinoderm plates) are concentrated along dark horizontal streaks and laminations. Mica appears as an accessory mineral at the 9931.6-9932.9 foot interval. Thin section analyses show that 1-15 percent of the sandstone matrix is chlorite-clay. The 9923.5-9926.2 foot interval is composed of 15-21 percent dolomite. Volcanic rock fragments are a common minor constituent, varying in amounts from 1 to 5 percent. Traces of glauconite, pyrite, muscovite, hornblende and biotite are also present.

The limestone is light-gray and arenaceous with medium to coarse quartz grains and minor mica. Abundant poorly preserved echinoderm and skeletal debris is present. The matrix is composed of 4 percent dolomite, 40 percent calcite, and 3 percent clay.

In general, porosity and permeability decrease downward in the cored interval (fig. 16). A marked decrease in porosity and permeability occurs at the 9929.7-9931.6 foot and 9934.5-9935.0 foot intervals. This decrease may be the result of poor sorting, with grain size varying from coarse silt to coarse sand, and a great amount of calcite cement (44-55 percent). Many grains show embayed outlines due to replacement by calcite along their borders. At the 9931.6 foot depth, the decrease in permeability and porosity may result from the increased amount (15 percent) of chlorite-clay matrix.

Core 2 (11,009.5-11,060.75 feet). Core 2 consists of alternating sandstone and silty-sandy shale. The sandstone is light-gray to buff, very fine-to coarse-grained, poorly sorted, moderately to well indurated, and cemented by calcite. The major constituent of the sandstone is quartz (up to 61%). Constituents present in smaller amounts include feldspar, biotite, muscovite, volcanic rock fragments, chlorite, clay nodules and chert. The 11,010-11,010.5 foot interval is crossbedded and contains foraminifer and echinoderm fragments. The 11,010-11,010.5 and 11,016.5-11,016.7 foot intervals show organic staining.

The silty-sandy, calcareous shale is dark gray to black and moderately indurated and is crossbedded in the upper intervals of the core. The major clastic constituent is quartz. Other constituents are feldspar, muscovite, biotite, organic matter, pyrite, micrite clasts, and minor authigenic chert. The shale is slightly fossiliferous, containing small shell fragments. Thin sections from 11,024.3 and 11,039.6 feet indicate silty dolomicrites, with minor fossil fragments and mica. Thin sections from 11,027.5, 11,031.6 and 11,034.6 feet indicate silty micrite with mica and organic debris. The 11,056.5-11,060.0 foot interval is a silty, sandy organic-bearing shale composed of a fine-grained clay and mica matrix and 60 percent silt and sand grains. Some of the cement is authigenic chert. This shale is slightly fossiliferous and has traces of hydrocarbons. The 11,043.0-11,049.0 foot interval is very fossiliferous, having large pelecypod shells at 11,046 feet. At 11,044.6 and and 11,045.5 feet, the samples are packstones containing poorly sorted ooliths and sand grains in a very fine crystalline siderite matrix.

Porosities and permeabilities are fairly consistent throughout core 2 with the exception of two zones (11,043.0 feet and 11,049-11,054.5 feet) where porosity and permeability values are higher (fig. 17). The first interval is a pebble zone; the second interval is a poorly-cemented, fine-to very coarse-grained sandstone.

Core 3 (12,572 - 12,587.3 feet). Core 3 is composed of fossiliferous, oolitic limestone. It varies from tan to light-gray, is fine-to medium-crystalline, moderately to well indurated, and has shaly streaks, zones and partings. The thin section analyses indicate that the limestone is a grainstone consisting of fossil debris enclosed in oolitic micrite envelopes and cemented with coarsely crystalline spar. The fossil debris includes poorly preserved echinoderms, mollusks, bryozoans, foraminifera and ostracodes. The 12,581.2-12,583.0 foot interval is a more shaly, fossiliferous, oolitic limestone with accumulations of clay-organic insoluble residues along stylolites. The bottom 4 feet of the core have some intervals of coarse quartz sandstone cemented by sparry calcite and containing fossil fragments in thick micrite envelopes. Porosities and permeabilities are consistently low, averaging 6 percent and 3 md, respectively (fig. 18).

Core 4 (13,773 - 13,794.5 feet). Core 4 is composed of alternating intervals of shaly sandstone and sandy shale. The sandstone intervals (13,733-13,776.1 and 13,782.0-13,782.8 feet) are very fine-to medium-grained quartz and vary in color from light-to dark-gray with black and dark-gray stringers. They are well sorted, slightly to moderately indurated and bioturbated. Thin section analyses indicate the shaly stringers are composed of clay-organic-micaceous matrix material. The organic material may be algal in origin. The mica is mainly muscovite with scattered flakes of chloritized biotite. Many flakes are bent and deformed from post-depositional compaction. Tourmaline, chlorite, zircon and pyrite are present in trace amounts. The cementing material is sparry calcite with minor amounts of authigenic chert.

The sandy, calcareous shale (intervals 13,776.1-13,782.0 feet and 13,782.8-13,786.0 feet) is black with light gray stringers. It is poorly sorted, slightly indurated, fossiliferous, and bioturbated. Thin section analyses show that the stringers are composed of detrital organic material, clay minerals, mica, and pyrite. The fossil fragments found throughout are recrystallized calcite, making positive identification difficult. A few echinoderm spines, ostracodes, and foraminifera are recognizable. Scattered sideritic peloids occur at 13,784.3 feet.

The 13,786.0-13,794.5 foot interval is a black, silty, slightly indurated, fossiliferous mudstone with poorly formed, streaky laminations. The fossil fragments are recrystallized and the only recognizable fossils are ostracodes, echinoderms and pelecypods. Quartz, mica, and feldspars make up the silt constituent which is surrounded by a clayey, micaceous, calcitic groundmass with dispersed sideritic peloids.

Porosities and permeabilities for core 4 average 4 percent and 1.0 md, respectively (fig. 19). Porosities in the sandstone interval at the top of the core (13,776 feet) are slightly higher, ranging from 5 to 11 percent. This sandstone is well sorted and only slightly indurated.

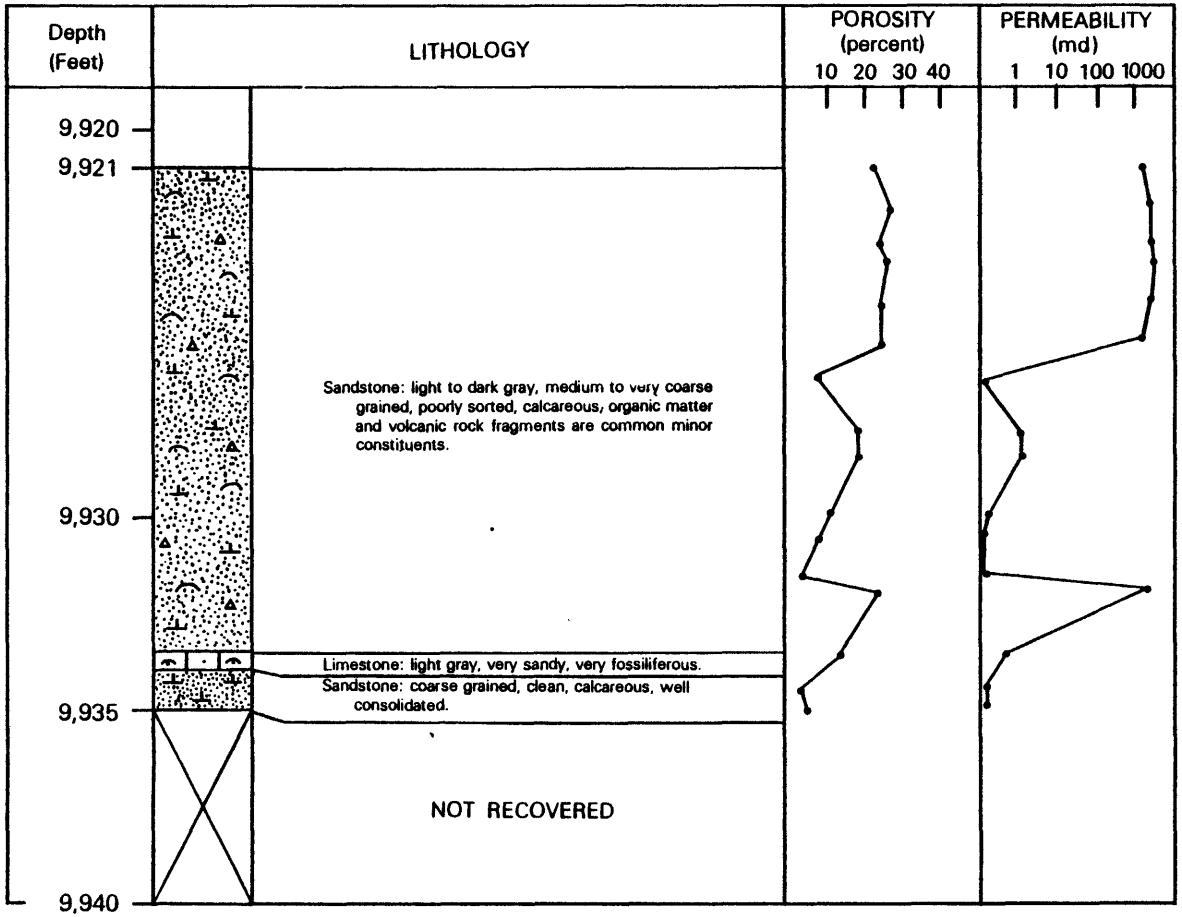

Figure 16.--Lithology, porosity, and permeability of conventional core 1, 9,921-9,935 feet, COST No. B-3 well.

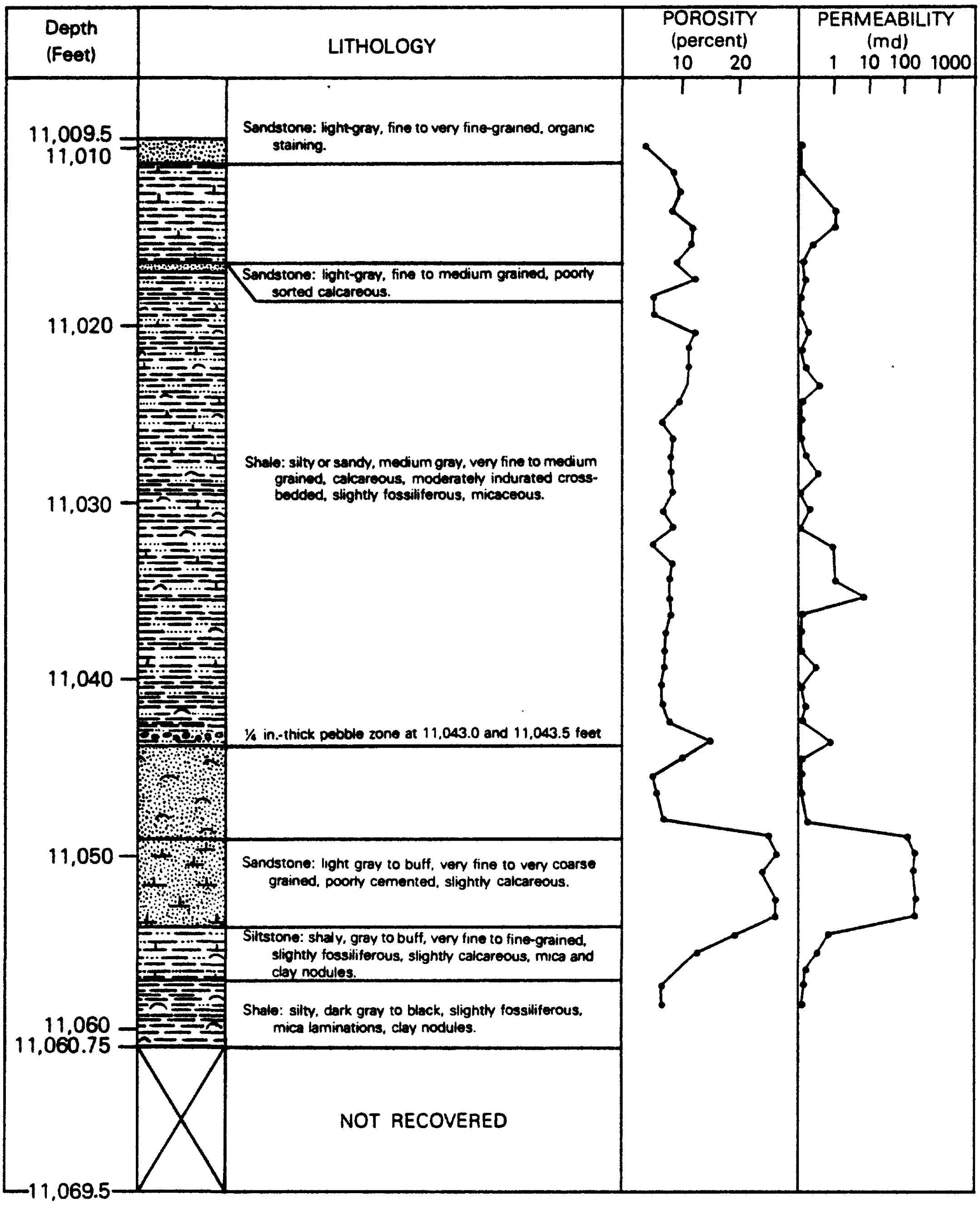

Figure 17.--Lithology, porosity, and permeability of conventional core 2, 11,009.5-11,060.75 feet, COST No. B-3 well.

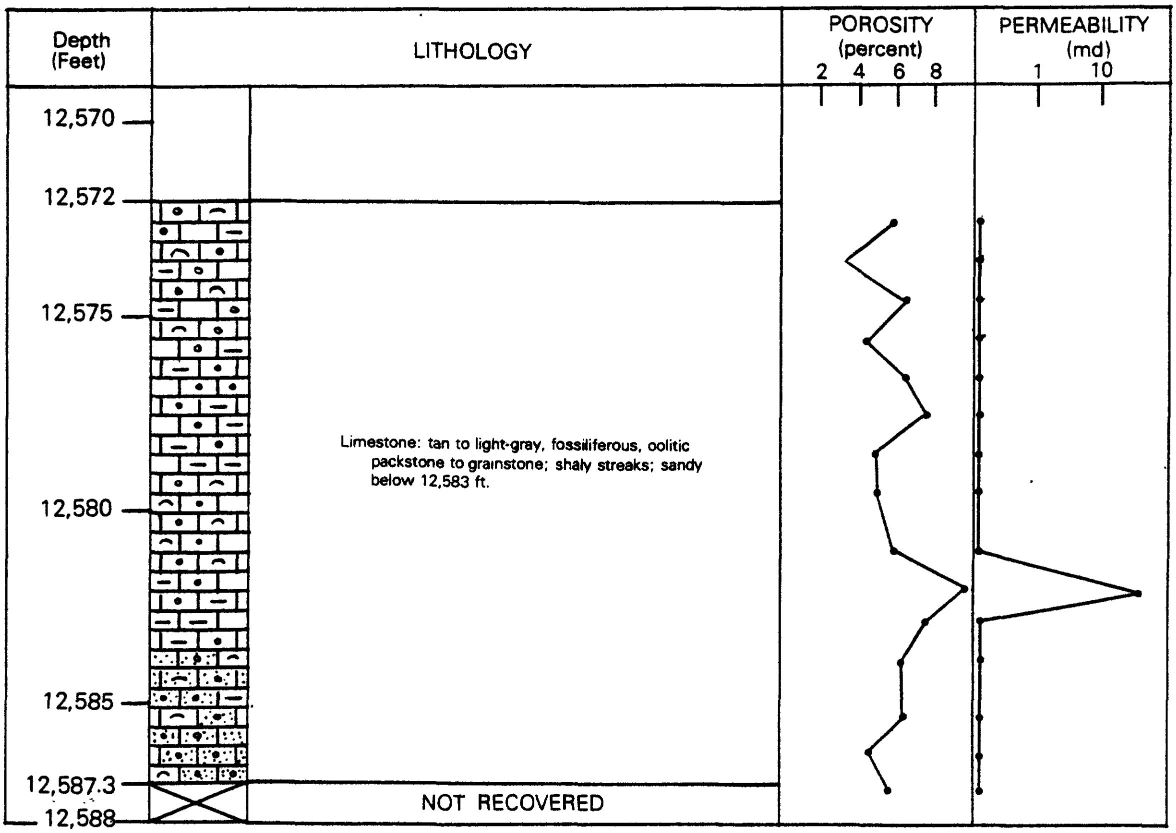

Figure 18.--Lithology, porosity, and permeability of conventional core 3, 12,572-12,587.3 feet, COST No. B-3 well.

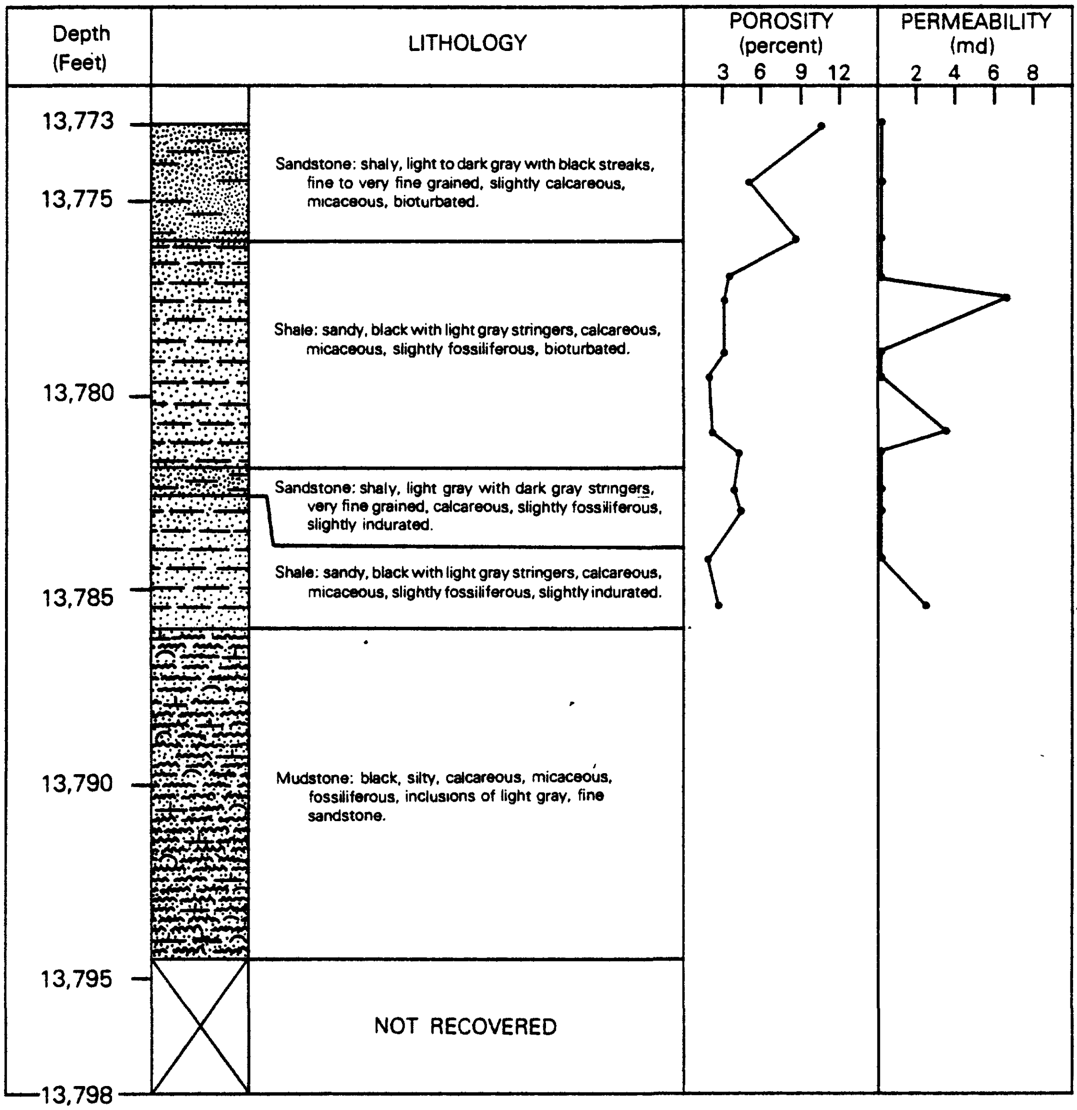

Figure 19.--Lithology, porosity, and permeability of conventional core 4, 13,773-13,794.5 feet, COST No. B-3 well.

GEOCHEMICAL ANALYSIS

By Michael A. Smith

Source-Rock Potential

The organic geochemistry of well cuttings from 120-foot intervals and sidewall and conventional cores was studied by Core Laboratories, Inc. (1979b), to provide data for evaluating the potential of strata in the COST No. B-3 well for petroleum generation. Lithologic descriptions, organic carbon analyses, and detailed light and gasoline-range hydrocarbon analyses were made for all samples. The amount and composition of solvent-extractable organic matter, vitrinite reflectance, and the type, thermal alteration index, fluorescence, and elemental analysis of kerogen were determined for every other cuttings sample. Well samples collected every 100 feet and samples of some sidewall and conventional cores were also analyzed on a shipboard pyrolysis unit by the operator (Chevron USA Inc., written communication, 1979). In addition, gas samples from the show near the bottom of the well were analyzed by Core Labs and the carbon isotope composition of both the gas and some kerogen and extract samples was determined by Phillips Petroleum Company (written communication, 1979). Values for the principal geochemical indicators are listed in table 3.

The stratigraphic section has been divided for this report into five geochemical zones as follows:

Zone 1 (3,840-5,000 feet)	Immature, potentially good oil source containing abundant biogenic methane.
Zone 2 (5,000-6,300 feet)	Immature, organic-lean, oil-prone source.
Zone 3 (6,300-11,100 feet)	Immature to moderately immature, organic-lean, gas-prone source.

Zone 4-A (11,100-13,000 feet)	Moderately mature, poor to fair oil source.
Zone 4-B (13,000-14,200 feet)	Mature, organic-lean nonsource section.
Zone 5-A (14,200-15,000 feet)	Mature, good gas source with high methane content.
Zone 5-B (15,000-15,820 feet)	Mature, very good gas source with very high methane content.

Figure 20 shows several indicators of organic richness plotted against well depth. The relative concentrations of organic matter in the geochemical zones is indicated by their weight percent of total organic carbon. Minimum amounts of 0.5 to 0.6 percent organic carbon in shale and 0.2 percent in limestone are required for source rocks with even a minimal potential for petroleum generation. Except for geochemical zone 2 and a few points in zones 3, 4-A, and 4-B, all cuttings samples have at least adequate concentrations of organic carbon. Zone 1 averages 1.88 percent, zone 5-A 0.99 percent, and zone 5-B 1.71 percent organic carbon; zones 1 and 5-B each have several very rich concentrations of more than 2 percent. The average organic carbon content in the well cuttings from other geochemical zones is 0.44 for zone 2, 0.82 for zone 3, and 0.69 for zones 4-A and 4-B.

Analysis of the sealed cuttings samples for their light and gasoline-range hydrocarbon content and composition provided additional information on the source-rock potential and maturation of the COST No. B-3 stratigraphic section. Air-space gas was sampled from the top of the sealed cans containing well cuttings and then part of the cuttings samples was disaggregated in a blender to release trapped hydrocarbons. The C_1

Table 3.--Organic geochemical measurements from COST No. B-3 well cuttings.

Depth (feet)	Total organic carbon (percent)	$C_1 - C_4$ (ppm)	Gas wetness (percent)	$C_5 - C_7$ (ppm)	C_{15+} (ppm)	Vitrinite reflectance (Ro percent)	H/C in kerogen
GEOCHEMICAL ZONE 1							
3,840	0.91	15,037	0.7	1,987	225	0.27	1.18
3,960	1.75	2,567	.5	409			
4,080	1.82	11,709	.8	1,173	255	.29	1.17
4,200	1.34	6,474	.5	1,506			
4,320	1.47	7,666	.7	1,523	291	.31	1.16
4,440	2.21	8,861	.6	889			
4,560	2.57	7,546	1.5	757	294	.32	1.22
4,680	2.95	6,912	1.2	639			
4,800	2.12	5,448	1.3	570	259	.32	1.23
4,920	1.70	4,328	2.0	910			
GEOCHEMICAL ZONE 2							
5,040	0.88	784	3.8	1,213	136	0.32	1.19
5,160	.69	3,313	1.9	1,344			
5,280	.43	1,991	2.2	737	35	.31	1.18
5,400	.22	1,333	2.0	539			
5,520	.30	2,191	2.9	605	21	.34	1.14
5,640	.45	3,404	2.1	194			
5,790	.34	2,938	3.1	168	30	.34	1.09
5,880	.30	3,673	2.3	43			
6,000	.15	2,423	1.7	44		.35	1.02
6,120	.45	1,431	1.9	62			
6,240	.64	787	2.3	106	15	.33	.60
GEOCHEMICAL ZONE 3							
6,360	1.06	3,707	3.6	170			
6,450	1.44	4,896	2.2	64	58	0.32	0.65
6,570	.90	2,172	3.4	117			
6,690	.96	1,398	3.2	47	57	.33	.62
6,810	1.03	3,619	2.4	75			
6,930	1.09	2,407	2.2	12	65	.34	.60
7,050	1.06	1,790	3.2	46			
7,170	1.27	853	4.6	84	99	.34	.61
7,290	1.21	2,005	6.1	63			
7,410	.77	1,233	5.8	19	163	.34	.64
7,530	1.08	1,038	5.7	92			
7,650	.92	844	7.0	23	200	.34	.70
7,770	1.06	581	7.1	48			
7,890	.94	1,254	8.1	36	130	.33	.66

Table 3.--Organic geochemical measurements from COST No. B-3 well cuttings--Continued

Depth (feet)	Total organic carbon (percent)	$C_1 - C_4$ (ppm)	Gas wetness (percent)	$C_5 - C_7$ (ppm)	C_{15+} (ppm)	Vitrinite reflectance (R_o percent)	H/C in kerogen
GEOCHEMICAL ZONE 3--Continued							
8,010	1.18	1,284	11.4	247			
8,130	.85	699	12.1	146	127	0.34	0.70
8,250	.27	980	9.6	100			
8,370	.53	1,011	10.3	85	207	.33	.79
8,490	.29	695	9.6	50			
8,610	.23	942	10.2	52	113	.34	.71
8,730	.98	1,005	13.3	77			
8,850	.81	687	15.2	72	160	.35	.66
8,970	1.10	1,703	12.2	253			
9,090	.69	1,268	13.6	128	248	.35	.80
9,210	.85	1,145	8.1	107			
9,330	.77	498	26.7	177	85	.35	.74
9,450	.64	1,590	15.1	214			
9,570	1.02	3,156	14.0	270	276	.37	.74
9,690	.92	3,053	22.5	305			
9,810	.98	402	19.5	395	439	.37	.72
9,930	.14	792	10.2	136			
10,050	.31	1,229	15.0	184	97	.37	.80
10,170	.58	638	29.3	142			
10,290	.90	520	27.8	180	88	.37	.69
10,410	.64	924	15.8	82			
10,530	.50	514	23.9	133	70	.38	
10,650	.90	589	24.7	72			
10,770	.37	638	23.2	106	77	.39	.67
10,890	.85	948	38.3	133			
11,010	.51	1,004	26.5	101	2,418	.39	.78
GEOCHEMICAL ZONE 4: Subzone 4-A							
11,130	0.43	1,253	19.6	380			
11,250	.65	1,672	25.7	433	177	0.39	0.86
11,370	.68	1,184	20.2	604			
11,490	.49	834	40.6	396	70	.39	.98
11,610	.76	1,123	33.4	460			
11,730	1.05	1,369	60.4	694	210	.39	.91
11,850	1.23	963	72.2	467			
11,970	.74	1,064	55.5	399			
12,090	.96	608	56.3	269	84	.40	.98

Table 3.--Organic geochemical measurements from COST No. B-3 well cuttings--Continued

Depth (feet)	Total organic carbon (percent)	$C_1 - C_4$ (ppm)	Gas wetness (percent)	$C_5 - C_7$ (ppm)	C_{15+} (ppm)	Vitrinite reflectance (Ro percent)	H/C in kerogen
GEOCHEMICAL ZONE 4: Subzone 4-A--Continued							
12,210	0.75	1,099	70.6	297	338	0.40	0.80
12,330	.60	554	56.2	302	366	.39	.77
12,450	.57	1,111	48.9	327			
12,570	.37	1,121	42.7	428			
12,690	.63	2,078	67.3	555	142	.39	1.05
12,810	.54	1,861	63.5	665			
12,930	.70	2,285	72.7	998	842	.44	.81
GEOCHEMICAL ZONE 4: Subzone 4-B							
13,050	0.67	747	71.9	408			
13,170	.58	2,273	59.4	682	262	0.45	0.80
13,290	.53	2,725	66.9	722			
13,410	.76	3,715	59.5	550	280	.46	.79
13,530	.64	5,005	60.7	697			
13,650	.67	4,397	63.6	1,369	152	.46	.71
13,770	1.04	4,339	57.3	1,214			
13,890	.80	5,227	63.3	354	172	.47	.83
14,010	.38	5,200	54.6	1,017			
14,130	.62	3,457	52.8	526	100	.48	.71
GEOCHEMICAL ZONE 5: Subzone 5-A							
14,250	0.98	22,155	23.8	376			
14,370	1.41	38,196	13.7	243	213	0.47	0.79
14,490	.89	47,823	11.1	393			
14,610	.71	3,803	35.1	238	244	.48	.74
14,730	.82	21,133	19.1	389			
14,850	1.19	41,489	9.3	148	344	.49	.78
14,970	.92	16,982	25.0	277			
GEOCHEMICAL ZONE 5: Subzone 5-B							
15,090	1.31	31,752	16.9	302	282	0.49	0.68
15,210	1.28	18,788	28.6	280			
15,330	1.59	15,573	20.7	132	242	.50	.69
15,450	2.80	43,651	15.8	256			
15,570	1.62	31,400	19.1	228	260	.49	.71
15,600		42,667	31.3	495			
15,630		49,954	10.1	268			
15,660		25,721	11.1	123			
15,690	1.47	35,555	17.5	257	240	.51	.70
15,720		36,293	21.3	263			
15,750		23,232	20.2	239			
15,780	1.24	39,996	21.4	425	129	.50	.74
15,820	2.38	65,538	17.8	488	405	.55	.71

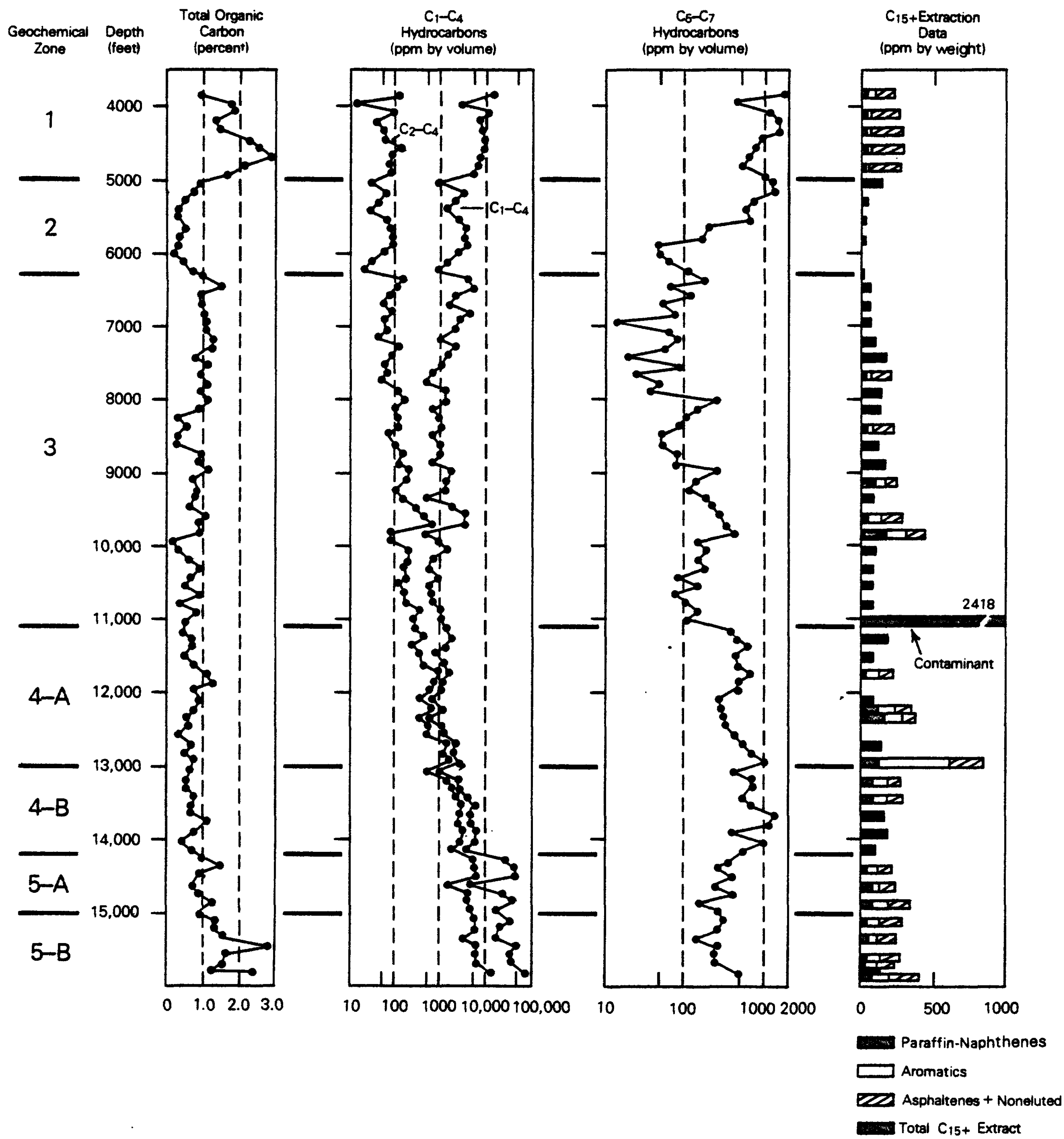

Figure 20.--Measurements of organic richness of sediments in the COST No. B-3 well.

through C_7 hydrocarbon content was determined by gas chromatography; the combined values for each sample are given in table 3 and plotted against depth in figure 20. Geochemical zones 1 and 5 are also very rich with respect to their light hydrocarbon content with an average of 7,655 ppm C_1 through C_4 hydrocarbons (99 percent methane) in zone 1 and 29,463 ppm (83 percent methane) in zones 5-A and 5-B. Other average light hydrocarbon concentrations are 2,206 ppm in zone 2, 1,393 ppm in zone 3, and 2,202 ppm in zones 4-A and 4-B. The large quantities of methane in zone 1 are biogenic gas but the highest methane concentrations, which are found in zones 5-A and 5-B, have been generated by thermal cracking and may be derived in part from coaly material in this section of the well. Two gas samples collected near the bottom of zone 5-B average 89.1 percent methane, 10.2 percent wet gas, and 0.7 percent C_{5+} hydrocarbons with a calculated gas gravity of 0.648 and gross heating value of 1,153 BTU/scf at 14.65 psia and 60°F for the dry gas. The C_2 through C_4 or wet gas hydrocarbons increase consistently with depth from 72 ppm in zone 1 to 5,087 ppm in zones 5-A and 5-B; this increase demonstrates greater thermal maturation and a higher potential for gas generation in deeper sections of the well. Even higher concentrations of the wet gas components, averaging 17,162 ppm in zones 5-A and 5-B, are seen in the sidewall core analyses where caving and gas loss from fracturing by the drill bit are not a factor. The highest quantity of gasoline-range (C_5 through C_7) hydrocarbons, 1,036 ppm, is found in zone 1 with concentrations dropping to 459 ppm in zone 2, 121 ppm (zone 3), 585 ppm (zones 4-A and,4-B), and 279 ppm (zones 5-A and 5-B). These values are too low to indicate any significant generation of liquid hydrocarbons by the source sections encountered in the B-3 well. Higher concentrations were measured in sidewall cores from all sections of the well except zone 1, with average values reaching 4,902 ppm in zones 4-A and 4-B and 4,588 ppm in zones 5-A and 5-B.

Soluble organic matter was extracted from 52 well cuttings and from 17 sidewall and 4 conventional core samples to provide additional data on the richness and oil-generating potential of the B-3 well. Samples containing more than 200 ppm extractable organic matter, the minimum amount required for liquid hydrocarbon generation, were separated into paraffin-naphthene and aromatic C_{15+} hydrocarbon fractions as well as the remaining asphaltene and noneluted compounds by silica-gel column chromatography. The total extractable C_{15+} bitumen for cuttings samples is given in table 3 and plotted with hydrocarbon fractions for the richer samples in figure 20. The average total bitumen is 265 ppm (66 ppm C_{15+} hydrocarbons) in zone 1 and 47 ppm in zone 2 increasing to 145 ppm (75 ppm C_{15+} hydrocarbons) in zone 3, 246 ppm (170 ppm C_{15+} hydrocarbons) in zones 4-A and 4-B, and 262 ppm (130 ppm C_{15+} hydrocarbons) in zones 5-A and 5-B. The richest cuttings sample with 2,418 ppm C_{15+} extractable organic matter and 2,009 ppm C_{15+} hydrocarbons was collected from the 120-foot interval below 11,010 feet, but this analysis was not included in the averages because of a large amount of pipe dope contamination and analyses for a conventional core from the same interval which averaged 390 ppm total bitumen (142 ppm C_{15+} hydrocarbons). Zones 4-A and 4-B contain greater high molecular weight hydrocarbon concentrations than zones 5-A and 5-B, and are therefore more oil prone and may already have generated some liquid hydrocarbons. In general, the small quantities of extractable C_{15+} bitumen throughout the well indicate few prospective oil-generating sections but also suggest that no serious drilling mud contamination of the geochemical well cuttings samples occurred.

Thermal Maturity

Except for biogenic gas, the potential source rocks of an area will begin to generate significant quantities of petroleum only after they have undergone geothermal diagenesis with a sufficient time-temperature history. Several criteria are used to measure the amount of thermal alteration that has occurred in the organic material in sediment; the results from three methods used to determine maturity in COST No. B-3 well sediments are shown in figure 21. Although all the analytical techniques used for the Atlantic COST wells show an increase in maturation with greater depth, the different types of data have not provided consistent evaluations of thermal history, and none of the currently accepted methods has been accurate for all lithologies, ages, types of organic matter, and depths of burial. For the B-3 well, the most widely used maturity indicators all show less thermal alteration than actually occurred.

The first indicator of thermal diagenesis in figure 21 is the visual index defined by Staplin (1969). Exposure to higher temperatures is inferred by color changes from light yellow through orange and brown to black for the organic matter in sediment including spores, pollen, plant cuticles, resins, and algal bodies. This color-based thermal alteration index (TAI) is assigned from transmitted light microscopy and can range from 1 for totally immature samples to 5 for metamorphosed rocks. Values for the B-3 well cuttings are at the lower, immature end of the scale. Although the TAI values increase consistently with depth, they still indicate moderately immature strata in zone 5; the 2+ to 3- values required for peak

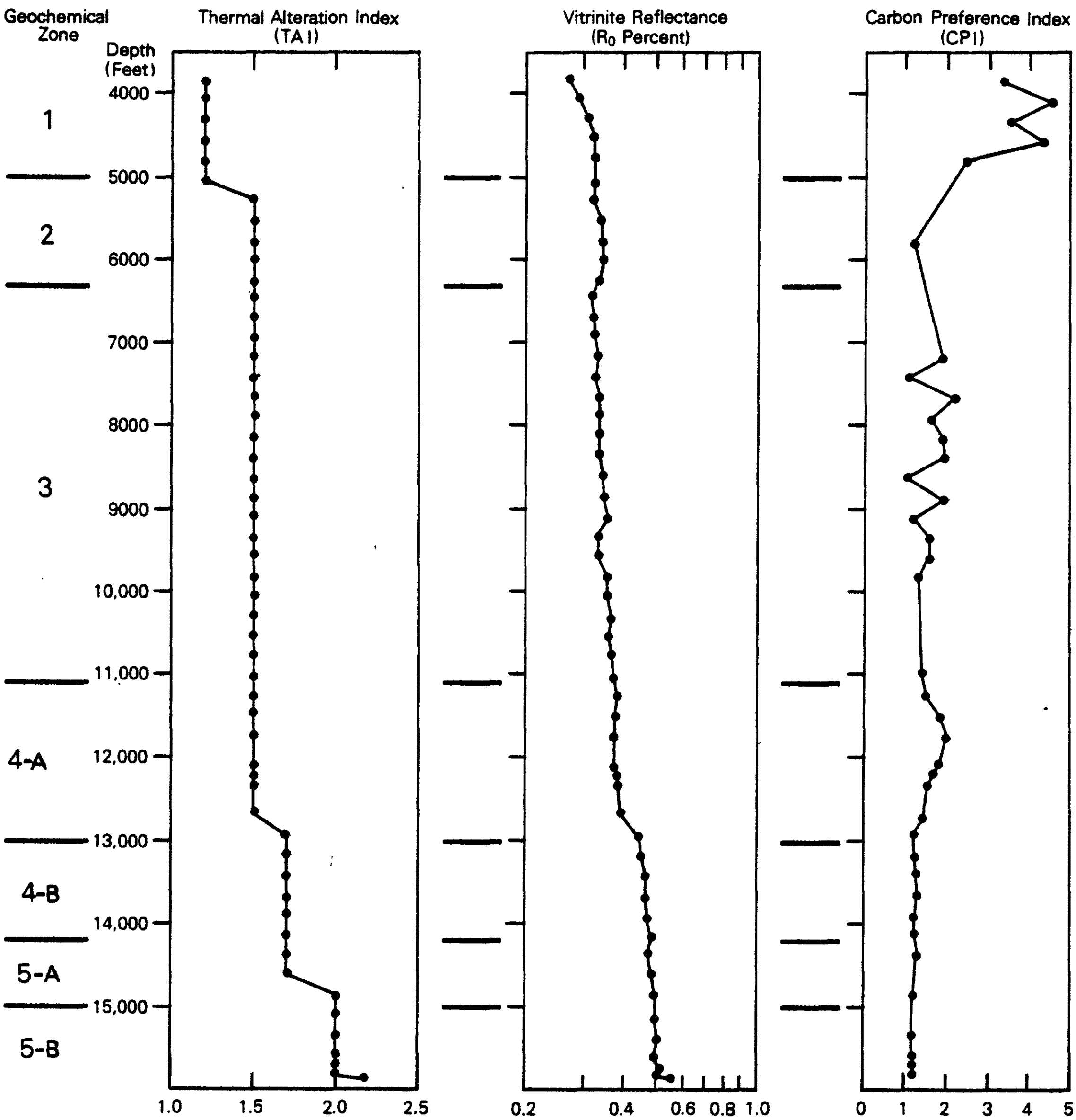

Figure 21.--Measurements of the maturity of organic matter in COST No. B-3 well sediments.

oil generation are not seen in this well.

A second method for measuring thermal maturity that shows the effect of duration of heating in addition to the highest temperature encountered is based on the reflectance capability (R_o) of polished vitrinite grains. Vitrinite reflectance data (fig. 21, table 3) show an increase in maturation with depth closely corresponding to the thermal alteration index. Dow (1977) suggested that significant amounts of oil generation can occur at R_o values above 0.6 percent with higher measurements needed for peak wet gas and dry gas generation and for the oil and gas floors. The highest vitrinite reflectance measurements reported by Core Laboratories, Inc. (1979b) in the B-3 well cuttings average 0.51 percent in zone 5-A (0.54 percent in sidewall cores), and immature oil could start to form at these depths if oil-prone source beds were present. Unfortunately, the wide range of reflectance data in most samples, varying from less than 0.15 to 2.50 percent with numerous individual peaks, made it difficult to obtain a reliable mean R_o value. The problem is illustrated by the results of analyses of five core samples from zones 3, 4-A, and 4-B at Pennsylvania State University for vitrinite reflectance quality control (Phillips Petroleum Company, written communication, 1979). These measurements are consistently about 0.35 percent higher than those plotted in figure 21 and indicate sufficient maturity for oil generation below approximately 9,000 feet. The vitrinite reflectance data from coal seams in zones 5-A and 5-B also provided higher readings than for other vitrinite particles found in this interval.

Detailed analysis of the hydrocarbon composition of cuttings samples can also provide a third type of maturity profile indicating diagenetic changes in the well. Thermal alteration involves a decrease in the predominance of odd-carbon-numbered straight-chain paraffins. These hydrocarbons are derived from waxy plant material and are characteristic of gas chromatograms for immature samples. The ratio of odd to even high molecular weight hydrocarbons in the C_{10+} paraffin-naphthene extract is called the carbon preference index (CPI) and is plotted for the B-3 well cuttings in figure 21. The high CPI values, averaging 3.66 in zone 1 and 1.58 in zone 3, and wide scatter between samples are typical of immature and moderately immature sections. Deeper in the well, the CPI measurements approach 1 (1.46 for zones 4-A and 4-B and 1.17 for zones 5-A and 5-B) and indicate mature source rocks. Other hydrocarbon compositional changes include an increase in the paraffin/naphthene and straight/branched chain ratios, especially in C_4 through C_7 compounds, and in gas wetness (the percentage of C_2 through C_4 wet gas components in the light hydrocarbon extract) with depth. The gas wetness jumps sharply near the top of zones 4-A and 4-B, which average 54 percent wet gas (fig. 20 and table 3), and strata below 11,700 feet appear to be mature according to this criterion.

Analyses from the pyrolysis unit aboard the Ben Ocean Lancer drill ship included the temperature for maximum liberation of hydrocarbon compounds. This temperature varied from $406^{o}$to $441^{o}C$ and increased with depth, an additional indication of maturation. The production index also suggests a depth of burial and degree of thermal evolution. This index is the ratio of the integral of the P1 (the amount of free hydrocarbons analyzed) peak to the sum of the integrals of the P1 and P2 (the quantity of hydrocarbon compounds derived from thermal cracking) peaks. This parameter increases steadily below 11,000 feet denoting mature sediments at this depth.

Fluorescence analysis--an additional determination of maturation levels--is also useful in eliminating fluorescent material from the nonfluorescent vitrinite during reflectance analysis. Fluorescence measurements have been made on bisaccate sporinite, a coal maceral which occurs with vitrinite of a known reflectance capability. Immature sporinite has white, light yellow, and green fluorescence with an emission spectral peak of less than 530 nanometers. The COST No. B-3 well samples exhibit a "first coalification jump", a rapid change to dark yellow, orange, and brown fluorescence and a spectral peak above 530 nanometers, at a depth of 10,800-11,900 feet. The jump occurs at vitrinite reflectance values of 0.5-0.6 percent and indicates the onset of possible oil generation. Thus fluorescence measurements, carbon preference index, gas wetness, and the pyrolitic production index all suggest that the stratigraphic section below 11,000 or 12,000 feet has undergone a sufficient thermal history to generate liquid hydrocarbons.

Hydrocarbon Source Character

Which kinds of hydrocarbons (oil, condensate, or gas) are generated in an area with adequate organic richness and thermal maturity depends on the predominant types of kerogen in the source rocks. Oil is formed from aquatic and unstructured organic matter and gas is produced by terrestrial and structured kerogen. Shown on figure 22 are the relative abundance, in B-3 samples, of four types of kerogen: amorphous (algal bodies and amorphous sapropel), herbaceous (plant cuticles, pollen, spores, resins, and waxy material), woody (primarily vitrinite), and coaly (inert

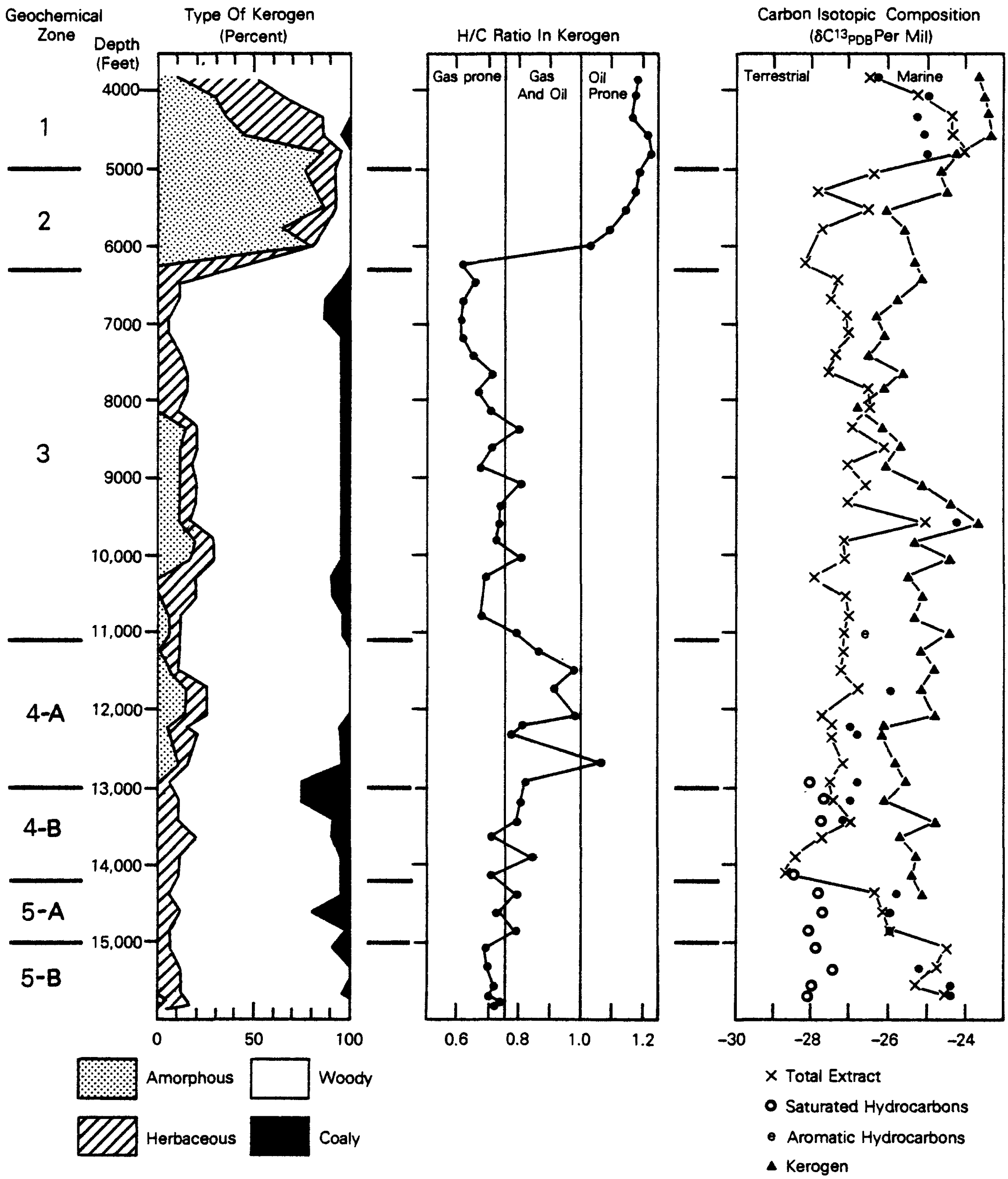

Figure 22.--Measurements showing the type of organic matter in COST No. B-3 well sediments.

and finely disseminated organic matter). Zones 1 and 2 contain primarily amorphous kerogen with some herbaceous material at the top of the well. Sufficient thermal alteration of these kerogen types could be expected to generate oil, although zone 2's organic material is too sparse to constitute a prospective oil source. Gas-prone woody kerogen predominates in the rest of the B-3 stratigraphic section. However, enough algal-amorphous kerogen is present in some zone 4-A samples, particularly side-wall cores, to qualify some beds as oil-prone source rocks.

The H and C content in kerogen from the B-3 well cuttings was determined by combustion in an elemental analyzer (fig. 22, table 3); care was taken to avoid oxidation. LaPlante (1974) suggested that elemental analysis of kerogen can not only indicate the type and quantity of hydrocarbons that will be generated but also show the degree of thermal maturation of well samples. The atomic H/C and O/C ratios will decrease along well defined kerogen evolution paths for oil-productive and gas source rocks with increasing depth of burial (Tissot and others, 1974). Oil-prone source rocks with H/C values exceeding 1.0 are found in zones 1 and 2 to a depth of 6,000 feet (fig. 22). Most deeper geochemical zones are gas prone and have a H/C ratio of less than 0.75; zone 4-A, contains a mixture of hydrocarbon source types, including some oil-prone beds.

Another indication of organic matter type and source, depositional environment, and potential petroleum yield is the stable carbon isotopic composition of the kerogen and solvent-extractable organic material. Phillips Petroleum Company (written communication, 1979) provided these data for aliquots of the C_{15+} extract obtained from Core Laboratories Inc., for 54 cuttings and core samples (fig. 22), including the saturated and aromatic hydrocarbon fraction compositions at certain depth intervals. The ratio of the two stable carbon isotopes, C^{13}/C^{12}, is measured for the samples and for a standard (the Peedee belemnite, PDB--Chicago) and is expressed as a δ value according to the formula:

$$\delta C^{13} \text{ (per mil)} = [(R_s - R_r)/R_r] \times 1,000$$

where R_s = C^{13}/C^{12} ratio in the sample and

R_r = C^{13}/C^{12} ratio in the reference standard.

The average carbon isotopic values for the total extract samples from zone 1 (-24.9 per mil) and zones 5-A and 5-B (-25.4 per mil) are heavier than the average of -27.3 per mil for the rest of the B-3 stratigraphic section; that is, they are enriched in C^{13}, indicating either a higher proportion of marine organic matter or deposition in an open marine environment. Information on the potential yield of petroleum can be derived from the difference between the kerogen and total extract isotopic values; unfortunately, there are no kerogen composition data for most of zones 5-A and 5-B, the section of greatest exploratory interest in the B-3 well. The gas samples from the show at the bottom of the well were analyzed compositionally and had average δC^{13} values of -35.3 per mil for methane, -27.9 per mil for ethane, and -25.3 per mil for propane. This methane has a carbon isotope distribution in the range of methanes generated by very mature source rocks, and is much heavier than biogenic methanes which have δC^{13} values of -50 to -70 per mil (Tissot and Welte, 1978). Probably any oil found in this section would have an average carbon isotopic composition between -23 and -24 per mil.

Summary and Geochemical Significance

Geochemical analysis of COST No. B-3 well samples has identified intervals with potential for both gas and oil generation. Gas from a tested section was also studied in detail. Data on thermal maturity are inconsistent, but seem to indicate that some hydrocarbon generation has occurred in at least the deepest 4,000 feet of this well. Average values of the measured parameters for well cuttings from each geochemical zone are listed in Table 4.

Zones 1, 5-A, and 5-B have the best organic richness as shown by total organic carbon measurements, and contain abundant methane. The deepest zones are also rich in wet gas and have good gas-source potential. The higher concentrations of C_{15+} hydrocarbons and total extractable organic matter in zone 4-A imply some oil-generating potential. Several maturity indicators--gas wetness, pyrolytic production index, CPI, and isobutane/n-butane ratio--suggest that a level of thermal diagenesis needed for liquid hydrocarbon generation has been reached in zone 4-A or 4-B. The kerogen type and H/C ratio identify zones 1, 2, and 4-A as the oil-prone sections of the well.

Geochemical correlations can be made with the COST No. B-2 well, drilled 32 miles to the north, even though the depositional environment of B-2 strata was closer to shore and facies changes exist in many correlative stratigraphic units. The richest interval in the B-2 well is a good to excellent gas source between 9,400 and 13,900 feet. This interval corresponds to the lower 1,000 feet of geochemical zone 3, zones 4-A, 4-B, 5-A, and most of 5-B in the B-3 well. It contains an average

Table 4--Summary of geochemical parameters by zone.

Geochemical zone--------	1	2	3	4-A	4-B	5-A	5-B
top (feet)------------	3,840	5,000	6,300	11,100	13,000	14,200	15,000
bottom (feet)----------	5,000	6,300	11,100	13,000	14,200	15,000	15,820
Organic richness							
Total organic carbon (weight percent)	1.88	0.44	0.82	0.70	0.67	0.99	1.71
Methane (ppm)	7,583.	2,155.	1,249.	609.	1,487.	23,186.	28,209.
C_2 - C_4 (ppm)	72.	51.	143.	652.	2,222.	4,183.	6,696.
C_5 - C_7 (ppm)	1,036.	459.	121.	480.	754.	295.	289.
Extractable organic matter (ppm)	265.	47.	145.	279.	193.	267.	260.
C_{15+} hydrocarbons (ppm)	66.	no data	75.	196.	127.	142.	123.
Thermal maturity							
Thermal alteration index	1.2	1.4	1.5	1.5	1.7	1.8	2.0
Vitrinite reflectance (R_o percent)	.30	.33	.34	.38	.46	.48	.51
Carbon preference index	3.66	1.19	1.58	1.60	1.24	1.24	1.14
Isobutane/n-butane	.25	.70	1.39	.91	.37	.46	.50
Gas wetness (percent)	1.0	2.4	13.1	50.4	61.0	19.6	19.4
Temperature of maximum pyrolysis yield (°C)	419.	418.	427.	430.	434.	436.	no data
Pyrolytic production index	.021	.010	.001	.064	.106	.124	no data
Organic matter type							
Kerogen type (percent)							
amorphous	41.	63.	6.	7.	0	0	1.
herbaceous	35.	10.	10.	9.	12.	7.	8.
woody	23.	27.	78.	79.	77.	85.	88.
coaly	1.	0	6.	5.	11.	8.	3.
H/C in kerogen	1.19	1.04	.70	.90	.77	.77	.70
Carbon isotopic values--total extract (per mil)	-24.9	-27.4	-27.0	-27.4	-27.9	-26.2	-24.9
Carbon isotopic values--kerogen (per mil)	-23.7	-25.2	-25.5	-25.5	-25.5	-25.1	no data

of 2.35 percent organic carbon and 18,102 ppm light hydrocarbons with the richest samples from an interval corresponding to zone 5-A. Gas wetness reaches a maximum average of 53.9 percent in an interval correlative with zone 4-A. The shallowest section in the B-2 well is sandy with little source potential compared to the organic-rich rocks which were deposited in a marine environment near the shelf edge in B-3's zone 1. The B-2 well also penetrated about 2,000 feet of organic-lean, terrestrial section which was not encountered at the bottom of the B-3 well.

PETROLEUM POTENTIAL

By Edvardas K. Simonis

For purposes of estimating petroleum potential, the section penetrated by the COST No. B-3 well can be divided into three zones on the basis of reservoir characteristics and stages of thermal maturation. Geochemical data and interpretations were provided by Core Laboratories, Inc. (1979b) and are discussed by Smith (preceding chapter, this report). The upper zone extending down to 8,200 feet is thermally immature and is dominated by mudstone and shale. The middle zone, 8,200-11,630 feet, though immature contains abundant thick-bedded sandstone with good reservoir properties. The lower zone, 11,630-15,820 feet, is thermally mature and consists of shale, limestone, sandstone and coal. Shale, abundant in all three zones, provides potential seals for hydrocarbon entrapment.

Upper muddy zone. The Tertiary and Upper Cretaceous section down to 8,200 feet is dominated by marine mudstone and shale. Glauconitic sands with average porosities exceeding 20 percent are concentrated in the intervals 6,700-6,900 feet and 7,600-7,820 feet. Cummulative thickness of these sands is approximately 200 feet. Chalky limestones provide potential for additional reservoirs.

Geochemical data indicate that the thermal maturation of kerogen in this zone is very low; and although the Tertiary section above 5,000 feet contains abundant hydrogen-rich algal organic matter that is considered to be potentially good oil source, only biogenic methane is likely to have been generated in the organic-rich part of the zone.

Regional seismic reflection data further show that increased maturation by deeper burial of this section cannot be expected anywhere in the entire region of the U. S. Atlantic continental shelf and slope. Therefore, this zone consisting of Tertiary and Upper Cretaceous sediments is considered to be the least prospective of the three zones.

Middle sandy zone. The Upper Cretaceous (Cenomanian) to Lower Cretaceous (Hauterivian) section between 8,200 and 11,630 feet consists of two sandstone sequences separated at 8,700 to 9,900 feet by a thick Albian-upper Aptian shale interval. More than 1,000 feet of sandstone, with porosity values concentrated in the 16 to 24 percent range, is present in this zone. Permeability values vary widely; most of the sidewall cores have permeabilities of less than 10 md but some are as much as 300 md, and values of as much as 3,970 md were recorded in conventional core 1 between 9,921 and 9,935 feet.

Comparison of this zone in the COST No. B-3 well with a similar sandy zone in the COST No. B-2 well discloses some interesting relationships which may be important in forming stratigraphic traps. Although the tops of the sandy zone occur at 8,200 feet in both wells, biostratigraphic studies completed to date indicate that whereas the upper 700 feet of the sands in the B-2 well are Albian, the upper sandy interval in the B-3 well is Cenomanian. In addition, the thick Albian-upper Aptian shale interval at 8,700-9,900 feet in the B-3 well is represented in the B-2 well by a time-equivalent section of thick-bedded sandstones. Individual sandstone beds in the B-2 well are interpreted to thin and/or pinch out toward the B-3 well, creating possibilities for stratigraphic traps.

Although this sandy zone contains the thickest section of potential reservoir rocks encountered in the well, geochemical data indicate that kerogen in most of the section has not reached the required maturity for significant hydrocarbon generation. Some intervals between 8,200 and 11,100 feet contain about 1 percent organic matter, an average value for shales; however, the organic matter is of terrestrial origin and hydrocarbon concentrations are very low. Only in the bottom part of the middle zone, below 11,100 feet, does thermal maturity approach the oil generating stage, and although the sediments are organically lean, a few thin zones contain a variety of kerogen types and are considered fair sources of oil. These potential source rocks and the proximity of the underlying thermally mature zone make the lower sands of the middle sandy zone attractive petroleum exploration targets.

Lower mature zone. The Lower Cretaceous and Upper Jurassic section, from 11,630 feet to 15,820 feet, consists of limestone, sandstone, shale, and minor amounts of coal. Marine shale dominates the Lower Cretaceous (Neocomian) section between 11,630 and 12,400 feet. Oolitic limestones are prominent in the shallow marine Jurassic section at 12,400 and 14,100 feet. Below 14,100 feet, thin beds of coal are common in a section deposited in terrestrial to marginal marine environments.

The sandstones are less abundant and thinner-bedded than in the age-equivalent section in the B-2 well. In the B-3 well they are dispersed throughout the Jurassic section as rather thin (10-30 ft) beds, although beds as much as 50 feet thick occur at the top of the Jurassic section between 12,400 and 12,600 feet. Porosity logs show approximately 140 feet of sandstone with porosity values in excess of 8 percent. Porosity values of sidewall cores are mainly in the 17-25 percent range; however, permeabilities are low, mostly below 10 md. Porosities and permeabilities of limestones are very low. Oolitic limestone in conventional core 3 recovered from 12,572 to 12,587.3 feet had porosities of less than 8 percent and permeabilities of less than 0.1 md except for a fractured zone at 15,282 feet where porosity was 9.7 percent and permeability was 47 md. Sandstones, therefore, are the main potential reservoirs and their reservoir characteristics are expected to improve westward toward the sediment source area. Reservoir characteristics of limestones are expected to improve eastward toward a feature seen on regional seismic lines which has been interpreted as a Jurassic to Early Cretaceous reef or carbonate platform.

The entire section below 11,630 feet is estimated to be thermally mature and certainly below 15,000 feet the kerogen is at a maturation state within the main phase of oil and gas generation. Down to 13,000 feet, presence of a variety of kerogen types indicates possible oil sources. Between 13,000 and 14,100 feet the section is considered a poor source because of low content of organic matter. Below 14,100 feet, good gas source is indicated by abundance of coaly kerogen, high concentration of dry gas, and a gas show encountered at 15,750 feet. The gas recovered at this depth by Repeating Formation Tester is dry: dominantly methane with low concentrations of heavier gases. No oil was recovered during the tests. At total depth gas-source parameters were still improving, indicating possible additional source beds below 15,820 feet.

Therefore, in vicinity of the B-3 well, the best potential for generating significant amount of hydrocarbons appears to be below

14,100 feet, although vertical migration of gas into reservoirs above 14,100 feet is a possibility. Dry gas is the main type of hydrocarbon to be expected.

Regional considerations. USGS reflection seismic records in the area of U. S. Mid-Atlantic continental slope show a feature which has been interpreted to be a Jurassic to Lower Cretaceous shelf-edge reef or carbonate bank (for example, Grow and others, 1979). It is located seaward (east) of the COST No. B-3 well and trends subparallel to the continental margin. In some seismic lines which were converted into depth sections (for example, Grow and others, 1979, p. 11-72), the Jurassic and Lower Cretaceous beds in the "back-reef" area appear to be tilted gently to the west; this westward dip is confirmed by dipmeter data in the COST No. B-3 well. Sandstones in the "back-reef" area thin and pinch out eastward or southeastward as shown by decreasing thickness and number of beds from the B-2 well to the B-3 well. These updip pinchouts create an ideal situation for stratigraphic traps in the area between the COST wells and the reeflike feature. Faults which were active mainly during Early Cretaceous (Grow and others, 1979, p. 74) provide possibilities for additional traps.

Reservoir characteristics of carbonates are expected to improve east of the B-3 well along the Jurassic and Lower Cretaceous shelf-edge reef or carbonate bank. The increase in amount of carbonates from the B-2 to the B-3 well confirms the interpretation of seismic data that the lithology of the Mesozoic shelf-edge is dominated by carbonates. Mattick and others (1978) consider the potential reservoir development in these shelf-edge carbonates to be analogous to the productive back-reef facies of the Cretaceous Edwards Limestone of Texas and the reef trend of the El Abra-Tamaulipas Formation of the Golden Lane in Mexico. This optimistic interpretation is tempered somewhat by lack of discoveries in the Middle Jurassic to Lower Cretaceous shelf-edge carbonate unit (the Abenaki Formation) of the Scotian shelf in Canada. Given (1977, p. 74) states that the Abenaki Formation is usually tight, but one well, the Shell G-32 Demascata, penetrated 550 feet of porous dolomite and limestone.

In summary, the geologic data obtained from the B-3 well, integrated with interpretation of seismic data indicate that in the area of the well all necessary prerequisites for generation and entrapment of gas are present in the Jurassic sediments. Vertical migration of hydrocarbons from thermally mature sources into the excellent Lower Cretaceous reservoir sands is a possibility enhanced by the presence of Early Cretaceous faults. The Upper Cretaceous and Tertiary section is considered least prospective, in light of low thermal maturation, limited reservoirs, and apparent scarcity of traps. East of the B-3 well, the Jurassic and Lower Cretaceous shelf-edge carbonates provide an attractive trend for exploration.

ENVIRONMENTAL CONSIDERATIONS

By Eric V. Kaarlela

Before the drilling permit was approved, an Environmental Analysis for the proposed COST No. B-3 well was prepared. This report, completed in September, 1978, is available for public review at the Public Information Room of the USGS, at 1725 K Street N. W., Washington, D. C. The report discussed those parts of the environment which might be affected by the proposed drilling operation and included summaries and reviews of solicited comments from other concerned Federal agencies, affected States, and local environmental and special-interest groups. The study concluded that drilling of the B-3 well would not significantly affect the human and physical environment and therefore would not require an Environmental Impact Statement. However, an Environmental Impact Statement (U. S. Department of Interior, 1978) covering the overall area was prepared for OCS Lease Sale 49 and copies may be inspected at the same Public Information Room listed above.

Chevron USA Inc. applied in June 1978 for the permit to drill the COST No. B-3 well. The site selected was determined by CDP seismic surveys to be away from any potential hydrocarbon-entrapping geological structure; thus the probability of the well penetrating a major hydrocarbon accumulation was considered to be small. As required for the permit to drill the stratigraphic test well, archeological, biological, and engineering site surveys were made. The results of these surveys were evaluated in the Environmental Analysis for the COST No. B-3 well, together with any hazards that might have an adverse effect on drilling.

Other than the impact of an oil spill, there would be little effect on the fish and wildlife of the area or nearby coastal tidewaters. Although some endangered and threatened species are known to occur in the Mid-Atlantic OCS, none are known to occur exclusively at the location of the well. The effect of an oil spill in the Mid-Atlantic is unpredictable but it could be extensive. Toxic hydrocarbons could pose a threat to free-floating larvae of fish and cause benthic contamination of surviving organisms. This might interrupt one or more reproductive cycles of certain species which in turn might adversely affect the fishing industry. In the unlikely event that such oil reached the shore, the recreational uses and esthetic value of the shore would also be adversely affected. As a safeguard, USGS regulations, permit stipulations, and OCS orders were enforced to provide maximum control over drilling operations and USGS inspectors continuously monitored operations for compliance. An oil-spill contingency plan was developed providing for a fast-response skimmer system with additional backup spill containment and cleanup equipment.

Hazards, both natural and man-made, that might endanger drilling operations were considered prior to approval of the permit to drill. High-resolution seismic data in the area showed no significant shallow gas accumulations or near-surface faulting. Geologic hazards associated with high-pressure zones at depth were not encountered. If they had been, however, a pressure-control program utilizing the weight of the drilling-mud column, blowout prevention equipment and well casing strings was available. The earthquake-related hazards were considered to be minimal as the area has little seismic activity. No seismic activity was noted during the drilling of the well.

Other natural hazards associated with weather, sand wave movement and sediment scour did not adversely affect the actual drilling operations. Adverse weather conditions did slow drilling operations but were never a problem. Bad weather stopped drilling on only 10 of 109 days. The conductor pipe settled after it had been set and before the surface casing was cemented. However, the settling did not hinder the drilling operations.

The only manmade hazards in this area were those associated with the risk of at-sea collision and other accidents associated with drilling operations. No such drilling accidents occurred.

The daily drilling operations did not affect the area's shipping, commercial fishing or recreational activities. Washed cuttings of approximately 600 cubic yards were dispersed on the ocean bottom near the drill site during drilling, and some drilling mud was dumped at sea after it was deemed to be free of oil or other toxic substances. The well was plugged and abandoned on January 25, 1979, in accordance with the OCS orders and regulations.

SUMMARY AND CONCLUSIONS

The COST No. B-3 is the first deep well to penetrate the U. S. Atlantic slope. The well was drilled by Chevron USA Inc. with 10 other expense-sharing companies to a total depth of 15,820 feet in the Baltimore Canyon Trough area, about 93 statute miles southeast of Atlantic City, N. J. Drilled in 2,686 feet water by the dynamically positioned drill ship Ben Ocean Lancer, the well was begun on October 9, 1978, and completed on January 25, 1979. Geological and engineering data obtained from this deep stratigraphic test were used by participating companies and the USGS for evaluating the petroleum potential, as well as possible drilling problems in deep-water areas in preparation for Lease Sale 49, held on February 28, 1979.

Four casing strings were set and cemented in the well; 30-inch casing was set at 2,894 feet, 20-inch at 3,753 feet, 13 3/8-inch at 5,736 feet, and 9 5/8-inch casing at 12,659 feet. Sea water was used to drill from 2,894 to 3,785 feet, sea water-gel from 3,785 to 5,766 feet, and gel-lignosulfonate mud for the remainder of the well. The mud weight increased from 9.0 ppg at the ontset to 11.7 ppg at total depth, although it decreased to 8.2 ppg due to gas flow between 15,750 and 15,780 feet. The total cost of the well was approximately $12 million. About 29 percent of the 109 days required to drill the well was spent drilling; 18 percent, tripping to change bits; about 13 percent fishing for lost bits and equipment; 10 percent for logging and testing, and the remainder for cementing, plugging, rig repair, and weather.

Eight geophysical logs were run in the well to determine lithology, porosity, and formation fluids, and to aid in stratigraphic correlation. Mud logs and pressure analysis logs were plotted during drilling and four wireline formation tests were made near the bottom of the well. An average temperature gradient of 1.36°F/100 feet was determined from geophysical log thermometer readings.

Four conventional cores and 1,466 sidewall cores were obtained from the well. The recovered conventional core intervals are 9,921-9,935 feet with average porosity of 16 percent and permeability of 1,356 md., 11,009.5-11,060.75 with 10 percent porosity and 19 md permeability, 12,572-12,587.3 with 6 percent porosity and 3 md permeablilty, and 13,773-13,794.5 with 4 percent porosity and an average of 1 md permeability. In general, conventional core porosity values are in closest agreement with density log values, except between 12,000 and 13,700 feet where core values more closely match those from the sonic log. Sidewall cores generally show higher porosities than conventional cores or logs.

The COST No. B-3 probably penetrated Pleistocene, Pliocene, and possibly upper Miocene rocks, although samples were not obtained until the well reached 3,800 feet, which is dated as middle Miocene. The B-3 drilled through 2,240 feet of Tertiary strata, reaching the Cretaceous at 6,040 feet; 2,650 feet of Upper Cretaceous rocks were penetrated to 8,690 feet; and after which the well encountered 3,710 feet of Lower Cretaceous strata. Upper Jurassic sediments were recognized at 12,400 feet and the well was still in Upper Jurassic (Kimmeridgian Stage) at total depth, 15,820 feet.

The stratigraphic sequence penetrated by the B-3 is divided into four major lithologic groups. Section I occurs from 3,790 to 6,080 feet and consists of Tertiary calcareous mudstone, claystone, and minor amounts of argillaceous limestone and siltstone deposited in middle shelf to upper slope environments. Section II, from 6,080 to 8,200 feet, includes mudstone, siltstone, and minor sandstone of Late Cretaceous age deposited in a prodelta to middle shelf environment. Section III, from 8,200 to 12,400 feet, contains sandstone, shale, and minor carbonate rocks of Early and Late Cretaceous age; these strata were laid down in environments ranging from outer shelf to deltas and river channels. The deepest section, IV, from 12,400 to 15,820 feet, comprises sandstone, limestone, and shale of Late Jurassic age deposited in near-shore tidal flat to outer shelf environments.

Comparison of the B-3 well with the COST No. B-2 well, which was drilled 32 statute miles north, shows the Tertiary in the B-3 to be thinner, more shaly and deposited in deeper water (more marine); the Upper Cretaceous in the B-3 is less sandy, thinner, and more marine; the Lower Cretaceous contains less sand and coal, is more marine, but is about the same thickness as in the B-2; and the Jurassic is stratigraphically thicker (more Tithonian), more marine, and contains more limestone than the B-2. Enough paleontological and lithological similarities were noted between the B-3 well and wells drilled on the Scotian Shelf of Canada to make some gross correlations.

A total of 1,625 feet of porous sandstones of petroleum reservoir quality (greater than 8 percent porosity) were logged in the well from geophysical log analysis. By depth interval, this includes 688 feet of effective porosity averaging 19 percent from 6,000 to 10,000 feet depth, 832 feet averaging 18 percent from 10,000 to 13,000 feet, and 105 feet with an average of 11 percent from 13,000 feet to total depth. Porosity diminishes rapidly below 12,000 feet where the rocks are predominantly limestone and shale; porosity of the sandstone in this section is reduced mainly by cementation and pressure solution. The section from 8,000 to 12,000 feet contains the best combination of potential reservoir rocks and sealing beds.

The petroleum potential of the strata penetrated by the well ranges from poor in the upper part of the section to good in the lowest part. The Tertiary and part of the Upper Cretaceous section down to 8,200 feet contains abundant reservoir rocks and hydrogen-rich organic matter, but lacks the thermal maturation to have generated anything but biogenic methane. The remainder of the Upper Cretaceous and part of the Lower Cretaceous section between 8,200 and 11,630 feet includes more than 1,000 feet of potential reservoir rocks; however, geochemical data indicate that kerogen in this interval is of terrestrial origin and has not quite reached the required maturity for petroleum generation. The Lower Cretaceous and Upper Jurassic section from 11,630 feet to total depth consists mainly of limestone, sandstone, and shale and includes more than 200 feet of potential reservoir rocks. This section is thermally mature, and except between 13,000 and 14,000 feet, contains sufficient organic matter to have generated dry gas, with some likelihood of oil above 13,000 feet. The best potential for hydrocarbons occurs below 14,100 feet although vertical migration of gas into reservoirs above this level may have occurred.

During drilling of the B-3 well, a show of gas was encountered in the interval from 15,744 to 15,752 feet. Mud log gas readings increased from 10 units to as high as 2,500 units and electric log analysis indicated the presence of 8 feet of gas-bearing sandstone averaging 12 percent porosity and a water saturation of 32 percent. Two formation tests in this zone recovered small amounts of gas; and the show, judged by the USGS to be significant, was publicly announced, in keeping with COST well regulations. The gas was probably contained in a small stratigraphic trap not discernible on seismic lines over the drill site.

REFERENCES CITED

Amato, R. V., and Bebout, J. W., eds., 1978, Geological and operational summary, COST No. GE-1 well, Southeast Georgia Embayment area, South Atlantic OCS: U.S. Geological Survey Open-File Report 78-668, 122 p., 3 plates.

Applin, P. L., and Applin, E. R., 1965, The Comanche Series and associated rocks in the subsurface in Central and South Florida: U.S. Geological Survey Professional Paper 447, 84 p.

Ballard, R. D., and Uchupi, Elazar, 1975, Triassic rift structure in Gulf of Maine: American Association of Petroleum Geologists Bulletin, v. 59, p. 1041-1071.

Core Laboratories, Inc., 1979a, Core studies, C.O.S.T. - Atlantic No. B-3 Well, Baltimore Canyon: Dallas, Texas, 174 p.

______1979b, Geochemical service report, Atlantic C.O.S.T. B-3, Baltimore Canyon, U.S.A.: Dallas, Texas, 200 p.

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

Given, M. M., 1977, Mesozoic and early Cenozoic geology of offshore Nova Scotia: Bulletin of Canadian Petroleum Geology, v. 25, p. 63-91.

Grow, J. A., Mattick, R. E., and Schlee, J. S., 1979, Multichannel seismic depth sections and interval velocities over outer continental shelf and upper continental slope between Cape Hatteras and Cape Cod, in Watkins, J. S., Montadert, Lucien, and Dickerson, P. W., eds., Geological and geophysical investigations of continental margins: American Association of Petroleum Geologists Memoir 29, p. 65-83.

Jansa, L. F., and Wade, J. A., 1975, Geology of the continental margin off Nova Scotia and Newfoundland: Geological Survey of Canáda Paper 74-30, p. 51-105.

Jansa, L. F., Williams, G. L., Wade, J. A., and Bujak, J. P., 1978, COST B-2 well (Baltimore Canyon) and its relation to Scotian Basin (abstract): American Association of Petroleum Geologists Bulletin, v. 62, p. 526.

LaPlante, R. E., 1974, Hydrocarbon generation in Gulf Coast Tertiary sediments: American Association of Petroleum Geologists Bulletin, v. 58, no. 7, p. 1281-1289.

Maher, J. C., 1971, Geologic framework and petroleum potential of the Atlantic Coastal Plain and Continental Shelf: U.S. Geological Survey Professional Paper 659, 98 p.

Mattick, R. E., Girard, O. W., Jr., Scholle, P. A., and Grow, J. A., 1978, Petroleum potential of U.S. Atlantic slope, rise, and abyssal plain: American Association of Petroleum Geologists Bulletin, v. 62, p. 592-608.

McIver, N. L., 1972, Cenozoic and Mesozoic stratigraphy of the Nova Scotia Shelf: Canadian Journal of Earth Sciences, v. 9, p. 54-70.

Muller, Jan, 1959, Palynology of Recent Orinoco delta and shelf sediments: Micropaleontology, v. 5, p. 1-32.

Owens, J. P., and Sohl, N. F., 1969, Shelf and deltaic environments in the Cretaceous-Tertiary formations of the New Jersey Coastal Plain, in Subitzky, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: Rutgers University Press, p. 235-278.

Owens, J. P., Sohl, N. F., and Minard, J. P., 1977, Cretaceous and lower

Tertiary beds of the Raritan and Salisbury embayments, New Jersey, Delaware, and Maryland: American Association of Petroleum Geologists Field Guide, 113 p.

Perry, W. J., Jr., Minard, J. P., Weed, E. G. A., Robbins, E. I., and Rhodehamel, E. C., 1975, Stratigraphy of Atlantic coastal margin of United States north of Cape Hatteras -- Brief survey: American Association of Petroleum Geologists Bulletin, v. 59, p. 1529-1548.

Petters, S. W., 1976, Upper Cretaceous subsurface stratigraphy of Atlantic Coastal Plain of New Jersey: American Association of Petroleum Geologists Bulletin, v. 60, p. 87-107.

Poag, C. W., 1977, Foraminiferal biostratigraphy, in Scholle, P.A., ed., Geological studies of the COST No. B-2 well, U.S. Mid-Atlantic Outer Continental Shelf area: U.S. Geological Survey Circular 750, p. 35-40.

______1978, Stratigraphy of the Atlantic continental shelf and slope of the United States: Annual Review, Earth and Planetary Sciences, v. 6, p. 251-280.

______1979, Important stratigraphic breaks in COST GE-1 well, Southeast Georgia Embayment (abs.): American Association of Petroleum Geologists Bulletin, v. 63, p. 510.

Ryan, W.B.F., Cita, M.B., Miller, E.L., Hanselman, D., Nesteroff, W.D., Hecker, B., and Nibbelink, M., 1978, Bedrock geology in New England submarine canyons: Oceanologica Acta, v. 1, no. 2, p. 233-254.

Scholle, P. A., ed., 1977, Geological studies on the COST No. B-2 well, U.S. Mid-Atlantic outer continental shelf area: U.S. Geological Survey Circular 750, 71 p.

Scholle, P. A., ed., 1979, Geological studies of the COST GE-1 well, U.S. South Atlantic outer continental shelf area: U.S. Geological Survey Circular 800, 114 p.

Simonis, E. K., 1979, Radiometric age determinations, _in_ Scholle, P.A., ed., Geological studies of the COST GE-1 well, U.S. South Atlantic outer continental shelf area: U.S. Geological Survey Circular 800, p. 71.

Smith, M.A., Amato, R.V., Furbush, M.A., Pert, D.M., Nelson, M., Hendrix, J.S., Tamm, L.C., Wood, G.Jr., and Shaw, D. R., 1976, Geological and operational summary, COST No. B-2 well, Baltimore Canyon Trough area, Mid-Atlantic OCS: U.S. Geological Survey Open-File Report 76-774, 79 p.

Stanley, E. A., 1965, Upper Cretaceous and Paleocene plant microfossils and Paleocene dinoflagellates and hystrichosphaerids from northwestern South Dakota: Bulletin of American Paleontology, v. 49, no. 222, p. 179-384.

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

Tissot, B. P., Durand, B., Espitalie, J., and Combaz, A., 1974, Influence of nature and diagenesis of organic matter in formation of petroleum: American Association of Petroleum Geologists Bulletin, v. 58, no. 3, p. 499-506.

Tissot, B. P., and Welte, D. H., 1978, Petroleum formation and occurrence--A new approach to oil and gas exploration: New York, Springer-Verlag, 538 p.

U.S. Department of the Interior, Bureau of Land Management, 1978, Final environmental impact statement for proposed 1979 Outer Continental Shelf oil and gas lease sale offshore the Mid-Atlantic States, OCS Sale No. 49, Washington, D.C., 3v.

Valentine, P. C., 1979, Calcareous nannofossil biostratigraphy and paleoenvironmental interpretation, in Scholle, P. A. ed., Geological studies of the COST GE-1 well, U.S. South-Atlantic Outer Continental Shelf area: U.S. Geological Survey Circular 800, p. 64-70.

Williams, G. L., 1975, Dinoflagellate and spore stratigraphy of the Mesozoic-Cenozoic, offshore eastern Canada: Geological Survey of Canada, Paper 74-30, v. 2, p. 107-161.