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GEOLOGICAL SURVEY CIRCULAR 750

Geological Studies on the COST No. B-2 Well, U.S. Mid-Atlantic Outer Continental Shelf Area

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P. A. Scholle, Editor

ABSTRACT

The COST No. B–2 well is the first deep stratigraphic test to be drilled on the United States Atlantic Outer Continental Shelf (AOCS) area. The well was drilled on the eastern flank of the Baltimore Canyon trough to a total depth of 16,043 feet; it penetrated a section composed almost entirely of sand and shale with subordinate amounts of limestone, coal, and lignite. Biostratigraphic studies have shown that the uppermost 5,000 feet is of Tertiary and Quaternary age and was deposited in nonmarine to deep marine environments. The Upper Cretaceous section is about 3,000 feet thick and is of dominantly shallow marine origin. The basal 8,000 feet of sediment has been tentatively determined to be entirely of Early Cretaceous age, the basal sediments being dated as Berriasian. This Lower Cretaceous section is primarily nonmarine to very shallow marine in origin.

Examination of cores, well cuttings, and electric logs shows that thick potential reservoir sands are found through much of the section. However, porosity and permeability decrease strikingly in the deeper parts of the Lower Cretaceous section as a result of compaction and cementation. Most of the sands are quite feldspathic, and progressive decomposition of feldspar stimulates authigenic clay and silica formation.

Studies of color alteration of visible organic matter, organic geochemistry, and vitrinite reflectance show that although many units have high organic-carbon contents, moderately low geothermal gradients may have retarded thermal maturation. This, in conjunction with the scarcity of marine-derived organic matter in the lower part of the section, suggests a relatively low potential for the generation of liquid hydrocarbons. However, the overall combination of source beds, reservoirs, seals, structures, and thermal gradients may be favorable for the generation and entrapment of natural gas. Furthermore, the presence of reservoir rocks, seals, and trapping structures may indicate a significant potential for entrapment of either natural gas or petroleum that was generated deeper in the basin and then migrated either laterally or vertically.

INTRODUCTION

Until recently, all information on the stratigraphic framework of the United States Atlantic Outer Continental Shelf (AOCS) had come from onshore wells, offshore bottom sampling or shallow coring, geophysical surveys, and extrapolation from Canadian offshore wells. Between December 14, 1975, and March 28, 1976, however, the first deep stratigraphic test well was drilled on the U.S. AOCS by Ocean Production Company acting as operator for a group of 31 petroleum companies, the Continental Offshore Stratigraphic Test (COST) Group. This hole, designated the COST NO. B–2 well, was drilled on the outer part of the AOCS about 91 miles east of Atlantic City, N.J., at lat 39°22′31.972″ N. and long 72°44′03.871″ W. (fig. 1). The well was drilled using the semisubmersible rig SEDCO–J. Water depth at the site is 298 feet, and drilling continued to a depth of 16,043 feet below the Kelly Bushing (or to 15,953 feet below sea level). The well is adjacent to the area offered for leasing on Aug. 17, 1976, as part of Lease Sale No. 40, shown on figure 1. The granting of federal leases within 50 miles of the drill site on Sept. 1, 1976, has made possible the publication of detailed information about the geological findings from the COST No. B–2 well, because Lease Stipulation No. 4 provides for public disclosure by the U.S. Geological Survey (USGS) of all geological information on the well 60 days after such leasing.

Considerable basic lithologic and stratigraphic data, most of it derived from industry reports, has been released (Smith and others, 1976). This circular summarizes some of that data and adds information from other USGS studies. It is by no means an exhaustive or completed program, but because the COST No. B–2 well has such immediate interest for both

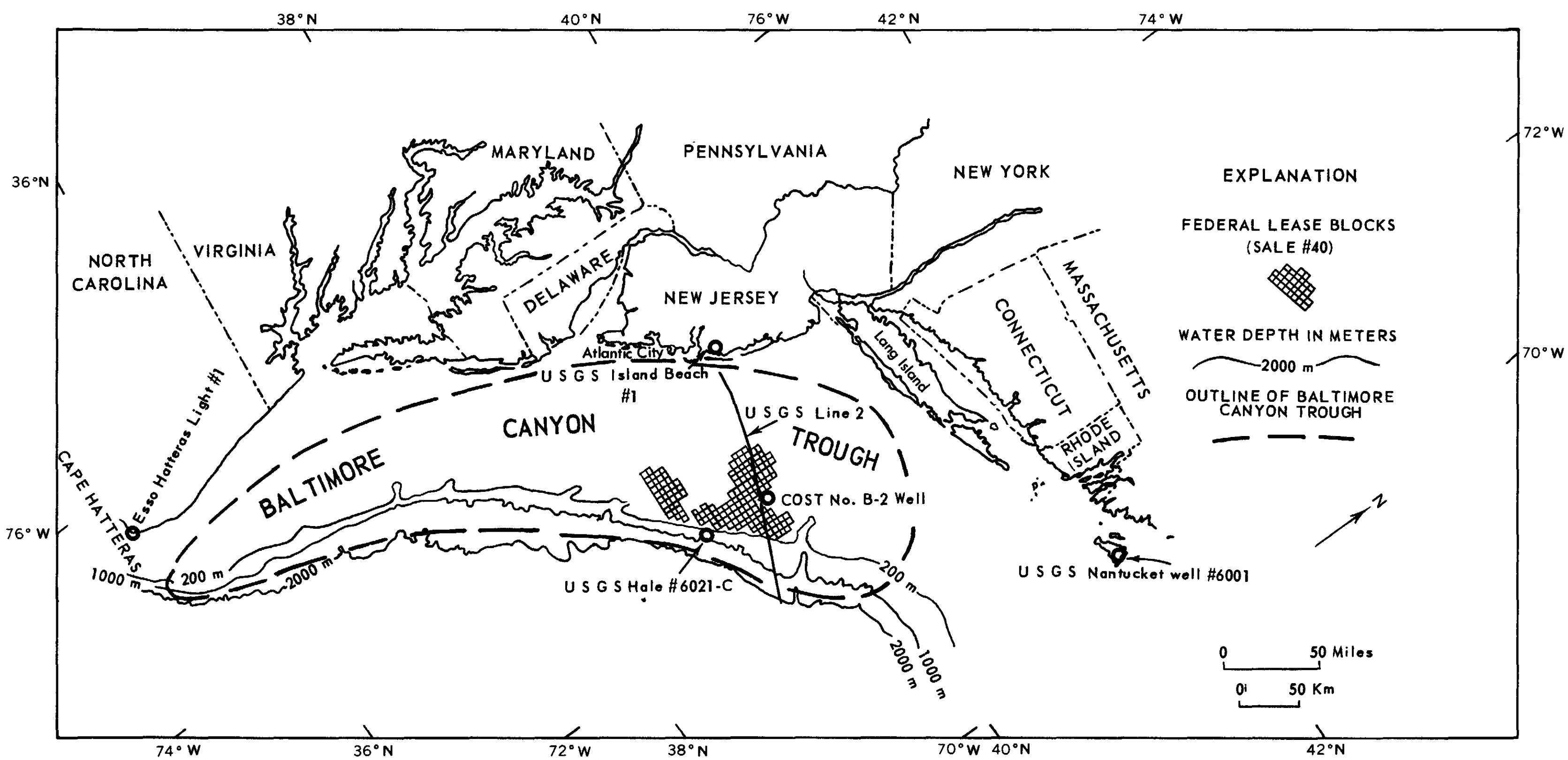


FIGURE 1.—Locality map showing site of COST No. B-2 well in relation to Baltimore Canyon trough, Lease Sale No. 40 blocks, and coastal States.

the petroleum industry and academic workers, we believe that publication of preliminary results is justified.

The publication is divided into separately authored sections on geological, geochemical, and geophysical topics. Environmental or operational details are not included, as these have been amply described by Smith and others (1976). Several diagrams are provided in the section, "Data Summary and Petroleum Potential," to compare the analytical results of USGS work with the industrial data summarized by Smith and others (1976).

All work reported on in this paper has been done using rotary drill cutting rather than conventional or sidewall cores. Electric logs and core descriptions were available, however, to aid in checking the accuracy of sample depth assignments. The cuttings, in conjunction with electric logs, thus provided a useful picture of the complete spectrum of lithologic variation within a given interval and were sometimes more useful than the spot samples provided by sidewall coring. All depth references in this report for electric log, core, or cuttings data are based on depth below the Kelly Bushing (K.B.) which is 90 feet above mean sea level and 388 feet above the sediment-water interface.

ACKNOWLEDGMENTS

Technical assistance in the preparation of this report is gratefully acknowledged from the following USGS personnel: Norman O. Fredriksen for examining Tertiary pollen, Fred E. May for examining dinoflagellates, and Robert H. Tschudy for examining megaspores. Zoe Ann Hamlin, Peter Stinger, Lois Tomlinson, and Sandra Wortman helped greatly in sample preparation and analysis. Early versions of this paper were reviewed by Richard Q. Foote, Oswald W. Girard, Jr., Raymond Christopher, Harlan R. Bergquist, and Robert E. Miller. We are indebted to them for their many helpful suggestions.

Geologic Setting

By R. E. Mattick

The COST No. B–2 well is near the axis of the Baltimore Canyon trough, an elongate, northeast-trending structural depression in continental basement rocks filled with more than 40,000 feet of sediment (fig. 1). The trough, a possible offshore extension of the Salisbury embayment, extends from about Long Island, N.Y., southwestward to the vicinity of Cape Hatteras, N.C. A diagrammatic cross section of the Baltimore Canyon trough is shown in figure 2. This seaward-thickening sedimentary wedge is built over a deeply buried fault zone which may represent a transition between continental and oceanic basement rocks. A seismic profile (fig. 3) shows that Jurassic and Cretaceous sedimentary rocks, which are gently dipping throughout most of the Baltimore Canyon trough area, are warped upward by a large basement intrusion on the Continental Shelf off New Jersey.

On the basis of magnetic and gravity data, early authors proposed that a volcanic or basement ridge, which may have acted as a sediment dam during Jurassic and Early Cretaceous time, is buried about 15,000 feet beneath the outer shelf and slope (Drake and others, 1959). Later, Mattick and others (1974) suggested that the main part of the Batlimore Canyon trough, the part underlying the mid-shelf area, is a broad graben to which is coupled a large horst, buried at a depth of about 25,000 feet beneath the shelf edge. Whether or not crystalline rocks or high-velocity sedimentary rocks are present deeper than about 20,000 feet at the shelf edge has not been determined from available seismic data. Schlee and others (1976) have speculated that the rocks are sedimentary and that the shelf edge is underlain by a deeply buried carbonate platform with reef deposits that formed atop a block-faulted margin after separation of the African and North American plates.

By analogy with the Coastal Plain, the basement beneath the Baltimore Canyon trough area is inferred to consist of Paleozoic and Precambrian(?) metamorphic rocks similar to those exposed in the Applachian Piedmont province (Perry and others, 1975). Down-faulted grabens in the basement probably are present locally and may be filled with Triassic rocks consisting of nonmarine arkosic sandstones, shales, basaltic lava flows, and diabase intrusions. Seismic evidence indicates that as much as 45,000 feet of sediments unconformably overlies the Triassic and pre-Triassic basement rocks (Mattick and others, 1975).

The basal part of the sedimentary section may contain Paleozoic and marine Triassic sediments. Seismic velocities of sedimentary rocks deeper than about 25,000 feet are in excess of 20,000 feet/sec.; these high velocities may indicate a thick section of chiefly Jurassic carbonate rocks underlain by evaporites (Mattick and others, 1976). By analogy with well data from the Scotian Shelf (McIver, 1972), we infer that these carbonate rocks are overlain by several thousand feet of Jurassic sands and shales.

According to Minard and others (1974), Lower Cretaceous sediments constitute a major deltaic sequence in the emerged Coastal Plain. The results from the COST No. B–2 well, which penetrated approximately 8,000 feet of Lower Cretaceous rocks that have a high percentage of massive sandstone, indicate that these deltaic sediments extend seaward across much of the Continental Shelf. However, on the basis of seismic-reflection velocities, Mattick and others (1975) believe that basal Lower Cretaceous rocks at the shelf edge are chiefly carbonate rocks.

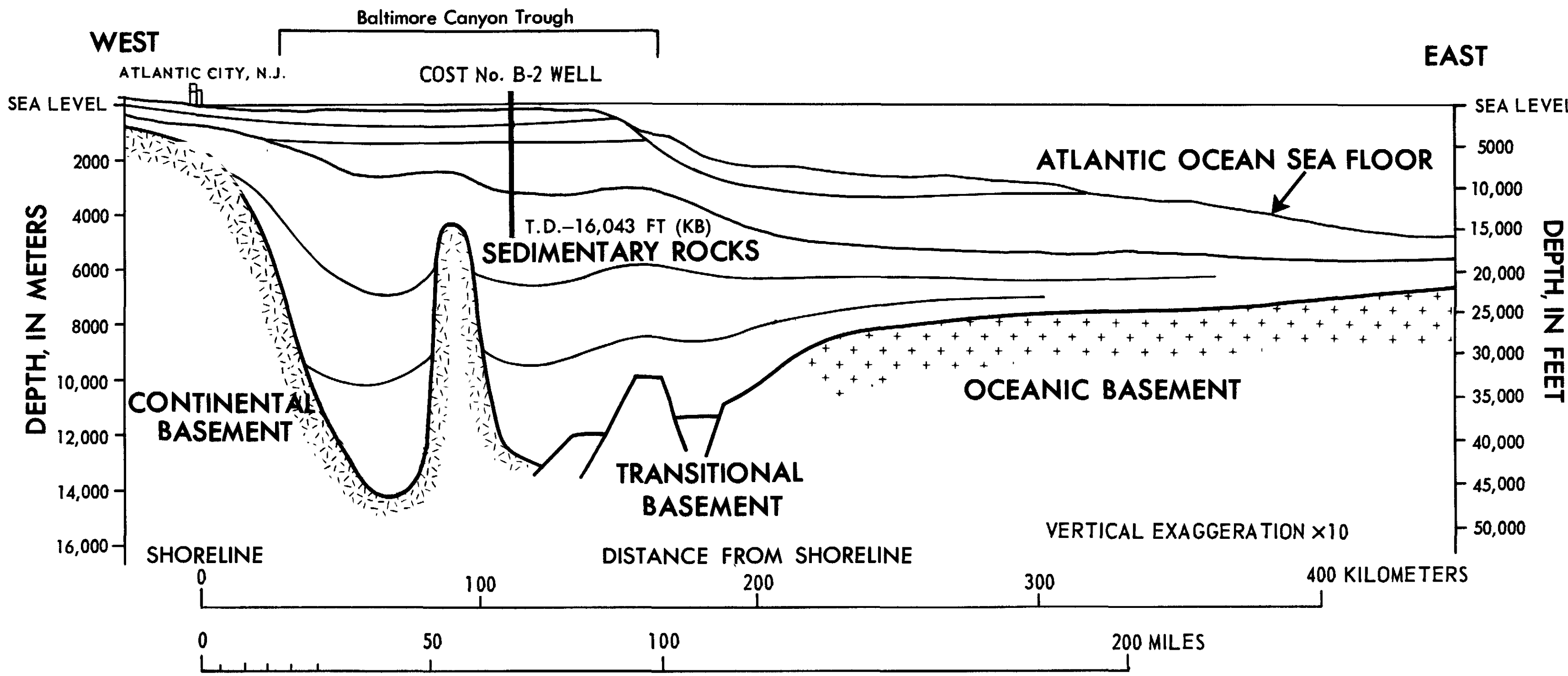


Figure 2.—Generalized cross section of the U.S. Atlantic Continental Shelf, Slope, and Rise. Section line is an extension of USGS Line 2 (fig. 1). Note large basement intrusion and location of COST No. B–2 well.

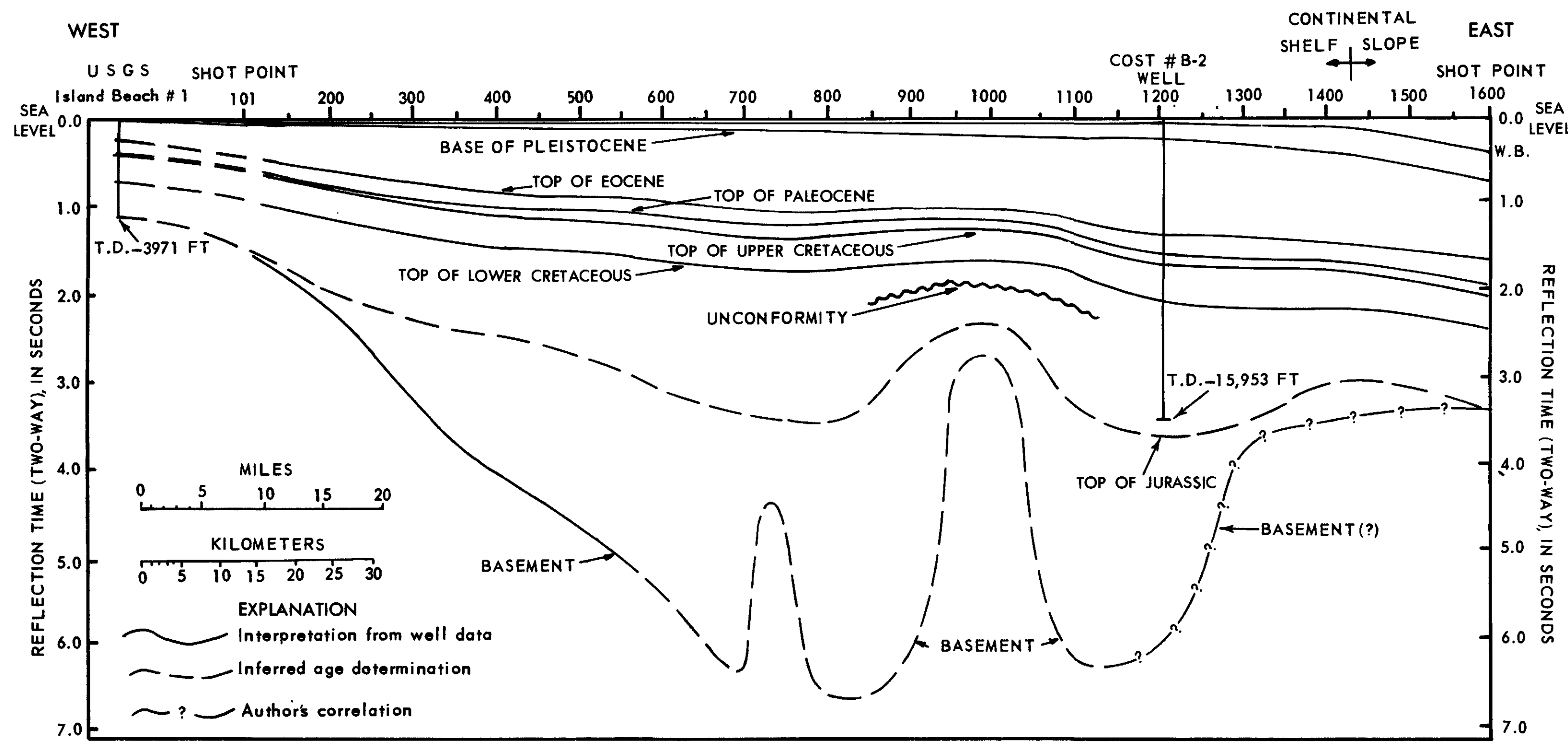


FIGURE 3.—Interpretive profile of a part of USGS Line 2 (fig. 1), showing Baltimore Canyon trough structure and geologic age horizons.

At the B–2 site, the Upper Cretaceous section is approximately 3,000 feet thick, and the Tertiary section is about 5,000 feet thick. On the basis of seismic correlation, these thicknesses appear to remain relatively constant over most of the AOCS area.

Some of the highest bonus bids of Lease Sale No. 40 involved lease blocks over a basement intrusion in the central Baltimore Canyon trough area (West, 1976). Figure 3 is a schematic diagram of a seismic-reflection record that crosses this feature. Jurassic(?) and Lower Cretaceous beds appear to have been arched several thousands of feet across an area approximately 15 miles wide. A seismic horizon slightly below the Lower Cretaceous-Upper Cretaceous boundary represents a marked unconformity at which at least 1,300 feet of sediment was removed by erosion.

The unconformity just below the Lower Cretaceous-Upper Cretaceous boundary probably dates the last major upward movement of the intrusive body. However, arching, thinning, and minor faulting of Upper Cretaceous beds, and slight thinning of lower Tertiary beds above the intrusive body could reflect later movement.

Other Cretaceous tectonic activity may be illustrated by growth faults along the shelf-slope break (Mattick and others, 1974). Emery and others (1970) reported that diapiric salt structures may be present along the Continental Slope and Rise off Nova Scotia. Sheridan (1974) extended this province southward and reported the possibility of salt diapirism in the Baltimore Canyon trough area.

Data Summary and Petroleum Potential

By P. A. Scholle

The COST No. B–2 well penetrated 15,655 feet of Mesozoic and Cenozoic section. Lithologic and paleoenvironmental studies, summarized in figure 4, indicate that the upper 2,000 feet of section has very sandy shallow marine to nonmarine deposits. Below that, to a total drilling depth of about 6,000 feet, a deeper water, finer grained section is present. From that level to the base of the well, the section consists of alternating sandstones and shales of shallow marine to nonmarine origin. This deeper part of the section contains many coal and lignite seams.

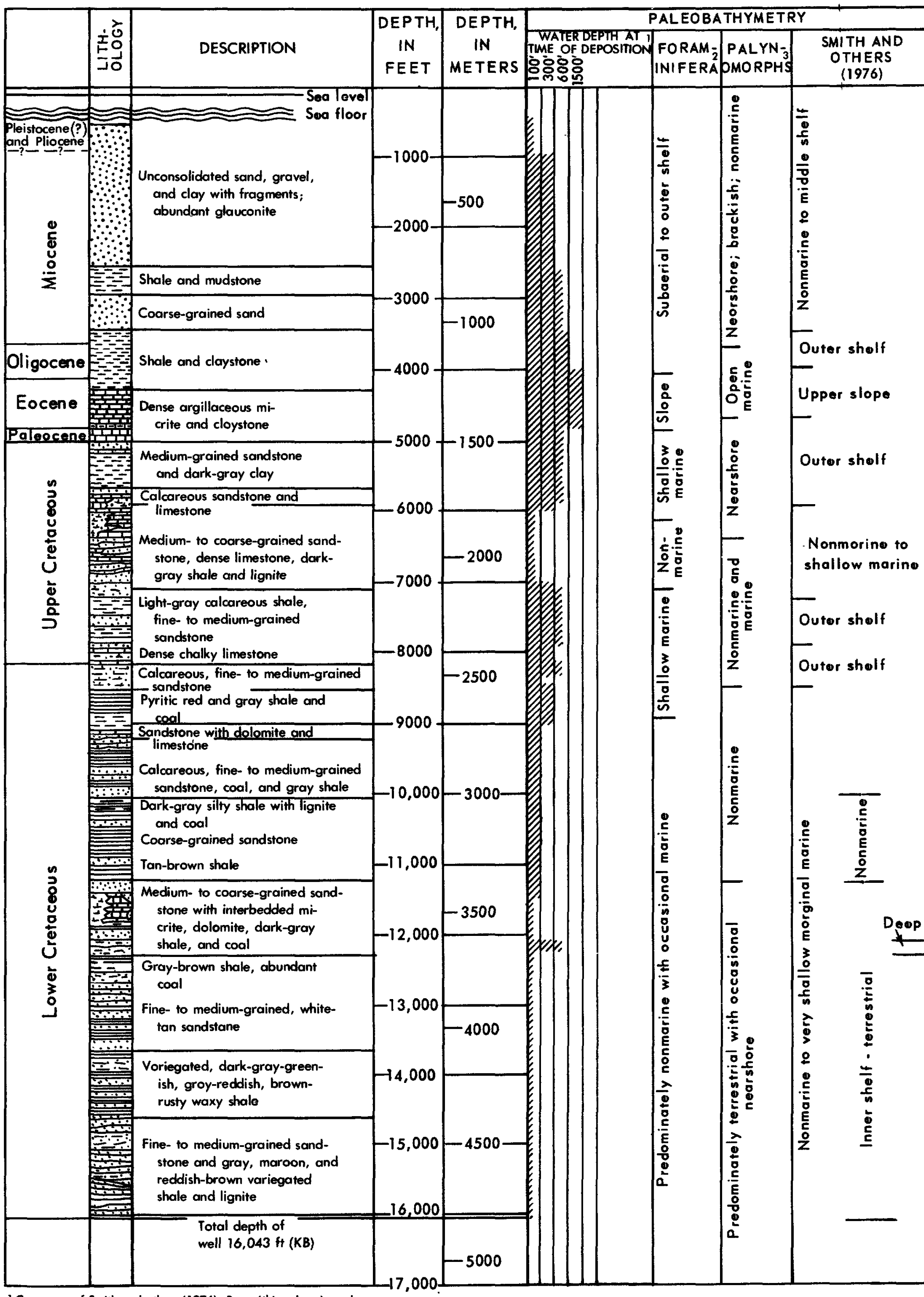
Biostratigraphic work completed to date (and summarized in table 1) shows general agreement between the various workers on most stage and series boundaries. The Cretaceous-Tertiary boundary is placed between 5,000 and 5,600 feet by different workers, and the Lower Cretaceous-Upper Cretaceous boundary is very close to the 8,200-foot level. Although the basal part of the section might well be Jurassic, the consensus now favors a Berriasian (Early Cretaceous) age for these sediments.

The rates of sedimentation of various stratigraphic units in the B–2 area were quite variable, as shown in table 2. For discussion purposes, the Miocene to Pleistocene rates have been taken as average; relative to these, the entire interval from Campanian to Oligocene had low rates of sedimentation. This corresponds generally with the time interval of deepest water sedimentation in this area. Albian to Santonian time was characterized by shallower water deposition and generally average sedimentation rates; Berriasian to Aptian time was marked by very shallow marine to nonmarine deposition and average to very high rates of sedimentation.

A major part of the Cretaceous section (that is, the section between 5,000 and 16,000 feet) consists of relatively thick sandstone units, some of which have significant reservoir potential. The reservoir quality of this sandstone, however, deteriorates consistently as depth increases. The relationship between depth and petrophysical characteristics determined from electric logs as well as from cores is shown in figure 5. The porosity loss below 12,000 feet is largely related to compaction effects and to progressive breakdown of feldspar accompanied by growth of authigenic clay and silica cement. Generation of calcite cement is also important, especially in zones that contain marine fossils or limestone. As seen on figure 5, these porosity losses, especially, the formation of authigenic clay, have a drastic effect on permeability. Thus, in the section below 12,000 feet few sandstones have more than 1 millidarcy (md) permeability.

Geochemical studies of the COST No. B–2 well have shown that the area not only has a relatively low geothermal gradient today but that apparently it has been that low or even lower throughout the Cretaceous to Holocene history. Data from color alteration of visible organic matter, pyrolytic-decomposition temperatures, carbon-preference index, and vitrinite reflectance are summarized in figure 6.

All methods indicate that the section down to at least 8,000 feet is thermally immature and is unlikely to have yielded hydrocarbons other than biogenically generated methane. Below 8,000 feet there is some disagreement in interpretation between the various analytical techniques. The techniques based on observations of visible organic matter indicate moderate to full thermal maturity in the 8,000- to 16,000-foot depth range. For example, vitrinite-reflectance values of 0.45 to 0.50, found at about 8,000 feet in the COST No. B–2 well, are generally taken as marking the earliest onset of possible liquid-hydrocarbon generation (Bar-



[1] Consensus of Smith and others (1976), Poag (this volume), and Valentine (this volume).
[2] Poag (this volume).
[3] Valentine (this volume).

FIGURE 4.—Generalized plot of lithologies and depositional environments of sediments in the COST No. B–2 well. Modified from Smith and others (1976).

TABLE 1.—*Comparison of biostratigraphic analyses from the COST No. B-2 well*

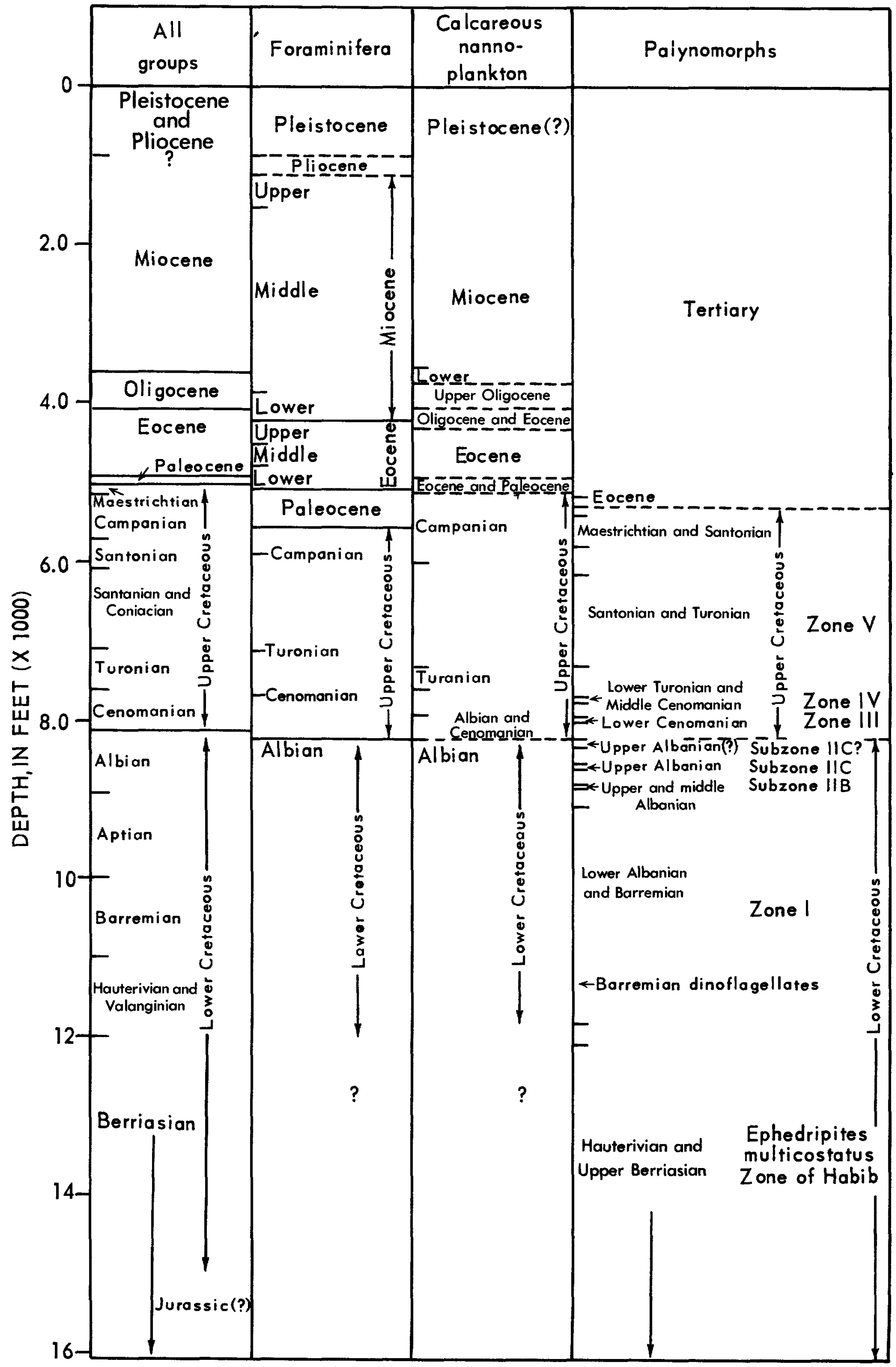


TABLE 2.—*Sedimentation rates of stratigraphic units of Berriasian to Pleistocene age in the COST No. B-2 well*

Unit	Sediment thickness (ft)	Duration (millions of years)[1]	Percent of total sediment	Percent of total time[1]	Relative sedimentation rate	Absolute sedimentation rate (ft/m.y.)
Pleistocene and Pliocene	522	5	3	4	Average	104
Miocene	2,686	18	17	13	Average	149
Oligocene	486	15	3	11	Low	32
Eocene	882	14	5	10	Low	63
Paleocene	36	11	<1	8	Very low	3
Maestrichtian and Campanian	736	13	5	10	Low	56
Santonian and Coniacian	1,321	8	8	6	High	165
Turonian	553	6	3	4	Average	92
Cenomanian	520	8	3	6	Low	65
Albian	770	8	5	6	Average	96
Aptian	1,100	7	7	5	High	157
Barremian, Hauterivian and Valanginian	2,000	16	12	12	Average	125
Berriasian	4,042	4	25	3	Very high	1,011
Total	15,654	133				

[1] From Berggren (1972) and Van Hinte (1976).

tenstein and Teichmüller, 1974; Hood and others, 1975; Vassyoevich and others, 1970). Likewise, vitrinite-reflectance values of 0.6 to 0.7, and sapropel-maturation values of 2.5 to 3.0 found below 12,000 feet in the COST No. B-2 well, mark the peak rate of liquid-hydrocarbon formation. Thus, on the basis of such data, the present temperature profile in the well, and provided that sediments containing suitable organic matter are present, significant liquid hydrocarbons should have been generated.

Geochemical analyses of disseminated organic matter yield a different picture, however. Studies of extractable organic matter presented by Claypool and others (this volume), Geochem Laboratories (1976), and Smith and others (1976) have indicated that none of the sediments penetrated in the COST No. B-2 well are mature with respect to liquid-hydrocarbon generation. Indications are that minor amounts of liquid and significant amounts of gaseous hydrocarbons may have been generated, but large amounts of liquid-petroleum hydrocarbons have not yet been generated.

These differences in apparent maturity found by means of visual and geochemical techniques are not easily explained. Considerable disagreement still exists about the exact time-temperature relations needed for oil formation and the effect of type of organic matter and other factors upon rates of formation (for example, Tissot and others, 1974). Thus, the noted discrepancies may be due to incorrect extrapolation of maturity versus oil-generation values from other basins. Indeed, recent workers have tended to place the main phase of oil generation at greater and greater depths and temperatures (for example, Hood and Castaño, 1974). On the basis of such work there is little discrepancy between visual and geochemical analyses; both would indicate only marginal maturity with respect to liquid-petroleum-hydrocarbon generation at the base of the COST No. B-2 well.

The type as well as the amount of organic matter present in the sediments plays a major role in the determination of the hydrocarbon potential of the section. In the COST No. B-2 well, some of the highest organic carbon contents (as much as 12 percent) are present between 3,000 and 6,000 feet and 9,500 and 14,000 feet. The lower of these two intervals has a very significant amount of coal, especially between 9,500 and 11,300 feet and 12,400 and 14,000 feet. The dominance of terrestrial over marine-derived organic matter in this interval strongly reduces the probability of generation of economic amounts of liquid-petroleum hydrocarbons but allows a high potential for generation of wet or dry gas. Furthermore, significant potential exists for lateral or vertical migration of liquid or gaseous hydrocarbons from structurally or stratigraphically deeper parts of the section.

Some supporting evidence for the presence of natural-gas deposits may come from Hole No. 6021-C of the USGS Atlantic Margin Coring Project (fig. 1), which was drilled at lat 38°57.92′ N., long 72°49.20′ W. The upper

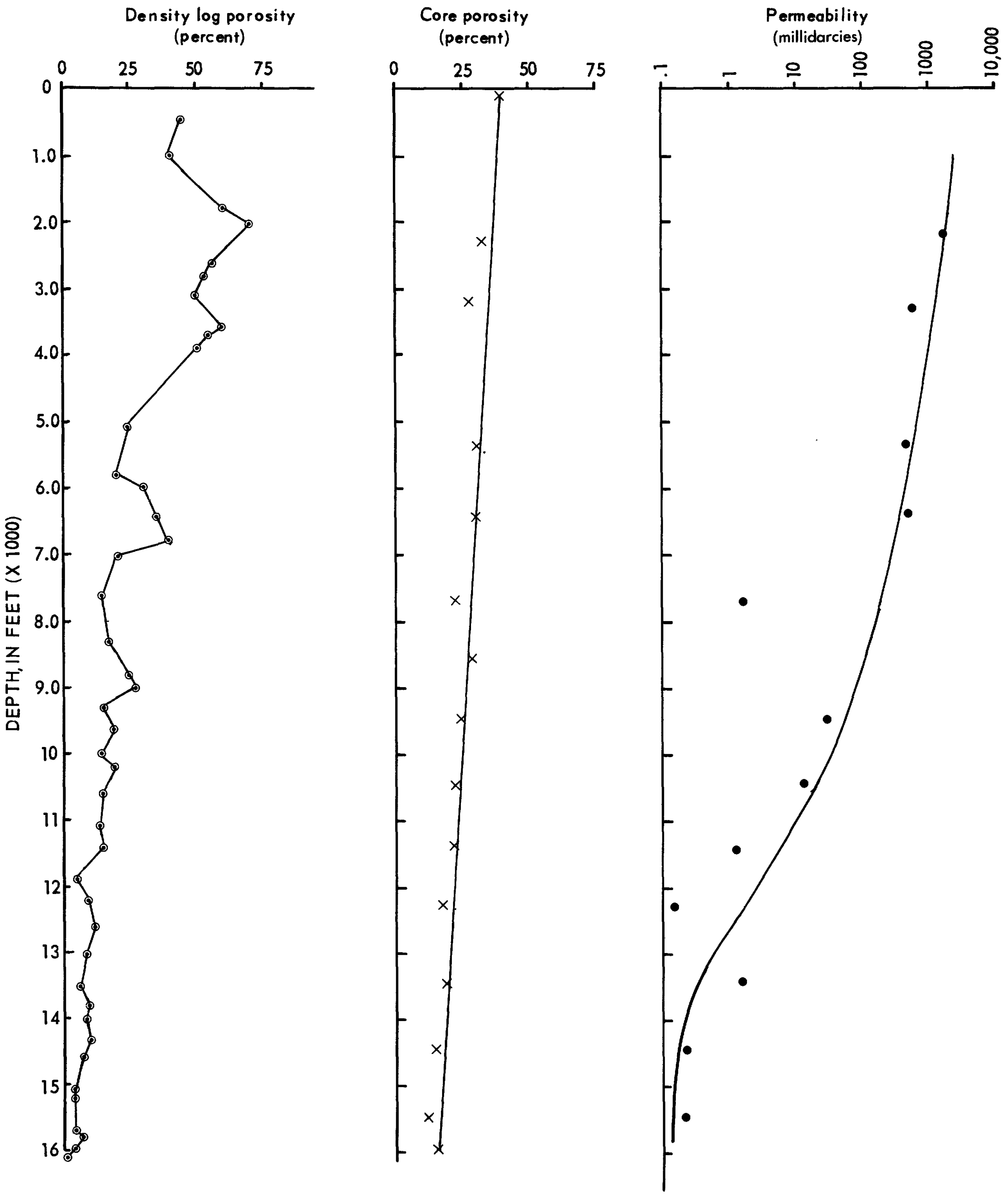


FIGURE 5.—Comparison of density log curve of porosity (from Rhodehamel, this volume) with measured core porosities and empirically determined permeabilities from Core Laboratories as given by Smith and others (1976).

1,000 feet of sediment was penetrated at this site and contained significant amounts of the light hydrocarbons (methane, ethane, and propane). Although R. E. Miller and D. M. Schultz (written commun., 1976) believe that the methane is dominantly biogenic in origin, some leakage from deeper natural-gas sources may exist. Several samples of gas-bearing mud from this borehole have been analyzed for stable carbon-isotopic composition of the

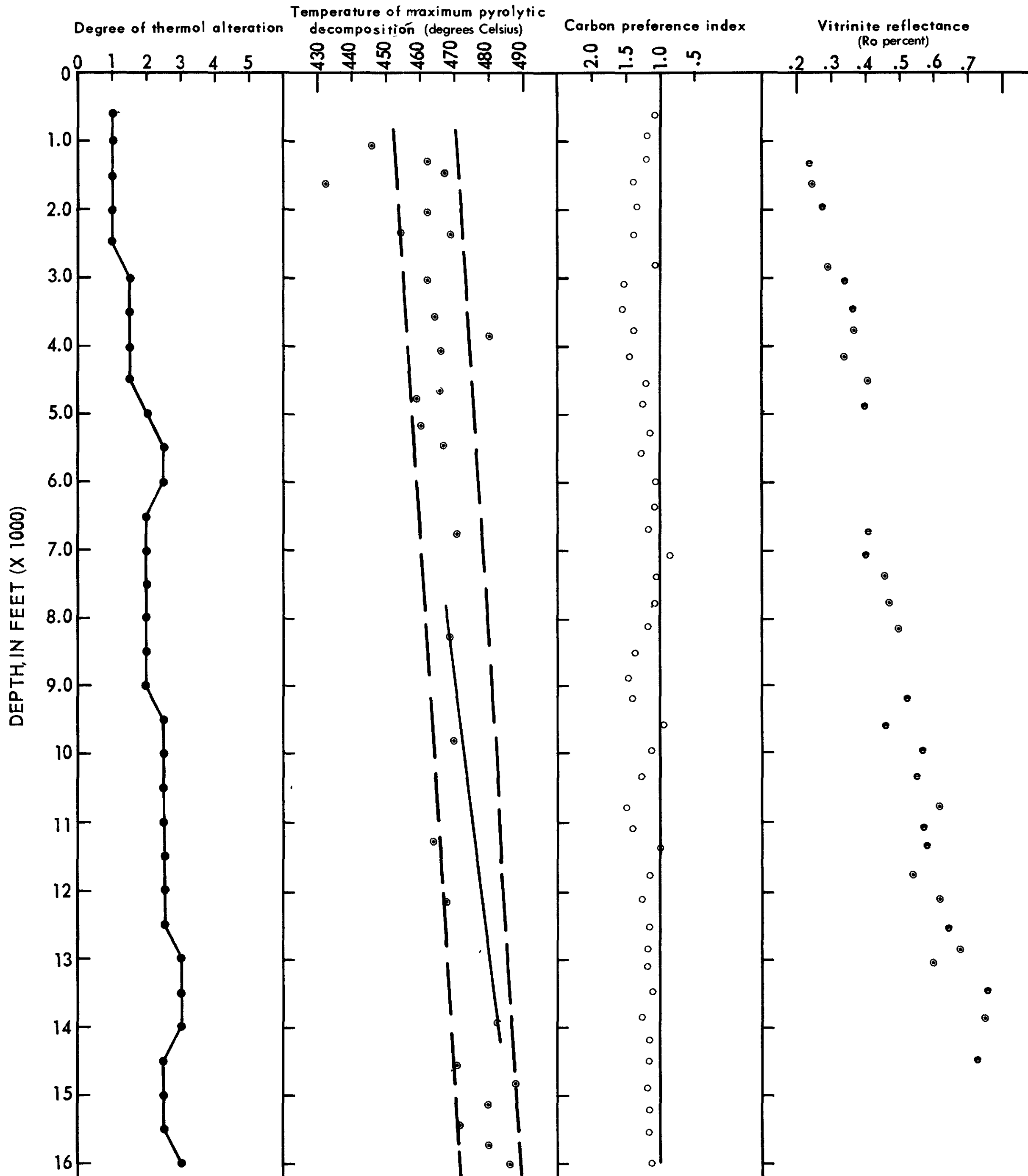


FIGURE 6.—Comparison of various measures of thermal maturity as a function of depth in COST No. B–2 well. Degree of thermal alteration is from Robbins (this volume); pyrolitic decomposition data are from Claypool and others (this volume); carbon-preference index and vitrinite-reflectance data are from Geochem Laboratories and Superior Oil Co., respectively, as reported in Smith and others (1976).

methane. These preliminary results ($\delta^{13}C_{PDB} \cong -35$ to -45 per mil) may indicate seepage from deeper parts of the section. However, because of the extremely small quantities of gas obtained and analyzed, the results should not be interpreted as unequivocal support for a thermogenic origin of the methane (G. E. Claypool, written commun., 1976).

Further indication of possible gas deposits comes from bright-spot analysis of USGS Line

2 (discussed in the section on Geophysical studies). A major amplitude anomaly, a considerable distance landward of the COST No. B–2 well site, has been tentatively interpreted as a natural-gas deposit.

Essentially five major factors are involved in the origin and entrapment of hydrocarbons: (1) source rocks, (2) temperatures sufficient to generate gas or oil, (3) reservoir rocks, (4) seals, and (5) trapping structures. Indications from the B–2 well are that rocks of high organic-carbon content are present from 3,000 to 6,000 feet and 9,000 to 14,000 feet and that some of these rocks are capable of generating considerable amounts of hydrocarbons. Temperatures may have been too low in much of this section to have generated liquid hydrocarbons, but they appear to have been sufficient for gas generation. Reservoir rocks are abundant throughout most of the COST No. B–2 well section, although the reservoir quality of most of the sandstone units degrades rapidly at depths greater than 10,000 to 12,000 feet. Seals, in the form of shale, are present in much of the section. Finally, as shown in the section "geologic setting," large structures are available for hydrocarbon entrapment in areas adjacent to the COST No. B–2 well. These structures may also enhance vertical migration of hydrocarbons along fractures from deeper parts of the section.

Data from the COST No. B–2 well indicate a higher potential for natural gas than for liquid petroleum. Moving in the direction of a more marine section would give a higher potential for oil generation, lower feldspar content (and thus less cementation at depth), and more shale seals. Likewise, moving to possible areas of higher paleogeothermal gradients would improve the potential for either oil or gas generation.

Lithologic Descriptions

By E. C. Rhodehamel

The COST No. B–2 well penetrated sediments deposited in environments ranging from nonmarine to deep water (table 3) and ranging in age from Holocene to earliest Early Cretaceous; basement rock was not penetrated. Although significant amounts of carbonate sediments are present in the lower Tertiary and Upper Cretaceous intervals, sandstone and shale predominate. The detailed lithologic log (table 4) includes tentative stratigraphic intervals provided by other investigators (Smith and others, 1976).

TECHNIQUES

Well cuttings (samples) were collected at 30-foot intervals between 610 and 4,620 feet and at 10-foot intervals between 4,620 and 16,043 feet. In this preliminary study, samples were analyzed at sampling intervals of 90 feet down to 4,620 feet, and intervals of 30 feet below that depth. Intervening samples were examined where initial sample volume was adequate. In addition to the well cuttings, four conventional cores were examined. These cores were taken at 5,030 to 5,090 feet with 1.5 feet of recovery; at 8,238 to 8,268 feet, with 28.4 feet of recovery; at 9,280 to 9,330 feet with complete recovery; and at 13,420 and 13,471 feet with 34.5 feet of recovery. More than 800 sidewall cores were taken; these cores were not directly examined in this study, but the core descriptions (Core Laboratories, 1976) were checked against lithologic picks from cuttings and logs.

Because of variations in drilling rate, mud circulation time, mudcake failures, hole washouts, and other operational factors, the lithologic samples for specified intervals often do not adequately represent the actual material penetrated; contamination and mixing from above are also factors. Furthermore, the samples were washed so that the natural muds and fines were lost while the drilling mud was being removed. Accordingly, it was necessary to rely heavily upon the various geophysical logs. The logs used most frequently were the spontaneous-potential (SP) and dual-induction logs (DIL), the formation-density compensated log (FDC), the simultaneous compensated neutron and formation-density logs (CNL–FDC), the natural gamma-ray log (GR), the borehole compensated sonic log (BHC), and the caliper log. These logs, along with the available washed well-cutting samples were the primary data sources for the assembly of the lithologic log presented below. The observations from 300 to 610 feet were made entirely from the gamma-ray log.

Summary lithologic descriptions have been provided by Smith and others (1976). The lithologic log presented here is a bed-by-bed description (unit lithologic description) of significant sedimentary layers. The general lithology is presented with only enough detail to indicate the rock type and some general qualifiers. The described lithology when assessed in its overall sediment context appears to provide rough but reasonable inferences as to the gross environments of deposition, especially when these assessments are combined with analyses of sedimentary structures from core slabs. These depositional environments are tentatively listed in table 3, and the lithologic log is given in table 4.

Zones of high radioactivity are found at 8,399, 8,655, 9,315, 9,585, 9,990, 12,223, 12,276, 13,292, and 13,331 feet. These horizons often contain phosphatic pebbles and glauconite and may represent hiatus surfaces.

SAND, SHALE, AND CARBONATE CONTENT

Compilation of the lithologic log provides a means of evaluating depth-related variations in the relative percentages of common rock types such as sandstone, shale (including siltstone

Table 3.—*Depositional environments determined from lithologic associations in COST No. B-2 well sediments*

[?, uncertain determination]

Approximate depth (feet)	Depositional environment						
	NONMARINE		MARINE				
				Open marine			
				Neritic			
	Terrestrial (fluvial, glacial, aeolian)	Transitional, (lagoonal, estuarine, tidal inlet)	Nearshore (beach, bar, tidal flat)	Inner	Middle	Outer	Bathyal (shallow upper slope)
300– 940	X	--	X	X	--	--	--
940– 3,700	--	--	X	X	X	?	--
3,700– 3,955	--	--	X	--	--	--	--
3,955– 5,010	--	--	X	X	X	X	X
5,010– 5,298	--	--	--	--	--	X	--
5,298– 5,315	--	X	X	--	--	--	--
5,315– 5,700	--	--	--	--	X	X	--
5,700– 5,900	--	--	--	--	X	--	--
5,900– 6,850	--	X	X	X	?	--	--
6,850– 7,020	--	--	X	--	--	--	--
7,020– 7,500	--	--	--	--	X	X	X
7,500– 7,680	--	X	X	X	--	--	--
7,680– 8,220	--	--	X	?	X	X	--
8,220– 8,970	--	--	X	X	X	--	--
8,970– 9,420	--	--	X	--	--	--	--
9,420–10,050	X	X	X	X	X	--	--
10,050–16,043	X	X	X	--	--	--	--

Table 4.—*Lithologic log of the COST No. B-2 well*

Depth (in feet)	Unit lithologic description
300– 550	Sand and gravel(?) (clean?).
550– 590	Sand and gravel(?) clayey.
590– 820	Sand becoming more clayey with depth.
820– 830	Clay.
830– 945	Sand, clayey.
945– 1,090	Sand, clean.
1,090– 1,100	Sand, clayey.
At 1,100	Approximate base of Holocene and Pleistocene and approximate top of Pliocene and Miocene.
1,100– 1,150	Sand, clean.
1,150– 1,180	Clay, sandy.
At 1,172	Identifiable middle Miocene.
1,180– 1,190	Clay and sand streaks.
1,190– 1,223	Clay.
1,223– 1,228	Sandstone layers.
1,228– 1,298	Sand containing intercalated clay layers.
1,298– 1,345	Clay containing sand layers.
1,345– 1,375	Sand, silty.
1,375– 1,400	Clay, sandy.
1,400– 1,420	Sand, clayey.
1,420– 1,765	Sand, clean.
1,765– 1,785	Sand, silty.
1,785– 1,835	Sand, clean.
1,835– 1,840	Sand, clayey.
1,840– 1,920	Sand, clean.
1,920– 2,000	Clay.
2,000– 2,410	Sand, clean.
2,410– 2,448	Clay.
2,448– 2,460	Sand, silty and clayey.
2,460– 2,470	Clay, silty.
2,470– 2,500	Sand or sandstone, fine-grained, silty.
2,500– 2,505	Sand or sandstone, fine-grained, silty.
2,505– 2,520	Sandstone, fine-grained.
2,520– 2,535	Sandstone, fine-grained, containing clay beds.
2,535– 2,750	Clay and (or) claystone (mudstone).

Table 4.—*Lithologic log of the COST No. B-2 well*—Continued

Depth (in feet)	Unit lithologic description
2,750– 2,775	Sandstone, fine-grained, micaceous.
2,775– 2,810	Clay and (or) claystone.
2,810– 2,945	Sandstone, fine-grained, silty and clayey, micaceous.
2,945– 3,005	Clay and (or) claystone, buff-colored.
3,005– 3,055	Silt and clay and (or) claystone.
3,055– 3,065	Sandstone very fine, silty.
3,065– 3,085	Siltstone and claystone becoming fine- to medium-grained sandstone as depth increases.
3,085– 3,162	Sand and sandstone, medium-grained, clean, detrital lignite.
At 3,162	Sandstone, calcareous and (or) limestone, very sandy.
3,162– 3,195	Sand and (or) sandstone, mostly medium-grained, becoming coarse-grained in places.
3,195– 3,210	Claystone and siltstone.
At 3,211	Limestone, very sandy and (or) sandstone, very calcareous.
3,212– 3,220	Sandstone.
3,220– 3,235	Clay (probably calcareous claystone, siltstone, or shale), very sandy limestone at 3,230 to 3,231 feet.
3,235– 3,240	Sandstone.
3,240– 3,255	Clay and (or) claystone, silty.
3,255– 3,278	Sandstone, fine, medium- to coarse-grained and silty.
3,278– 3,280	Limestone, sandy and silty or sandstone, silty, very calcareous.
3,280– 3,500	Siltstone, claystone, somewhat sandy.
3,500– 3,535	Sandstone, fine-grained, silty and clayey.
3,535– 3,546	Claystone and (or) siltstone, sandy.
3,546– 3,547	Limestone, dark-grayish-brown, clayey, also siltstone, dark and calcareous.
3,547– 3,645	Claystone or shale, calcareous.
At 3,596	Base of Miocene.

TABLE 4.—*Lithologic log of the COST No. B-2 well*—Continued

Depth (in feet)	Unit lithologic description
3,645– 3,655	Sandstone, somewhat calcareous and silty.
3,655– 3,720	Claystone and siltstone, sandy, especially from 3,700 to 3,720 feet.
3,720– 3,930	Sand, clean, containing many silty sand intervals.
3,930– 3,955	Claystone and silty clay, calcareous, dark-grayish-brown to brown, possibly somewhat dolomitic.
3,955– 4,050	Clay or claystone, silty, calcareous at the top, becoming fine- to medium-grained sandstone at about 4,000 feet.
4,050– 4,965	Calcareous mud (marl and possible chalk), light-gray to buff-colored, much calcareous sand.
At 4,082	Base of Oligocene.
At 4,964	Base of Eocene.
4,965– 5,000	Limestone, sandy or calcareous sandstones, sandstone at 4,975 feet.
At 5,000	Base of Paleocene.
5,000– 5,170	Sandstone, coarse, becoming finer and more silty with depth.
At 5,100	Base of Maestrichtian.
5,170– 5,200	Sand, fine-grained, silty; possibly calcareous sandstone.
At 5,200	Limestone bed (thin).
5,200– 5,296	Cay, sity, (siltstone and claystone) dark-grayish-brown to gray, some mica present.
At 5,296	Limestone bed, thin, light-gray, slightly clayey.
5,297– 5,300	Sand, fine- to very fine grained, poorly sorted, clayey, gypsiferous, containing pyrite fragment (water worn), glauconite, lignite, fossil fragments, some limestone fragments.
5,300– 5,400	Siltstone and claystone, dark-grayish-black to brown, micaceous.
5,400– 5,685	Clay and (or) siltstone and claystone containing some calcareous clay zones and occasional beds of sandstone and calcareous sandstone, fossiliferous.
5,685– 5,796	Sandstone, very silty, becoming much more sandy with depth, micaceous, slightly calcareous.
At 5,736	Base of Campanian.
5,796– 5,825	Sandstone, silty and containing calcareous sandstone layers at 5,798 to 5,825 feet.
5,825– 5,920	Sandstone, silty, becoming less silty and slightly more calcareous with depth, a sandy limestone at 5,918 feet.
5,920– 5,930	Sandstone.
5,930– 5,950	Siltstone and claystone, calcareous; sandy limestone bed at 5,932 feet.
5,950– 5,975	Sandstone, fine- to coarse-grained and silty.
5,975– 6,060	Sandstone, silty, micaceous and calcareous; very sandy limestone beds at 5,960 and 5,990 feet.
6,060– 6,075	Claystone, sandy.
6,075– 6,082	Sandstone, clean and porous, shell fragments.
6,082– 6,098	Claystone, sandy and calcareous, light-gray.
6,098– 6,118	Sandstone, fine- to coarse-grained, very clean; thin detrital lignite bed at 6,110 to 6,111 feet.

TABLE 4.—*Lithologic log of the COST No. B-2 well*—Continued

Depth (in feet)	Unit lithologic description
6,118– 6,122	Claystone, light-gray, calcareous, lignitic fragments, limonitic and hematitic staining .
6,122– 6,165	Sandstone, clean, porous, lignitic, pyritic, calcareous, with fossil fragments.
6,165– 6,172	Limestone, gray, clayey, sandy, somewhat less calcareous at the base, glauconite, micas, pyrite nodules, and lignitic, limonitic, and aragonitic fragments.
6,172– 6,240	Sand, some very porous (clean).
6,240– 6,253	Sandstone, fine-grained, silty, and calcareous; abundant lignitic and coaly fragments at 6,245 to 6,250 feet.
6,253– 6,270	Sandstone, very porous at 6,262 feet.
6,270– 6,282	Sandstone, silty, calcareous, containing some very impure limestones and dolomitic limestones, chert, glauconite, lignite, and hematite.
6,282– 6,338	Sandstone, clean, micaceous, lignitic, pyritic; very porous from 6,300 to 6,315 feet.
6,338– 6,345	Clay, calcareous, micaceous, sandy, gray, some pyrite and detrital lignite.
6,345– 6,478	Sandstone, calcareous, especially at 6,345 feet and from 6,383 to 6,408 feet, clean, porous and coarse grained from 6,410 to 6,460 feet.
At 6,478	Limestone very clayey, gray, containing lignitic fragments.
6,478– 6,500	Sandstone, very calcareous, and (or) limestone, very sandy.
6,500– 6,502	Clay, calcareous, possibly a calcareous shale, gray.
6,502– 6,512	Sand, porous.
6,512– 6,580	Shale, and (or) mudstone, sandy, calcareous, dark-gray, micaceous; very calcareous from 6,512 to 6,540 feet.
6,580– 6,595	Sand or sandstone, calcareous.
6,595– 6,605	Clay or shale, very calcareous.
6,605– 6,615	Sandstone, porous, very slightly calcareous.
6,615– 6,655	Clay or shale, sandy and calcareous.
6,655– 6,715	Sandstone, calcareous; gray, silty, calcareous beds at 6,661, 6,684, and 6,713 feet.
6,715– 6,770	Clay and silt, gray to buff, sandy, and very calcareous; shell fragment near the base.
6,770– 6,795	Sandstone, calcareous at 6,775 feet and at 6,791 to 6,795 feet.
6,795– 6,805	Clay or shale, light-gray, sandy, and very calcareous.
6,805– 6,825	Sandstone, slightly calcareous at the top, becoming very porous toward base; lignitic(?) zone at 6,818 feet.
6,825– 6,835	Clay or shale, dark-gray, calcareous.
6,835– 6,840	Sandstone, porous.
6,840– 6,847	Clay or shale, sandy, calcareous, dark-gray.
6,847– 6,850	Sandstone, silty, calcareous.
6,850– 6,980	Clay or shale, dark-brownish-gray to gray, calcareous, sandy, gradually becoming very calcareous near the base, detrital lignite, mica.
6,980– 6,995	Sandstone, porous. calcareous; detrital lignite(?) at 6,980 feet.
6,995– 7,005	Silt or siltstone, gray, calcareous.
7,005– 7,018	Clay or shale, light-gray, silty, micaceous, sandy, and calcareous.

TABLE 4.—*Lithologic log of the COST No. B-2 well*
—Continued

Depth (in feet)	Unit lithologic description
7,018– 7,022	Silt and (or) siltstone, sandy, very calcareous.
7,022– 7,500	Shale, claystone, siltstone and fine-grained sandstone section, gray, very calcareous, some porous sandstone beds, fossiliferous, micaceous, carbonaceous, and pyritic.
At 7,057	Base of Santonian-Coniacian.
7,500– 7,675	Sandstone, silty, gray, very calcareous from 7,620 to 7,670 feet, some brown vuggy dolomite interbedded with porous sand and siltstones.
At 7,610	Base of Turonian.
7,675– 7,780	Siltstone and shale, sandy, very calcareous, containing intercalated limestone beds, light-gray from 7,730 to 7,745 feet, fine-grained, calcareous, glauconitic siltstone.
7,780– 8,160	Sandstone and sand, fine-grained, some micaceous siltstones, dark-gray and brown, very calcareous throughout, buff-colored limestones, slightly dolomitic, especially from 7,770 to 7,830 feet, from 7,900 to 7,915 feet, and from 8,010 to 8,055 feet.
At 8,130	Base of Cenomanian (base of Upper Cretaceous).
8,160– 8,222	Siltstone and shale, sandy, very calcareous, many limestone beds throughout.
8,222– 8,260	Sandstone, very clean, porous, calcareous, especially at 8,222 and 8,255 feet.
8,260– 8,282	Siltstone-sandstone, very calcareous.
8,282– 8,295	Sandstone, clean, porous.
8,295– 8,305	Siltstone and shale, calcareous.
8,305– 8,445	Sandstone, locally calcareous, very porous at 8,375 to 8,385 feet, highly radioactive sandstone at 8,399 feet, possibly glauconite or phosphate pebble zones.
8,445– 8,452	Sandstone, shaly and calcareous, very calcareous at 8,450 feet.
8,452– 8,470	Sandstone, clean, porous.
8,470– 8,495	Sandstone, shaly, slightly calcareous.
8,495– 8,505	Siltstone, calcareous.
8,505– 8,522	Sandstone, calcareous.
8,522– 8,528	Siltstone and shale, calcareous.
8,528– 8,635	Sandstone, very slightly calcareous, thin limestone bed at 8,581 feet.
8,635– 8,655	Limestone, shaly and (or) calcareous shale.
8,655– 8,665	Sandstone, clean, porous, highly radioactive sandstone at 8,655 feet, possibly a glauconite or phosphate pebble zone.
8,665– 8,710	Limestone, shaly.
8,710– 8,735	Sandstone, clean, very porous.
8,735– 8,770	Shale and siltstone, calcareous; thin carbonaceous shale(?) at 8,745 feet.
8,770– 8,775	Sandstone, clean, porous.
8,775– 8,840	Shale, very calcareous, containing some thin sandstone beds.
8,840– 8,875	Sandstone, very porous at base; abundant carbonate reduces porosity at top.
8,875– 8,900	Shale, very calcareous or a shaly limestone.
At 8,900	Base of Albian.
8,900– 8,970	Sandstone, very clean, porous, slightly calcareous at base.

TABLE 4.—*Lithologic log of the COST No. B-2 well*
—Continued

Depth (in feet)	Unit lithologic description
8,970– 8,995	Shale, very cacareous; probable lignite or coal bed at 8,993 feet.
8,995– 9,035	Sandstone, very porous.
9,035– 9,048	Shale, very calcareous.
9,048– 9,085	Sandstone, clean, very porous, somewhat calcareous at base.
9,085– 9,110	Shale, calcareous and sandy.
9,110– 9,142	Sandstone, calcareous.
9,142– 9,144	Shale, sandy, calcareous.
9,144– 9,170	Sandstone with limestone beds.
9,170– 9,180	Limestone.
9,180– 9,190	Sandstone, calcareous.
9,190– 9,220	Sandstone, calcareous, especially at 9,200 feet.
9,220– 9,235	Limestone, shaly.
9,235– 9,255	Sandstone, calcareous.
9,255– 9,270	Shale, sandy and calcareous.
9,270– 9,280	Sandstone, clean and porous at base.
9,280– 9,295	Shale, siltstone and sandstone intercalations, sandy, and calcareous.
9,295– 9,305	Sandstone.
9,305– 9,315	Shale, and siltstone, calcareous(?); strongly radioactive zone at 9,315 feet, possibly a glauconite or phosphate pebble zone.
9,315– 9,345	Sandstone, calcareous especially at 9,335 feet.
9,345– 9,355	Shale and limestone.
9,355– 9,365	Sandstone.
9,365– 9,372	Shale, rather calcareous.
9,372– 9,422	Sandstone, very porous, clean.
9,422– 9,428	Shale, calcareous.
9,428– 9,431	Shale, washout zone, coal bed at 9,428 feet.
9,431– 9,442	Sandstone.
9,442– 9,450	Shale, washout zone, coal bed at 9,448 feet.
9,450– 9,462	Sandstone, calcareous and shaly.
9,462– 9,487	Sandstone, becoming more porous with depth.
9,487– 9,495	Shale, sandy, very calcareous.
9,495– 9,518	Sandstone, calcareous.
9,518– 9,530	Shale, very calcareous.
9,530– 9,610	Sandstone, clean, highly porous; very radioactive sandstone at 9,585 feet, possibly phosphatic or glauconitic.
9,610– 9,620	Shale, calcareous, sandy.
9,620– 9,680	Sandstone, calcareous at 9,630 feet.
9,680– 9,725	Shale, sandy, very calcareous from 9,708 to 9,725 feet.
9,725– 9,748	Sandstone, porous, interbedded with less porous, carbonate-cemented zones.
9,748– 9,775	Shale, very calcareous throughout.
9,775– 9,790	Sandstone, porous.
9,790– 9,820	Shale, very calcareous, somewhat sandy at 9,798 feet.
9,820– 9,853	Sandstone, porous, becoming more carbonate cemented toward base.
9,853– 9,945	Limestone, shaly and sandy.
9,945– 9,958	Sandstone, high porosity.
9,958–10,000	Limestone, shaly and sandy, containing thin beds of sandstone; high radioactivity at 9,900 feet, possibly in glauconitic or phosphatic sandstone.
At 10,000	Base of Aptian.
10,000–10,025	Sandstone, high-porosity.
10,025–10,050	Limestone, shaly, some calcareous shales.
10,050–10.055	Sandstone.

TABLE 4.—*Lithologic log of the COST No. B-2 well*
—Continued

Depth (in feet)	Unit lithologic description
10,055–10,230	Limestone, shaly and (or) calcareous shale; washout zone from 10,060 to 10,200 feet probably because of dark carbonaceous shale and coal.
10,230–10,246	Sandstone.
10,246–10,248	Coal.
10,248–10,253	Limestone.
10,253–10,303	Sandstone, very porous.
10,303–10,306	Coal and dark shale, iron-oxide-stained.
10,306–10,325	Shale, very calcareous, and (or) shaly limestone.
10,325–10,430	Sandstone, very porous.
10,430–10,450	Shale, calcareous, washout; probably a coal seam present.
10,450–10,456	Sandstone or siltstone.
10,456–10,480	Shale, calcareous, washout; probably a coal seam present.
10,480–10,530	Sandstone, very porous.
10,530–10,540	Shale, calcareous, and shaly limestone layer.
10,540–10,565	Sandstone.
10,565–10,582	Shale, calcareous; sandy, probably carbonaceous shale at 10,578 feet.
10,582–10,610	Sandstone.
10,610–10,755	Shale, calcareous; a few thin shaly limestones interbedded with thin, fine-grained sandstone; washout at 10,710 and 10,720 feet; coal seams and rounded limestone concretions at 10,732 feet.
10,755–10,800	Sandstone, porous; washout at 10,800 feet may indicate thin coal seam.
10,800–10,805	Shale, very carbonaceous.
10,805–10,820	Sandstone, fair porosity.
10,820–10,835	Shale, slightly calcareous and (or) shaly limestone.
10,835–10,847	Sandstone, porous.
At 10,848	Washout, suggests shale containing thin coal seam.
10,849–10,894	Shale, some sandstone, slightly calcareous, especially at 10,876 feet.
At 10,895	Coal seam.
10,895–10,906	Sandstone.
10,906–10,955	Shale, calcareous (especially at 10,919 feet); coal seam at 10,927 to 10,928 feet, Fe_2O_3 staining; coal at 10,945 feet.
10,955–10,985	Sandstone, high-porosity.
10,985–11,058	Shale containing shaly limestone beds, especially at 10,998 feet; probable coal seams at 11,000 and 11,042 feet.
11,058–11,122	Sandstone, very high porosity.
11,122–11,135	Shale, calcareous.
11,135–11,240	Sandstone, porous; calcareous, nonporous sandstone at 11,200 feet; coal seam at 11,139 feet.
11,240–11,245	Dolomite(?) or dolomitic limestone(?).
11,245–11,338	Sandstone, porous, but also tight, containing some calcareous beds, especially at 11,280 and 11,300 feet.
11,338–11,428	Shale, sandy, calcareous; some limestone, sandy and shaly.
11,428–11,445	Sandstone, siltstone, dense.
11,445–11,473	Shale, calcareous, carbonaceous, sandy, and shaly.
11,473–11,500	Sandstone, clean, porous.
11,500–11,550	Limestone, shaly to clean, possible dolomitic limestone layers present.
11,550–11,575	Sandstone, clean, porous, becoming denser at the base.
11,575–11,605	Limestone, in part dolomitic and sandy.
11,605–11,620	Sandstone, porous; calcareous layer at 11,615 to 11,617 feet.
11,620–11,635	Shale, very calcareous to shaly limestone.
11,635–11,655	Sandstone, calcareous, slightly porous. careous sandstone.
11,655–11,765	Limestone, shaly, alternating with calcareous sandstone.
11,765–11,835	Sandstone, very porous; calcareous zone at 11,800 feet.
11,835–11,870	Limestone and (or) shaly limestone.
11,870–11,880	Sandstone.
11,880–11,925	Limestone and dolomite(?) at 11,895 feet.
11,925–11,940	Sandstone, porous to nonporous, calcareous.
11,940–11,975	Limestone, shaly, and calcareous shale.
11,975–12,030	Sandstone containing coal bed at 11,980 feet; calcareous at 12,012 feet.
At 12,000	Base of Valanginian.
12,030–12,045	Limestone, and calcareous shale.
12,045–12,060	Sandstone, very porous from 12,048 to 12,056 feet.
12,060–12,100	Limestone, shaly, and calcareous shale; thin sandstone at 12,008 feet.
12,100–12,112	Sandstone, calcareous.
12,112–12,140	Limestone, dolomitic.
12,140–12,168	Sandstone, calcareous.
12,168–12,210	Limestone, shaly.
12,210–12,240	Sandstone; high radioactivity at 12,223 feet, possibly because of glauconitic or phosphatic zone.
12,240–12,274	Limestone, shaly containing conspicuous limestone bed at 12,263 to 12,266 feet.
12,274–12,282	Sandstone, high radioactivity at 12,276 feet.
12,282–12,322	Limestone, shaly; dolomitic limestone at about 12,311 feet.
12,322–12,332	Sandstone, calcareous.
12,332–12,334	Coal and carbonaceous shales.
12,334–12,355	Sandstone, calcareous, slightly porous.
12,355–12,402	Shale, calcareous.
12,402–12,418	Sandstone, porous.
12,418–12,420	Coal.
12,420–12,430	Sandstone, calcareous, changing to sandy limestone as depth increases.
12,430–12,440	Limestone, dolomitic.
12,440–12,462	Shale, sandy, calcareous; limestone layers at 12,452 to 12,453 feet; sandstone layer at 12,441 feet.
12,462–12,464	Shale and coal.
12,464–12,482	Shale, sandy and somewhat calcareous, becoming more arenaceous as depth increases.
12,482–12,492	Shale, sandy, calcareous.
12,492–12,500	Limestone shaly, slightly dolomitic.
12,500–12,520	Shale, calcareous, sandy near the base.
12,520–12,575	Shale, calcareous.
12,575–12,579	Coal, some shaly beds.
12,579–12,595	Shale, sandy and calcareous.
12,595–12,621	Sandstone, porous.
12,621–12,623	Coal.
12,623–12,633	Sandstone, slightly porous.
12,633–12,670	Shale, carbonaceous, some coal.
12,670–12,708	Shale, very calcareous.
12,708–12,715	Sandstone, calcareous layers.
12,715–12,845	Limestone and dolomitic limestone.
12,845–12,856	Coal and carbonaceous shale.
12,856–12,872	Shale, very calcareous.

TABLE 4.—*Lithologic log of the COST No. B-2 well* —Continued

Depth (in feet)	Unit lithologic description
12,872–12,890	Limestone and shale; conspicuous limestone beds at 12,875 to 12,882 feet.
12,890–12,916	Sandstone, calcareous.
At 12,916	Shale, sandy, carbonaceous.
12,917–13,003	Limestone, dolomitic, alternating with calcareous sandstone.
13,003–13,007	Coal.
13,007–13,075	Alternating calcareous sandstone and limestone beds; limestone becomes more dolomitic as depth increases.
13,075–13,090	Sandstone and arenaceous limestone.
13,090–13,100	Sandstone and limestone beds; high radioactivity and limestone at 13,090 feet, possible glauconite or phosphate pebble zone.
13,100–13,138	Alternating calcareous sandstone and limestone.
13,138–13,140	Coal bed.
13,140–13,160	Sandstone and limestone.
13,160–13,170	Sandstone.
13,170–13,190	Shale, carbonaceous, coal at 13,179 feet.
13,190–13,200	Sandstone, tight, slightly calcareous.
13,200–13,280	Sandstone, clean, porous except at 13,208, 13,225, and 13,270 feet where calcite cement is especially abundant.
13,280–13,294	Shale, sandy, calcareous.
13,294–13,302	Sandstone or siltstone, high radioactivity at 13,292 feet.
13,302–13,330	Shale, calcareous, carbonaceous at 13,314 feet.
13,330–13,350	Sandstone, clean, porous, high radioactivity at 13,331 feet.
13,350–13,375	Shale, carbonaceous siltstone.
13,375–13,429	Sandstone, porous.
13,429–13,440	Shale, carbonaceous, some siltstone.
13,440–13,443	Coal.
13,443–13,449	Shale and siltstone, carbonaceous, calcareous(?).
13,449–13,452	Coal and carbonaceous shale.
13,452–13,500	Alternating calcareous shale, siltstone, and sandstone; limestone at 14,492 feet.
13,500–13,520	Sandstone, siltstone, probable siliceous cement.
13,520–13,524	Coal(?) and carbonaceous shale.
13,524–13,528	Shale.
13,528–13,538	Siltstone.
13,538–13,555	Limestone, sandy; dolomite or dolomitic limestone at 13,543 and 13,548 feet.
13,555–13,565	Sandstone, moderately porous, shaly.
13,565–13,572	Siltstone.
13,572–13,574	Coal seam.
13,574–13,605	Shale, carbonaceous, alternating with noncalcareous sandstone.
13,605–13,630	Sandstone, porous, somewhat calcareous at top.
13,630–13,642	Sandstone, calcareous.
13,642–13,655	Sandstone, slightly calcareous.
13,655–13,730	Shale, noncalcareous; calcareous at 13,677 feet.
13,730–13,758	Shale, becoming less calcareous and more sandy with depth.
13,758–13,825	Sandstone, clean, porous; limestone beds at 13,759 to 13,760 feet and at 13,808 to 13,810 feet.
13,825–13,890	Shale, carbonaceous; some siltstone and sandstone layers.
13,890–13,922	Sandstone, limestone bed at 13,912 to 13,920 feet.
13,922–13,925	Shale, carbonaceous.

TABLE 4.—*Lithologic log of the COST No. B-2 well* —Continued

Depth (in feet)	Unit lithologic description
13,925–13,940	Siltstone.
13,940–14,010	Shale and sandstone.
14,010–14,055	Sandstone; limestone at 14,011 and 14,045 feet.
14,055–14,070	Sandstone or siltstone.
14,070–14,098	Sandstone, noncalcareous.
14,098–14,185	Alternating calcareous and noncalcareous sandy shale and siltstone; limestone at 14,111 and 14,133 feet.
14,185–14,195	Sandstone.
14,195–14,235	Shale, sandy, in places slightly calcareous; siltstone, noncalcareous, at 14,235 feet.
14,235–14,270	Sandstone, porous to tight, calcareous (especially at 14,255 feet).
14,270–14,360	Shale and siltstone, sandy, mostly noncacareous; calcareous at 14,286, 14,296, and 14,310 feet, 14,314 to 14,318 feet.
14,360–14,408	Sandstone, clean somewhat calcareous; impure limestone bed at 14,378 feet.
14,408–14,544	Shale and siltstone, sandy, calcareous at 14,430 feet.
14,544–14,546	Coal seam, thin, and fissile shale and siltstone.
14,546–14,570	Sandstone, clean, slightly calcareous at 14,548 feet.
14,570–14,608	Shale and siltstone; impure limestone bed at 14,606 to 14,608 feet; shaly sandstone at 14,598 to 14,602 feet.
14,608–14,625	Sandstone, noncalcareous.
14,625–14,668	Sandstone, porous and clean, calcareous from 14,638 to 14,645 feet.
14,668–14,697	Shale and siltstone, dense, sandy, very slightly calcareous; highly carbonaceous at 14,670 feet.
14,697–14,703	Sandstone, micaceous.
14,703–14,715	Shale and siltstone, sandy.
14,715–14,745	Sandstone, calcareous.
14,745–14,753	Shale and siltstone, sandy.
14,753–14,775	Sandstone, calcareous.
14,775–14,885	Shale and siltstone.
14,885–14,890	Sandstone, probably fine grained, silty, calcareous.
14,890–14,943	Shale and siltstone.
14,943–14,968	Sandstone containing very calcareous beds at 14,943 and 14,960 feet.
14,968–15,030	Shale and siltstone.
15,030–15,085	Shale and siltstone, arkosic to subarkosic, micaceous, angular; calcite-cemented sandstone beds at 15,030 feet.
15,085–15,108	Sandstone, calcareous.
15,108–15,205	Shale and siltstone, occasionally sandy; calcareous at 15,110 to 15 120 feet; dolomitic limestone at 15,136 to 15,140 feet.
15,205–15,245	Sandstone beds, calcareous and noncalcareous, very coarse to medium-grained.
15,245–15,325	Shale and siltstone, some sandy claystone.
15,325–15,362	Sandstone, clean, very coarse, slightly calcite cemented; some beds quartz cemented.
15,362–15,443	Shale and siltstone; sandstone beds at 15,375 and 15,418 feet.
15,443–15,476	Sandstone, moderately porous, mostly noncalcareous.
15,476–15,482	Shale, carbonaceous, and coal.

TABLE 4.—*Lithologic log of the COST No. B-2 well*
—Continued

Depth (in feet)	Unit lithologic description
15,482–15,515	Sandstone, mostly noncalcareous.
15,515–15,595	Shale, siltstone.
15,595–15,610	Shale, sandy, and shaly sandstone.
15,610–15,687	Shale and siltstone, probably several thin coal seams.
15,687–15,705	Sandstone, sparse to abundant calcareous cement.
15,705–15,805	Shale, siltstone, and claystone, interbedded with occasional thin sandstone beds.
15,805–15,865	Sandstone, calcareous, coarse-grained sand to gravel.
15,865–15,882	Shale and siltstone.
15,882–15,895	Sandstone, slightly calcareous, coarse-grained.
15,895–15,950	Sandstone, calcareous and noncalcareous (alternating).
15,950–15,997	Shale, siltstone, and sandy siltstone; interbedded with sandstone, at 15,978 feet.
15,997–16,043	Sandstone, low porosity in places but vuggy and fairly porous elsewhere, very coarse to medium-grained, calcareous to noncalcareous, some siliceous cement.

and claystone), and carbonate rocks. Groupings of these rock types (table 5) are made to provide an insight into the amounts of reservoir rock available. Certain parts of the shaly section above 9,100 feet and of the sandstone section below 9,100 feet, are very calcareous and have low porosity and high density; these particular calcareous shales and sandstones are classified with the limestone and dolomite grouping. Figure 7 is a graph showing the various measured, adjusted, and combined percentages of these three groupings of rock types penetrated in 1,000-foot intervals.

The dominance of sandstone and shale in the Baltimore Canyon trough is apparent. In fact, significant numbers of sandstone reservoirs and impermeable capping shales exist throughout the rock column, except perhaps for the 7,100–8,100-foot interval. Most of the sandstone beds are thicker than 10 feet, and some sandstone sections are more than 100 feet thick (see table 4). Table 5 shows that a major part of the section below 5,100 feet (essentially the Cretaceous section) is composed of sandstone. However, as shown in the following discussion dealing with sandstone porosities, a significant percentage of this sandstone has low porosity.

TABLE 5.—*Sand, shale, and carbonate content in the COST No. B-2 well*
[Values in parentheses are the actual measured values of shale and (or) sand lithology before subtraction of calcareous units, values in percent]

Interval (feet)	Major lithologies		
	Sand sandstone	Clay, shale siltstone and claystone	Limestone, dolomite, calcareous shale, and (or) sandstone [1]
1,100– 2,100	75.5 (75.5)	24.5 (24.5)	0
2,100– 3,100	42.5 (42.5)	61.5 (61.5)	0
3,100– 4,100	35.5 (35.5)	61.5 (64.5)	3.0
4,100– 5,100	10.0 (10.0)	88.5 (90.0)	1.5
5,100– 6,100	51.5 (51.5)	46.5 (48.5)	2.0
6,100– 7,100	65.5 (65.5)	33.3 (34.5)	1.2
7,100– 8,100	20.3 (25.8)	74.2 (74.2)	5.5
8,100– 9,100	28.6 (33.5)	61.6 (66.5)	9.8
9,100–10,100	50.3 (58.8)	32.2 (41.2)	17.5
10,100–11,000	41.5 (47.5)	52.5 (52.5)	6.0
11,100–12,100	24.5 (60.5)	39.5 (39.5)	36.0
12,100–13,100	8.2 (30.0)	70.0 (70.0)	21.8
13,100–14,100	41.8 (50.5)	49.5 (49.5)	8.7
14,100–15,100	23.5 (26.5)	73.5 (73.5)	3.0
15,100–16,043	24.0 (26.0)	74.0 (74.0)	2.0

[1] Dense (low-porosity) calcareous zones are subtracted from the shale categories in most footages above 9,100 feet. Below 9,100 feet, the dense calcareous zones are subtracted from the sandstone column.

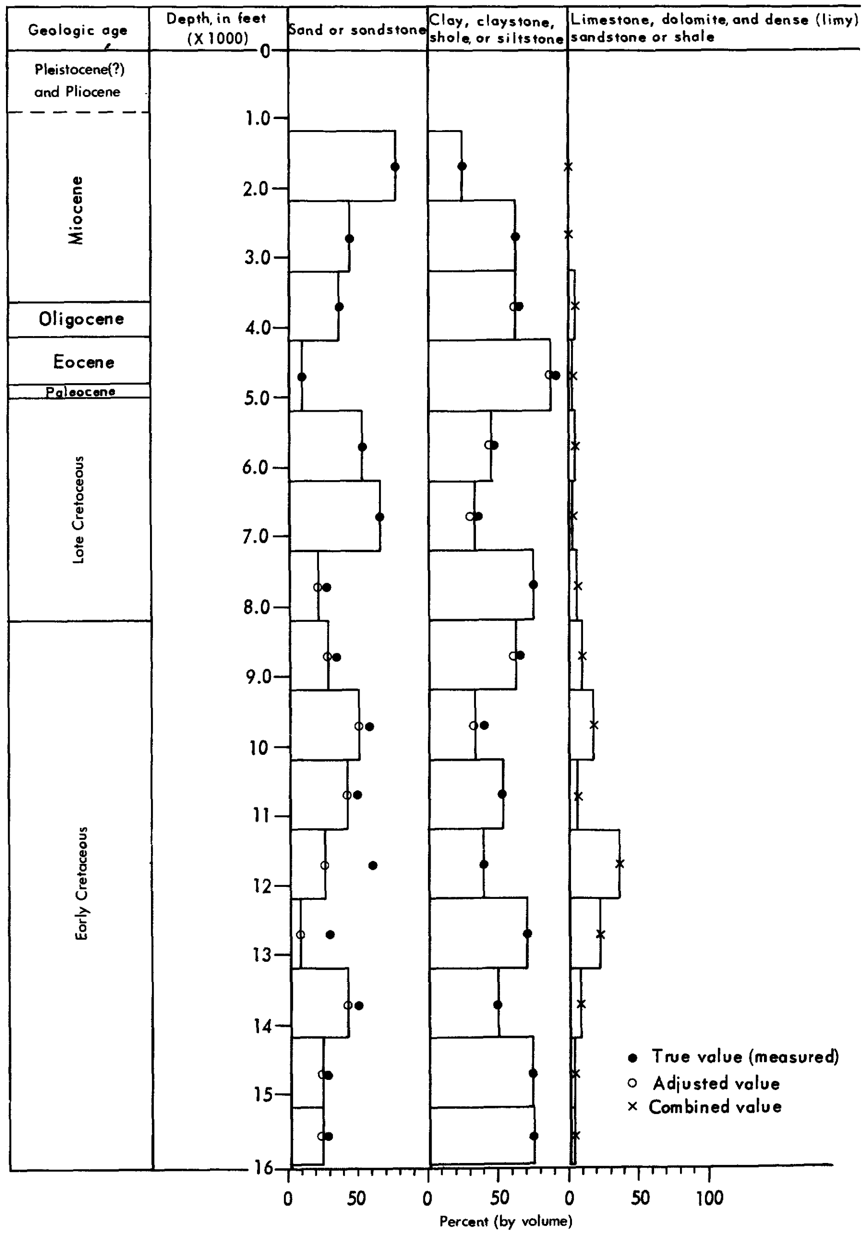


FIGURE 7.—Sand, shale, and carbonate content as a function of depth. Carbonate column includes dense, calcareous sandstones or shales. True values refer to the actual amounts of sand or shale measured; adjusted values are those derived by subtracting strongly calcareous units; combined values are given where the total carbonate amount is a combination of limestones, limy shales, and calcareous sands.

Sandstone Porosities

By E. C. Rhodehamel

Sandstone-porosity (ϕ) values were derived from the BHC (sonic), FDC (density), and CNL (neutron) logs. Rather good agreement exists between porosity values determined from the sonic (ϕ_s), and density (ϕ_d) logs. However, the CNL–FDC (neutron and density) log showed that the neutron porosities (ϕ_n) were generally 2 to 30 percent higher than the ϕ_d values. Because the ϕ_d was calculated on the basis of sandstone densities, the calcareous zones, and particularly the dolomitic zones, tended to provide apparently low ϕ_d values. On the other hand, the neutron log tends to measure true porosity as long as the major source of hydrogen is in the form of water or oil. When other sources of hydrogen (that is, lignite, coal, or bound waters in shale, gypsum, and cristobalite) are present, the neutron-porosity log measures inordinately high porosities. The presence of natural gas, on the other hand, leads to incorrectly low ϕ_n values. The disparity between ϕ_d and ϕ_n is therefore accentuated in these zones. As the ϕ_n values were judged to be too high throughout much of the section, these porosities were not tabulated.

Figure 8 shows the plots of ϕ_d and ϕ_s versus depth. These data are taken on the average of about 200-foot intervals from the more extensive tabulations of ϕ_d and ϕ_s given in table 6.

The values of ϕ_d and ϕ_s are in reasonably good agreement throughout the entire section. ϕ_d values range from 68 percent at about 2,000 feet to 2 percent at 16,007 feet. ϕ_s values range from 55 percent in a poorly consolidated section at about 1,400 feet to 6 percent at about 15,000 feet. Both logs show decreasing porosity as depth increases. Reduction in porosity with depth is to be expected in mineralogically immature sediments because of sediment compaction resulting from overburden pressure increase, as well as progressive cementation. Table 6 also presents porosity values determined by Core Laboratories (Smith and others, 1976). The porosity values were directly measured on conventional and sidewall cores. Corresponding permeability values (fig. 5) were calculated from a plot of the grain size, shaliness, and permeability relationships of Gulf Coast samples.

The conventional core analyses (table 6) show a decrease in porosity with increased burial depth very similar to that noted in the log values; the permeabilities show a correspondingly rapid decrease with depth. The sidewall-core porosity values, on the other hand, show less of a decrease with progressive burial, and at the base of the well, these values were considerably higher than porosities determined by log analysis.

The section "Lithologic Description" notes that about 50 percent of the Cretaceous section in the B–2 well consists of rather thick sandstone units. These units have porosities ranging from about 41 percent at 5,700 feet (near the top of the Cretaceous) to about 4 percent near the base of the test hole. However, as shown by the data in table 6, the major part (as much as 75 percent) of the Cretaceous sandstone section has less favorable reservoir characteristics (porosities less than 10–15 percent), especially in deeper parts of the well.

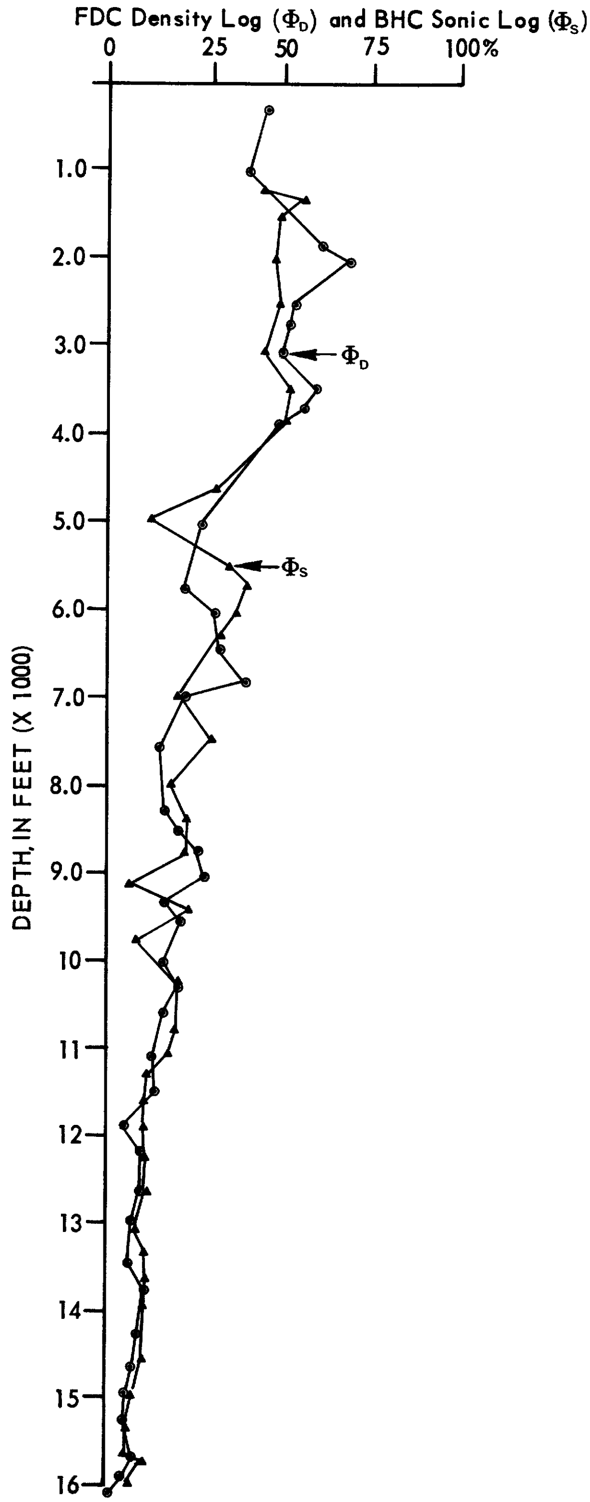


Figure 8.—Density and sonic log porosity as a function of depth.

TABLE 6.—*Comparison of porosity (ϕ) values determined from electric log and core measurements on COST No. B–2 well samples*

[Core ϕ data from Core Laboratories, Inc. (Smith and others, 1976). Asterisk denotes determination from sidewall core samples]

Depth (in feet)	FDC (density log) ϕ_d	BHC (sonic log) ϕ_s	Core ϕ	Remarks
318 – 336	45?	---	----	Values probably too low.
775 – 800	41?	---	----	
990 – 1,025	40?	---	----	
1,228 – 1,298	---	45	----	
1,275.0	---	---	28.4*	
1,345 – 1,360	---	55	----	
1,550 – 1,570	---	49	----	
1,842	60	---	----	
1,750 – 1,762	---	45	----	
2,009.0	---	---	29.0*	
2,036	68	---	----	
2,089.0	---	---	29.0*	
2,311.0	---	---	34.2*	
2,334.0	---	---	34.0*	
2,448.0	---	---	29.6*	
2,480 – 2,500	53	48.5	----	
2,509.0	---	---	33.9*	
2,760 – 2,770	52	44	----	
3,056.0	---	---	31.5*	
3,070 – 3,100	49	---	----	
3,095 – 3,100	---	44	----	
3,161.5	---	---	24.9*	
3,165.0	---	---	26.6	
3,230.5	---	---	26.7*	
3,262.0	---	---	32.2*	
3,508 – 3,522	59	52	----	
3,545	---	51	----	
3,645 – 3,652	46	52	----	
3,746 – 3,756	55	50	----	
3,800 – 3,900	48	---	----	
3,860 – 3,870	---	<50	----	
4,040	---	38	----	
4,410 – 4,418	---	31	----	
4,975 – 4,985	---	<12	----	Calcareous cement.
5,003 – 5,030	28	---	----	
5,030 – 5,070	32	33	----	
5,030.2	---	---	24.7	
5,031.0	---	---	30.9*	
5,031.4	---	---	7.7	
5,070 – 5,150	32	---	----	
5,072.0	---	---	24.4*	
5,096.0	---	---	32.6*	
5,100 – 5,150	---	38	----	
5,140.0	---	---	30.6*	
5,520 – 5,540	---	35	----	Rather poor definition.
5,615 – 5,620	---	39	----	
5,680 – 5,700	---	41	----	
5,695 – 5,795	22	---	----	
5,750 – 5,775	---	29	----	
5,920 – 5,930	22	---	----	
5,920 – 5,931	---	34	----	
5,964.0	---	---	26.1*	
5.991.0	---	---	32.4*	
6,015.0	---	---	33.2*	
6.033 – 6,045	31	37	----	
6,079.0	---	---	31.2*	
6,102.0	---	---	28.6*	
6,107.0	---	---	28.9*	
6,125.0	---	---	33.1*	
6,136.0	---	---	29.0*	
6,157.0	---	---	32.8*	
6,185 – 6,206	33	34	----	
6,186.0	---	---	31.4*	
6,204.0	---	---	25.4*	
6.235.0	---	---	25.8*	
6.264.0	---	---	30.0*	
6,300 – 6,315	---	32	----	
6,301.0	---	---	31.6*	
6.329.0	---	---	31.0*	
6,351.0	---	---	31.2*	
6,372.0	---	---	19.1*	

TABLE 6.—*Comparison of porosity (ϕ) values determined from electric log and core measurements on COST No. B–2 well samples*—Continued

Depth (in feet)	FDC (density log) ϕ_d	BHC (sonic log) ϕ_s	Core ϕ	Remarks
6,418 – 6,430	---	33	----	
6,420 – 6,430	33	---	----	
6,421.0	---	---	26.1*	
6,489.0	---	---	28.7*	
6,507.0	---	---	31.8*	
6,563.0	---	---	24.5*	
6,572.0	---	---	23.3*	
6,655 – 6,680	---	30	----	
6,669.0	---	---	32.0*	
6,693.0	---	---	26.6*	
6,785.0	---	---	32.0*	
6,808.0	---	---	22.7*	
6,818	38	---	----	
6,819	---	---	22.2*	
6,953.0	---	---	28.5*	
6,980 – 6,995	---	21	----	
6,991.0	---	---	21.4*	
6,992	22	---	----	
7,555	---	29	----	
7,560 – 7,580	15	---	----	
7,565.0	---	---	25.1*	
7,574.0	---	---	23.7*	
7,575	---	29	----	
7,659.0	---	---	25.4*	
7,795	---	17	----	
7,975.0	---	---	25.0*	
8,225 – 8,255	---	19	----	
8,225 – 8,265	17	---	----	
8,230.0	---	---	24.4*	
8,238.3	---	---	17.4	
8,239.5	---	---	16.2	
8,240.7	---	---	26.5	
8,241.2	---	---	18.6	
8,242.5	---	---	23.1	
8,243.5	---	---	18.4	
8,244.0	---	---	23.3*	
8,244.5	---	---	19.7	
8,245.8	---	---	19.2	
8,246.9	---	---	18.5	
8,247.8	---	---	20.7	
8,248.8	---	---	18.6	
8,249.6	---	---	11.7	
8,250.6	---	---	17.4	
8,251.4	---	---	18.2	
8,252.4	---	---	18.4	
8,253.0	---	---	23.2*	
8,253.7	---	---	18.4	
8,254.5	---	---	20.8	
8,255.5	---	---	16.9	
8,256.5	---	---	12.6	
8,257.3	---	---	15.7	
8,258.2	---	---	16.8	
8,258.9	---	---	13.2	
8,259.9	---	---	9.7	
8,260.5	---	---	6.8	
8,261.1	---	---	13.1	
8,261.8	---	---	4.3	
8,262.8	---	---	3.6	
8,263.1	---	---	26.3	
8,264.9	---	---	28.7	
8,289.0	---	---	29.3	
8,321.0	---	---	30.7*	
8,325 – 8,340	---	22	----	
8,375.0	---	---	24.8*	
8,375 – 8,385	---	22.5	----	
8,399.0	---	---	28.3*	
8,410 – 8,420	---	22	----	
8,411.0	---	---	30.2*	
8,454 – 8,480	20	---	----	
8,479.0	---	---	26.0*	
8,530 – 8,560	---	26	----	
8,533.0	---	---	27.0*	

TABLE 6.—*Comparison of porosity (ϕ) values determined from electric log and core measurements on COST No. B–2 well samples*—Continued

Depth (in feet)	FDC (density log) ϕ_d	BHC (sonic log) ϕ_s	Core ϕ	Remarks
8,559.0	---	---	30.6*	
8,580.0	---	---	27.5*	
8,587.0	---	---	29.6*	
8,606.0	---	---	28.2*	
8,659.0	---	---	27.2*	
8,715 – 8,730	---	21	----	
8,715 – 8,735	25	---	----	
8,730 – 8,738	---	23	----	
8,770 – 8,775	28	---	----	
8,849.0	---	---	29.4*	
8,870.0	---	---	29.4*	
8,910 – 8,950	---	23	----	
8,917.0	---	---	28.1*	
8,956.0	---	---	24.2*	
8,995 – 9,035	28	---	----	
9,065 – 9,380	10–14	---	----	Averaged over the interval.
9,110 – 9,140	---	6	----	Calcareous.
9,147.0	---	---	25.8*	
9,173.0	---	---	20.8*	
9,187.0	---	---	27.2*	
9,207.0	---	---	25.2*	
9,236.0	---	---	30.5*	
9,280 – 9,330	17	---	----	
9,280.3	---	---	18.5	
9,280.7	---	---	15.1	
9,281.2	---	---	13.6	
9,282.5	---	---	13.8	
9,283.2	---	---	11.3	
9,382.5	---	---	18.4	
9,283.8	---	---	17.9	
9,284.7	---	---	12.0	
9,285.3	---	---	6.1	
9,286.5	---	---	8.7	
9,287.6	---	---	5.5	
9,288.5	---	---	25.7	
9,289.5	---	---	25.3	
9,291.3	---	---	7.9	
9,292.5	---	---	15.8	
9,293.0	---	---	27.8*	
9,293.3	---	---	13.4	
9,294.5	---	---	9.7	
9,295	---	23	----	
9,295.6	---	---	5.3	
9,296.3	---	---	9.7	
9,297.2	---	---	17.2	
9,297.5	---	---	8.1	
9,298.8	---	---	5.9	
9,299.3	---	---	8.2	
9,300.3	---	---	7.2	
9,302.2	---	---	27.4	
9,302.7	---	---	19.8	
9,303.7	---	---	17.4	
9,304.4	---	---	23.7	
9,305.4	---	---	28.1	
9,306.3	---	---	15.8	
9,306.6	---	---	23.7	
9,307.7	---	---	22.4	
9,308.4	---	---	27.3	
9,309.2	---	---	7.1	
9,309.7	---	---	24.8	
9,310.4	---	---	24.3	
9,310.8	---	---	8.5	
9,311.5	---	---	9.5	
9,312.5	---	---	15.8	
9,313.4	---	---	18.6	
9,313.7	---	---	12.2	
9,314.2	---	---	16.6	
9,315.2	---	---	14.7	
9,317.8	---	---	8.3	
9,318.6	---	---	8.4	Fractured.
9,323.3	---	---	9.9	
9,324.5	---	---	13.2	
9,325.6	---	---	21.3	

TABLE 6.—*Comparison of porosity (φ) values determined from electric log and core measurements on COST No. B–2 well samples*—Continued

Depth (in feet)	FDC (density log) ϕ_d	BHC (sonic log) ϕ_s	Core φ	Remarks
9,326.4	---	---	23.2	
9,327.6	---	---	20.8	
9,328.4	---	---	17.9	
9,329.6	---	---	24.4	
9,357.0	---	---	27.0*	
9,362 – 9,412	24	---	----	
9,402 – 9,415	---	23.5	----	
9,467.0	---	---	9.8*	
9,530 – 9,610	21	---	----	
9,534.0	---	---	26.8*	
9,539.0	---	---	23.7*	
9,545.0	---	---	27.3*	
9,550 – 9,580	---	22.5	----	
9,569.0	---	---	28.5*	
9,597.0	---	---	9.9*	
9,623.0	---	---	19.3*	
9,635.0	---	---	27.5*	
9,655 – 9,660	---	>19	----	
9,659.0	---	---	28.2*	
9,728.5	---	---	29.9*	
9,748.0	---	---	27.8*	
9,770 – 9,778	---	---	9.0	
9,773.0	---	---	20.4*	
9,778.0	---	---	22.5*	
9,779	---	32.5	----	
9,820 – 9,835	13	---	----	
9,825.0	---	---	27.8*	
9,882	---	8	----	
9,918.0	---	---	30.1*	
9,953.0	---	32.5	22.8*	
9,978	---	<8	----	
10,000 –10,025	16	---	----	
10,007.0	---	---	27.0*	
10,051.0	---	---	24.4*	
10,230 –10,245	17.4	---	----	
10,253 –10,303	20	---	----	
10,255 –10,290	---	19.5	----	
10,256.0	---	---	22.4*	
10,325 –10,428	16	---	----	
10,346.0	---	---	21.7*	
10,350 –10,430	---	<18	----	
10,409.0	---	---	20.8*	
10,429.0	---	---	21.8*	
10,490 –10,530	---	>20	----	
10,499.0	---	---	20.9*	
10,555.0	---	---	17.2*	
10,582 –10,610	16	---	----	
10,595 –10,610	---	>20	----	
10,770 –10,780	---	>20	----	
10,791.0	---	---	26.5*	
10,805 –10,820	18	---	----	
10,817.0	---	---	23.8*	
10,899.0	---	---	24.7*	
10,960 –10,980	---	20	----	
10,967.0	---	---	21.5*	
11,035	12	---	----	
11,037.0	---	---	22.7*	
11,058 –11,122	13	---	----	
11,060 –11,115	---	<18	----	
11,064.0	---	---	24.0*	
11,102.0	---	---	22.0*	
11,115 –11,130	---	<12	----	
11,141.0	---	---	20.3*	
11,173.0	---	---	18.5*	
11,205 –11,230	---	<12	----	
11,216.0	---	---	25.0*	
11,255 –11,265	---	<12	----	
11,257.0	---	---	24.4*	
11,280 –11,295	---	12	----	
11,310 –11,320	---	19	----	
11,384.0	---	---	20.7*	
11,385	---	11	----	

TABLE 6.—*Comparison of porosity (ϕ) values determined from electric log and core measurements on COST No. B–2 well samples*—Continued

Depth (in feet)	FDC (density log) ϕ_d	BHC (sonic log) ϕ_s	Core ϕ	Remarks
11,424 –11,434	---	19	----	
11,435.0	---	---	18.8*	
11,476 –11,496	13	---	----	
11,483.0	---	---	22.8*	
11,537.0	---	---	20.2*	
11,559.0	---	---	22.3*	
11,607.0	---	---	18.3*	
11,635 –11,652	6	---	----	
11,638 –11,655	---	11.5	----	
11,780 –11,800	---	12	----	
11,870 –11,880	5	<12	----	
11,873.0	---	---	20.7*	
11,928 –11,938	10	---	----	
11,975	14	---	----	
11,980 –12,002	---	12	----	
11,981.0	---	---	18.9	
11,984 –12,028	11	---	----	
11,999.0	---	---	16.5*	
12,021.0	---	---	12.6*	
12,050 –12,055	---	20	----	
12,107	---	---	19.1*	
12,135 –12,150	---	<12	----	
12,139.0	---	---	17.2*	
12,155 –12,165	---	19	----	
12,157.0	---	---	18.0*	
12,214 –12,220	10	---	----	
12,215 –12,245	---	<12	----	
12,218.0	---	---	15.4*	
12,234	8	---	----	
12,289.0	---	---	11.6*	
12,400 –12,420	---	12	----	
12,402 –12,417	12	---	----	
12,515.0	---	---	20.4*	
12,595 –12,620	10	---	----	
12,597.0	---	---	12.5*	
12,600 –12,615	---	11.5	----	
12,627.0	---	---	18.1*	
12,705 –12,720	---	11	----	
12,711.0	---	---	19.7*	
12,984 –12,989	8	---	----	
13,070 –13,095	---	8	----	
13,075	4	---	----	
13,083.0	---	---	21.2*	
13,085	4	---	----	
13,094	8	---	----	
13,150 –13,170	---	10	----	
13,165.0	---	---	21.1*	
13,195 –13,260	---	<12	----	
13,200 –13,280	8	---	----	
13,217.0	---	---	23.6*	
13,243.0	---	---	18.2*	
13,295 –13,300	---	<11	----	
13,349.0	---	---	22.1*	
13,380 –13,440	9.2	---	----	
13,390 –13,400	---	<12	----	
13,409.0	---	---	21.0*	
13,410 –13,430	---	<13	----	
13,420 –13,440	7	---	----	
13,420.2	---	---	12.8	
13,421.6	---	---	13.1	
13,422.4	---	---	10.9	
13,423.3	---	---	12.5	
13,424.3	---	---	14.0	
13,425.0–13,425.4	---	---	13.7	Pinpoint fluorescence, weak odor.
13,425.8	---	---	12.5	
13,425.9–13,426.0	---	---	16.0	Pinpoint fluorescence, weak odor.
13,426.8	---	---	13.6	
13,427.6	---	---	11.4	
13,427.0–13,428.0	---	---	12.7	Pinpoint fluorescence, weak odor.
13,428.3	---	---	13.9	
13,428.0–13,429.0	---	---	16.4	Pinpoint fluorescence, weak odor.
13,429.3	---	---	11.5	

TABLE 6.—*Comparison of porosity (φ) values determined from electric log and core measurements on COST No. B-2 well samples*—Continued

Depth (in feet)	FDC (density log) ϕ_d	BHC (sonic log) ϕ_s	Core φ	Remarks
13,429.0–13,430.0	---	---	15.3	Pinpoint fluorescence, weak odor.
13,430.3	---	---	4.9	
13,430.0–13,431.0	---	---	11.3	Pinpoint fluorescence, weak odor.
13,431.2	---	---	11.6	
13,431.0–13,432.0	---	---	14.1	Pinpoint fluorescence, weak odor.
13,432.6	---	---	10.6	
13,432.0–13,433.0	---	---	14.1	Pinpoint fluorescence, weak odor.
13,433.2	---	---	10.6	
13,433.6	---	---	4.1	
13,434.3	---	---	7.0	
13,434.6	---	---	7.5	
13,435.4	---	---	4.0	
13,436.5	---	---	3.2	
13,437.7	---	---	3.5	
13,438.7	---	---	5.8	
13,439.7	---	---	4.5	
13,440.5	---	---	5.6	
13,441.5	---	---	7.0	
13,453.7	---	---	4.7	
13,454.6	---	---	7.7	
13,479.0	---	---	21.0*	
13,518.0	---	---	17.6*	
13,603 –13,630	10	---	----	
13,610 –13,640	---	<12	----	
13,614.0	---	---	18.5*	
13,758 –13,825	11	---	----	
13,770 –13,820	---	11	----	
13,905 –13,915	---	11.5	----	
13,906.0	---	---	12.9*	
13,931.0	---	---	15.9*	
13,987.0	---	---	17.9*	
14,020 –14,050	<9	---	----	
14,070.0	---	---	20.8*	
14,092.0	---	---	21.5*	
14,240 –14,270	9	---	----	
14,252.0	---	---	16.3*	
14,375 –14,400	---	9	----	
14,380 –14,405	<8	---	----	
14,384.0	---	---	9.5*	
14,550 –14,570	---	<11	---	
14,562.0	---	---	17.5*	
14,608 –14,627	7.6	---	----	
14,610 –14,625	---	10	----	
14,619.0	---	---	19.9*	
14,650 –14,665	---	10	----	
14,654.0	---	---	14.7*	
14,720 –14,745	---	8	----	
14,755 –14,775	3.5	---	----	
14,781.0	---	---	10.6*	
14,789.0	---	---	7.6*	
14,890	---	11	----	
14,945 –14,965	5.7	---	----	
14,948 –14,958	---	8	----	
14,950	---	---	13.7*	
14,960.0	---	---	17.7*	
15,095 –15,100	---	9	----	
15,205 –15,245	5.4	---	----	
15,205 –15,250	---	7	----	
15,242.0	---	---	17.4*	
15,324.0	---	---	13.9*	
15,326 –15,330	---	6.5	----	
15,345 –15,360	---	6.5	----	
15,346.0	---	---	15.4*	
15,375.0	---	---	14.4*	
15,417.0	---	---	17.9*	
15,443 –15,465	8.6	---	----	
15,445 –15,458	---	7	----	
15,447.0	---	---	17.4*	
15,458 –15,472	---	<6	----	
15,506.0	---	---	15.0*	
15,602 –15,610	---	7	----	
15,690 –15,695	---	<6	----	

TABLE 6.—*Comparison of porosity (φ) values determined from electric log and core measurements on COST No. B-2 well samples*—Continued

Depth (in feet)	FDC (density log) ϕ_d	BHC (sonic log) ϕ_s	Core ϕ	Remarks
15,695 –15,702	---	<12	----	
15,703 –15,710	---	6.5	----	
15,803 –15,808	---	6	----	
15,805 –15,865	8.3	---	----	
15,813 –15,844	---	6	----	
15,854 –15,874	---	7	----	
15,875 –15,898	---	8	----	
15,883	---	---	10.8*	
15,890.0	---	---	11.0*	
15,905 –15,910	5	---	----	
15,922	---	---	10.5*	
15,948 –15,956	---	>7	----	
15,954.0	---	---	12.3*	
15,968 –15,976	---	7	----	
15,995 –16,015	2	---	----	

Sandstone Petrography

By P. A. Scholle

Sandstone chips were handpicked from rotary drill cuttings at 72 levels below 8,000 feet. Sandstone at these depths was judged likely to have the greatest overall reservoir potential and diagenetic complexity. One or more thin sections were cut for each interval, and from 4 to 10 chips representative of each interval were used. The sections were stained for potassium feldspars and were examined by means of a standard petrographic microscope. The results are shown in table 7.

The grain-size columns merely indicate the coarseness of the material examined petrographically and do not necessarily reflect the average grain size of sand in that interval. Coarser sand and gravel commonly would disaggregate into individual constituent grains, making examination of representative rock textures impossible. This petrographic analysis, therefore, emphasizes the finer grained and more lithified units in the section. Nevertheless, the overall changes in rock composition, fabric, and diagenesis described in the selected samples are probably representative of the whole section.

COMPOSITION

The entire section from 8,000 to 16,000 feet is feldspathic, and most sandstone is classed as subarkose. From 8,000 to about 12,800 feet, potassium feldspar (orthoclase and microcline) predominates, plagioclase is quite subordinate or absent. From about 12,800 feet to the bottom of the well, plagioclase feldspar increases in abundance and constitutes a significant rock-forming element. The change in feldspar composition most likely reflects changes in provenance rather than selective interstratal destruction of plagioclase because, whenever present, plagioclase is less altered than the potassium feldspar.

Rock fragments are present throughout the section although they are never a major rock-forming element. Both sedimentary (shale and limestone) and metamorphic (slate, phyllite, schist, and gneiss) rock fragments were noted at many levels, and no particular evidence of progressive unroofing of source areas was seen.

Most of the sediment from 8,000 to 9,740 feet contains glauconite of both pelletal and vermicular types. Some trace of glauconite is found to depths of about 10,100 feet; virtually none is present below that depth. The glauconite, in conjunction with the calcareous fossils and abundance of limestone noted in between 8,000 and 10,140 feet, indicates dominantly marine depositional conditions.

Sandstone throughout the 8,000–16,000-foot section is micaceous and pyritic, although at some intervals the pyrite has undergone partial alteration to iron oxide. Lignitic inclusions are present, especially near 10,000 feet, 11,000 feet, 12,600–13,000 feet, and 13,900–15,100 feet. Heavy minerals are present but were not specifically studied in this initial investigation. The occurrence of authigenic overgrowths on detrital tourmaline in the 15,260-foot sample indicates that marine incursions are present even in this part of the section because the boron of marine waters is needed to produce such overgrowths.

DIAGENESIS AND CEMENTATION

The loss of porosity as a function of burial depth in the COST No. B–2 well is noted in the section "Sandstone Porosities" and in direct laboratory measurements of petrophysical properties of the sidewall and conventional cores (Smith and others, 1976). The causes of this depth-related porosity loss are complex but are decipherable from petrographic analysis.

TABLE 7.—*Petrography of sandstone from the COST No. B-2 well*

Depths given in feet and represent 30-foot sampling intervals from stated depth downward; X=common; XX=very common; t=trace; ?=possible

Grain size:
- S=Silt
- Fi=Fine to very fine sand
- M=Medium sand
- C=Coarse sand and gravel

Constituents:
- Q=Quartz
- K=K-Feldspar
- P=Plagioclase
- RF=Rock fragments
- GL=Glauconite
- PY=Pyrite
- MI=Mica
- LI=Lignite

Diagenesis
- Fr=Fresh unaltered feldspar
- Al=Altered (sericitized, vacuolized, or calcitized) feldspar
- Co=Compaction features
- Or=Grain orientation

Cement
- Qo=Quartz overgrowths
- CL=Clay (authigenic)
- CA=Calcite
- DO=Dolomite
- SI=Siderite

Rock name (Classification from Folk, 1968)
- QA=Quartzarenite
- FQA=Feldspathic quartzarenite
- SA=Subarkose
- A=Arkose
- Mst=Mudstone

Miscellaneous
- F=Fossiliferous
- Ls=Limestone
- Oo=Oolite
- Sc=Sericite
- Chl=Chlorite
- MRF=Metamorphic rock fragments
- SRF=Sedimentary rock fragments
- CF=Calcitized feldspar
- PC=Poikilitic calcite
- To=Tourmaline overgrowths

	Grain size				Constituents							Diagenesis				Cements						
Depth	S	Fi	M	C	Q	K	P	RF	GL	PY	MI	LI	Fr	Al	Co	Or	Qo	CL	CA	DO	SI	Rock name	Miscellaneous
8,030	X	X			X	X	X		X		X		X		X				XX			FQA-SA	F, Ls
8,210	X	X			X	X			X	X									XX			FQA	F, Ls, PC
8,250	X	X		X	X	X	t		XX	t			X						XX			SA	F, Ls
8,290	X		X	X	X	X		X	X		X				X			X	XX			FQA-SA	F, Ls, SRF
8,390		X	X		X	X					X		X		t				XX			SA	F, Ls, PC
8,420	X		X		X	X			X	X	X		X			X	t	X	X			FQA	F, Ls, PC
8,480	X	X			X	X		X	X	t	X			?		X			XX			SA-A	SRF, PC
8,510	X	X			X	X			X	X					X		t	t	X			SA	PC
8,570	X		X		X	X				t	t								XX			FQA-SA	Ls
8,700	X	X			X	X				X			X					X	X	X		QA-SA	Chl-Sc
8,780	X	X			X	X		X		X							t	X	X			FQA-SA	F, Ls, SRF
8,870	X				X	t			X	X	X	X			X			X	X	?		QA	F, Ls
8,980	X				X	X					X				X			X	X	X	?	FQA	F, Ls
9,080	X				X	X			t	X					X	X		?	X			SA-Mst	F
9,170		X	X		X	X		X	t	X			X					?	XX			SA-A	F, Ls, MRF
9,260	X	X	X		X	X			X	XX			X						XX			SA-A	F, Ls
9,380	X	X			X	X		X		X			X		X			X	X		X	SA	F, PC, MRF SRF
9,410	X	X			X	X	t	X		X	X		X					X	XX	?	X	SA	SRF, MRF, PC
9,510	X	X			X	X	t	X	X	t	X				X	X	t	X				FQA	
9,620	X	X			X	X	t	X	t	X		t			X			X	X			SA-A	PC, Ls, SRF
9,710	X	X			X	X	t		t	t		X	X		X			X	X			SA	F, Ls
9,740		X	X		X	X			X	X	X				X				XX			SA	F, Ls
9,860	X	X			X	X	X			X	X				X				XX			SA-A	F
9,950	X	X	X		X	X		X		X	X		X		X	X		X	XX			FQA-SA	F, Ls, Ser, MRF
10,010	X	X			X	X	t	X		t	X		X		X	X		X	XX			SA-A	Ls, Sc, PC, SRF
10,070	X	X		X	X	X			X	X	X	X				X						QA-SA	Ls, F
10,140	X				X	X					X	X			X		t	X	X		?	SA-Mst	Ls
10,330	X				X	X	?			X	X				X			X	X		X	SA-QA	
10,420	X				X	X				X	X	X			X							SA-Mst	
11,320	X	X			X	X				X	X	X	X					X	X			SA-Mst	F
11,530	X	X			X	X				X	X		X					t	XX			SA-QA	
11,620		X	X		X	X		t					X					t	X	t	t	A-SA	PC, F, Oo
11,740		X	X		X	X	t				X							X	X			SA	
11,830	X	X			X	X				X	X						X	X	X			FQA	
11,920	X	X			X	X					X				X		t	X	X			SA	
12,000	X	X			X	X		X		X	X				X			X	XX			A-SA	Oo, F, Ls SRF
12,130		X			X	X					X		X		X			t				SA	PC, SRF
12,250	X	X			X	X		X		X	X				X	X	X	X				SA-QA	SRF
12,340	X	X			X	X		X		X			X		X			t	X			QA-SA	F, PC, SRF
12,600	X	X			X	t		X			X	X		X	X		t	X	X		t	QA	SRF, Sc
12,740		X			X	X				X	X		X						X			SA-A	PC, Oo, F
12,830		X	X		X	X	t	X		X				t				t	XX		X	SA-QA	PC, SRF, CF
12,980		X			X	X	X	X			X	X		t	X		t		X			QA-SA	SRF, MRF, Ls
13,100	X	X	X		X	X	t	X		t	X				X		X		X	?	X	SA-QA	SRF, Ls
13,220		X	X		X	X	X			t				t	X		X	X	X			SA	
13,370	X	X			X	X	X	t		X	X			X	X			X				A-SA	SRF, Sc
13,570	X	X			X	X	X				X			X	X		t	XX			X	SA	Sc
13,660		X	X		X	X	t	X		X	X			X			X	X	t			FQA-SA	SRF, Sc
13,810		X	X		X	X	X	X			X			X	X		X	X	t			A-SA	Sc
13,910		X	X		X	X	X	X		X		X	X		X		X	X				SA-A	SRF
14,050		X	X	X	X	X	X	X		X				X			X	X	t			SA-A	SRF
14,140		X	X		X	X	X	t			X	X		X	X		X	XX	X			A-SA	CF, SRF
14,210			X	X	X	X	X	X			X	X		X			X	X	X			A-QA	
14,270			X	X	X	X	X				X	X		X			t	X	XX			SA	PC, CF
14,300		X	X	X	X	X	X			X				X			X	X	t			SA-A	
14,420	X	X	X		X	X					X			t			X	X	X			QA-SA	MRF+SRF
14,570		X	X		X	X	t				X	X	X			X	X	XX				SA	

TABLE 7.—*Petrography of sandstone from the COST No. B–2 well*—Continued

Depth	Grain size				Constituents								Diagenesis			Cements					Rock name	Miscellaneous
	S	Fi	M	C	Q	K	P	RF	GL	PY	MI	LI	Fr	Al	Co	Or	Qo	CL	CA	DO	SI		
14,750			X		X	X	X	t						X				X	X			QA-SA	SRF, CF
14,810		X	X		X	X	X	t		X	X	X		X	X		t	X	X			QA-SA	
14,870	X		X		X	X	t	t			X						t	X	X			QA	CF
14,930		X	X		X	X	X	X			X	X		X			X	X	X	X		QA-SA	SRF
14,990	X		X		X	t		X		X	X				XX			X	X			QA	SRF
15,140		X			X	X	X	X				X		t				X	X			SA	PC
15,260			X		X		X				X			XX			X	X	X			SA	To
15,380			X	X	X	X	X							X	X		X	X				SA	
15,470			X	X	X	X	X							X	X		X	X	X			QA-SA	
15,530		X	X		X	X	X	X						X	X		X	X				QA	SRF
15,650	X	X			X	X	X	X				X		t			X	X	t			SA	
15,740	X		X		X		X		X								X		X	?		QA	CF
15,800		X			X	X	X	X			X				X		?	X				FQA	SRF
15,950			X	X	X	X	X							X			X		X			QA	
16,040				X	X	X	X							X				X		?		QA-SA	

In the depth interval examined, compaction effects are significant. Crushing of relatively soft grains (such as glauconite or mica), reorientation of elongate grains, and shattering or twinning of brittle minerals are commonly noted. Grain interpenetration through pressure-solution embayment was less commonly found. Thus, mechanical compaction resulting from increased subsurface lithostatic pressures has played an important role in porosity loss.

Perhaps even more important, however, are the chemical effects of mineral alteration and cement precipitation. Starting at 12,600 feet or earlier, alteration of feldspar (both potassium feldspar and plagioclase) becomes progressively more important as burial depth increases. This alteration takes the form of sericitization, kaolinization, vacuolization, or calcite replacement and varies from one unit to the next. However, the general increase in feldspar alteration with depth can be correlated with the increasing importance of authigenic clay minerals and quartz overgrowths as cementing agents. In many of the samples from 13,000 feet downward, kaolinite, illite, sericite, or authigenic silica produce almost complete obliteration of primary porosity.

Calcite is also extremely important as a cementing agent. In the depth range from 8,000 to 13,000 feet, calcite is clearly the major cement. Below 13,000 feet it remains important but begins to be overshadowed by clay and silica cement. The abundance of calcareous fossils, limestone, and limestone clasts in the parts of the section containing the greatest amounts of calcite cement indicates that at least some of the cement may be derived by in situ dissolution of calcareous material and reprecipitation as cement. The common poikilitic textures of the calcite cement indicate that the presence of carbonate skeletal or rock fragments is a factor in the nucleation of calcite cement.

Other calcareous cement, including dolomite, ankerite, and siderite, is occasionally observed but is rarely of major importance. The only zones containing significant siderite cement are at 9,300–9,500 feet, 10,330 feet, and between 12,800 and 13,600 feet.

CONCLUSIONS

The predominance of arkosic sediments throughout the section coupled with their burial-related decomposition leads to significant porosity loss in the deeper part of the section in the COST No. B–2 well. In addition, zones containing significant marine fossils, limestone, or associated calcareous shale have the greatest amounts of carbonate cement. Prospects for improved porosity at equivalent or greater depths at other sites are relatively unfavorable unless a significantly less arkosic section is found or unless some other factor such as geopressuring or oil saturation has retarded the breakdown of feldspar.

Foraminiferal Biostratigraphy

By C. W. Poag

Upper Tertiary sediments in the COST No. B–2 well were deposited in shallow marine or nearshore subaerial environments. During the early Tertiary, however, especially during the Eocene, carbonate rocks were deposited at Continental Slope water depths. Most of the Upper Cretaceous strata are fully marine, containing diagnostic planktonic and benthic fossils that indicate shelf conditions of deposition. In contrast, during the Early Cretaceous, many of the beds accumulated under subaerial conditions, as shown by the lack of marine fossils and the abundance of terrestrial palynomorphs. The age of the oldest strata penetrated was not established in this foraminiferal study.

The following discussion of foraminifers is based on preliminary analyses of samples from rotary cuttings taken at widely spaced intervals, ranging from 100 to 500 feet. The conclusions are tentative and are subject to revision upon further detailed study.

PLEISTOCENE

The youngest sample examined came from 610 feet and contained an abundant benthic fauna of Pleistocene species, most of which have living representatives off New Jersey today. Diagnostic forms include *Elphidium orbiculare, E. clavatum, Cibicidoides lobatulus, Epistominella vitrea, Nonionella atlantica,* and *Bulimina aculeata.* Similar assemblages are present to 790 feet and contain scattered occurrences of reworked Eocene species.

PLIOCENE

At 880 feet, the first significant change in species composition occurs. Particularly diagnostic is *Buliminella gracilis*, which is abundant in the Miocene and extends in fewer numbers into the Pliocene. Its sparsity and its association with a meager planktonic fauna of *Globigerina bulloides* and *Globigerinoides trilobus* appear to indicate a Pliocene age for this sample.

MIOCENE

The first examined sample containing significant numbers of typical Miocene species was at 1,090 feet. *Buliminella gracilis* is abundant and is accompanied by *Lenticulina spinosa, Florilus pizzarensis*, and abundant specimens of *Uvigerina* sp. and *Cibicidoides* sp. No diagnostic planktonic species are present. From 1,090 feet to 1,480 feet, similar but sparser faunas dominated by *B. gracilis* are present.

At 1,510 feet is the first indication of middle Miocene age. *Turborotalia siakensis*, which becomes extinct in Zone N. 14 (Blow, 1969), is rare in this sample. *Buliminella gracilis* is still the predominant taxon. The Miocene section above 1,510 feet, therefore, is placed in the upper Miocene.

Similar shallow-water faunas dominated by *B. gracilis*, which is often the only taxon present, are present throughout the interval between 1,510 feet and 2,710 feet. *Turborotalia siakensis* occurs sparsely in scattered samples throughout this interval. At 2,710 feet, the foraminiferal association is the same, but diatoms begin to appear in significant numbers. At 2,800 feet, among an abundance of diatoms, *T. peripheroacuta* appears, indicating a middle Miocene age, no younger than Zone N. 12 and no older than N. 10. At 2,890 feet, diatoms are still abundant, along with *B. gracilis.* Occasional specimens of *T. siakensis* and *T. peripheroacuta* are found and radiolarians are present occasionally.

The next major faunal change takes place at 3,880 feet, where *B. gracilis* is no longer predominant, and where *Globigerinita ciperoensis* and *Turborotalia continuosa* indicate an early Miocene age, no younger than Zone N. 6.

EOCENE

At 4,200 feet, the first rich late Eocene fauna is found. Typical planktonic species include *Turborotalia cocoaensis, T. cerroazulensis, T. pomeroli, T. ampliaperatura, Globigerinatheka index, Hantkenina alabamensis,* and *Pseudohastigerina micra.* The rich benthic fauna includes *Bulimina jacksonensis, Sigmoidella plummerae, Anomalina alazanensis,* and *Lenticulina subpapillosa.* This assemblage is no younger than Zone P. 17 (Blow, 1969).

Middle Eocene species are present in the sample at 4,500 feet. Diagnostic forms include *Acarinina densa, Truncorotaloides topilensis, Morozovella aragonensis,* and *Acarinina pentacamerata.* These forms represent Zones P. 11 to P. 8.

The sample at 4,800 feet is of early Eocene age, containing *Planorotalites chapmani, Pseudohastigerina wilcoxensis, Subbotina frontosa,* and *S. inaequispira.*

PALEOCENE

At 5,110 feet, the presence of *Acarinina uncinata, A. soldadoensis, Morozovella velascoensis, M. kolchidica,* and *M. aequa* suggests a late Paleocene age, probably Zone P. 5. A few reworked Cretaceous species also begin to appear.

An unusual association of shallow-water agglutinated foraminifers, abundant plant fragments, and gypsum crystals at 5,300 feet cannot be dated by means of foraminifers; it suggests restricted environmental conditions that might exist in a lagoon or estuary.

CRETACEOUS

The first sample examined containing abundant Late Cretaceous species came from 5,600 feet. Diagnostic forms include *Globotruncana fornicata, G. elevata, G. arca, Rugoglobigerina rugosa, Cibicidoides micheliniana, Planulina texana, Kyphopyxa christneri, Lenticulina pondi,* and *Pseudogaudryinella capitosa.* This assemblage appears to be of Campanian or Early Maestrichtian Age. At 5,900 feet, the first *Bolivinoides* was observed, appearing to be *B. miliaris,* a late Campanian and early Maestrichtian species.

From 5,900 feet to 7,100 feet, the faunas appear to be largely cavings from younger Tertiary beds. Few, if any, indigenous Cretaceous species are present. At 7,100 feet, however, the presence of *Globotruncana helvetica,* and *G. imbricata* indicates sediments of Turonian Age. *G. helvetica* is still abundant at 7,400 feet.

At 7,700 feet, Cenomanian species are present. They include *Rotalipora cushmani, Praeglobotruncana stephani,* and *P.* cf. *turbinata.*

The Lower Cretaceous strata (Albian) begin at approximately 8,200 feet, marked by *Favusella washitensis.*

Below this point, the foraminiferal faunas are sparse and appear to be primarily composed of cavings from the younger beds. Few, if any, indigenous specimens occur.

PALEOECOLOGY

During the Early Cretaceous, the B–2 area apparently was a coastal region in which primarily continental deposits accumulated, as shown by the sparsity of marine fossils and the abundance of terrestrial plant remains, coal beds, and nonmarine sand and clay. At some time during the Albian, however, a shallow marine sea occupied the B–2 site, and deposited marine microfossils and nannofossils. The generally shallow marine environment persisted throughout most of the Late Cretaceous. The notable exceptions are represented by the sediments from approximately 7,100 feet to 6,200 feet, in which no marine fossils are present, and the sample at 5,300 feet, which may have accumulated in estuarine conditions.

During the Paleocene, shallow shelf conditions again were predominant. During the Eocene, however, the water depth increased to the equivalent of that on today's Continental Slope; the richest faunal remains in the B–2 well accumulated during this period.

During the Miocene and Pliocene, the environment fluctuated frequently from inner- to outer-shelf depths, and occasionally subaerial erosion took place marked by oxidation and abrasion of fossil remains. The rich diatom floras of the middle Miocene reflect a specialized environment of high nutrient content, brought about, perhaps, by cool waters upwelling along the shelf edge. The Late Miocene faunas are of very low diversity and are found amidst sandy beds in what appear to have been prograding deltas. The Pleistocene was a time when coarse glacial sand and gravel accumulated in shallow marine waters and in terrestrial coastal-plain environments. No obvious cyclicity of glacial-interglacial sequences was noted during the preliminary analysis.

Nannofossil Biostratigraphy

By P. C. Valentine

This preliminary study is based on an analysis of samples from rotary cuttings spaced at 100-foot and 300-foot intervals. Discrete rock fragments representing each of the major lithologic units present in a single sample were selected and processed. The oldest assemblage identified in a sample was considered to indicate the age of the strata at that level. As many as five subsamples were studied from a single 10- to 30-foot-interval sample. Settling techniques were used to concentrate the sample for study of the calcareous nannofossils. Zonal data are summarized in table 8.

PLEISTOCENE THROUGH MIOCENE (≅700 FEET TO ≅3,730 FEET)

Strata of Pleistocene through Miocene age are present to a depth of approximately 3,800 feet. The highest sample available for study was from 700 to 730 feet, in which calcareous nannofossils are rare and tentatively indicate a Pleistocene age. Samples from 790 feet through 3,520 feet are essentially barren. Diatoms, however, are particularly abundant from 2,890 feet through 3,520 feet; this interval has been dated as middle Miocene on the basis of a study of the foraminifers. Recent studies have shown that this sequence of mainly shallow-water terrigenous clastic sediment is characteristic of this age interval elsewhere on the Continental Shelf north of Cape Hatteras.

Calcareous sediments of early Miocene age are found from 3,580 feet to 3,730 feet. Two samples (3,580–3,610 feet and 3,700–3,730 feet) were investigated from this interval and found to contain the following assemblage, which is representative of the upper part of the *Triquetrorhabdulus carinatus* Zone of Bukry (1973, 1975): *Coccolithus eopelagicus, C. pelagicus, Coronocyclus nitescens, Cyclicargolithus abisectus, C. floridanus* (abundant), *Discoaster adamanteus, D. deflandrei, D. druggi, D. saundersi* (common), *D. variabilis, Discolithina spp., Helicosphaera euphratis, H. intermedia, H. recta, Reticulofenestra* cf. *R. scissurus* of Bramlette and Wilcoxon (1967), *Sphenolithus capricornutus, S. dissimilis, S. moriformis,* and *Triquetrorhabdulus carinatus.*

OLIGOCENE (≅3,790 FEET TO ≅4,050 FEET)

Calcareous strata of late Oligocene age are found in the interval bounded by samples from 3,790 to 3,820 feet and 4,030 to 4,050 feet. These sediments contain the following assemblage, characteristic of the *Sphenolithus ciperoensis* Zone of Bukry (1973, 1975): *Chiasmolithus altus, Coccolithus eopelagicus, C. pelagicus, Cyclicargolithus abisectus* (abundant), *C. floridanus* (abundant), *Dictyococcites bisectus, Discoaster deflandrei, D. rufus, D. saundersi, Discolithina* spp., *Helicosphaera bramlettei, H. euphratis, H. intermedia, H. wilcoxoni, Reticulofenestra* cf. *R. scissurus* of Bramlette and Wilcoxon (1967), *Sphenolithus dissimilis, S. moriformis, S. ciperoensis,* and *Zygrhablithus bijugatus.*

OLIGOCENE THROUGH EOCENE (≅4,080 FEET TO ≅4,320 FEET)

Calcareous strata of earliest Oligocene to latest Eocene age are present in the interval bounded by samples from 4,080 to 4,110 feet and 4,290 to 4,320 feet. These sediments contain the following assemblage, indicative of the *Coccolithus subdistichus* and *Isthmolithus recurvus* Subzones of Bukry (1973, 1975): *Chiasmolithus oamaruensis, Coccolithus eopelagicus, C. pelagicus, C. sarsiae of Bybell* (1975), *C. subdistichus* (common), *Cyclicargolithus floridanus, Cyclococcolithina formosa, C. kingii, Dictyococcites bisectus, D. scrippsae, Discoli-*

Age	Boundary (m.y.)	Calcareous Nannofossil zone	Calcareous Nannofossil subzone	COST No. B-2 well (depth in feet)
Quaternary	0.2	*Emiliania huxleyi*		
	0.3	*Gephyrocapsa oceanica*	*Ceratolithus cristatus*	
	0.9		*Emiliania ovata*	
	1.6	*Crenalithus doronicoides*	*Gephyrocapsa caribbeanica*	
	1.8		*Emiliania annula*	
Pliocene	2.0	*Discoaster brouweri*	*Cyclococcolithina macintyrei*	
	2.1		*Discoaster pentaradiatus*	
	2.5		*Discoaster surculus*	
	3.0		*Discoaster tamalis*	
	3.5	*Reticulofenestra pseudoumbilica*	*Discoaster asymmetricus*	
	4.0		*Sphenolithus neoabies*	
	4.4	*Ceratolithus tricorniculatus*	*Ceratolithus rugosus*	
	5.0		*Ceratolithus acutus*	
Miocene	5.6		*Triquetrorhabdulus rugosus*	
	6.6	*Discoaster quinqueramus*	*Ceratolithus primus*	
	7.0		*Discoaster berggrenii*	
	7.5	*Discoaster neohamatus*	*Discoaster neorectus*	
	11.0		*Discoaster bellus*	
	12.0	*Discoaster hamatus*	*Catinaster calyculus*	
	13.0		*Helicopontosphaera kamptneri*	
	13.2	*Catinaster coalitus*		
	13.4	*Discoaster exilis*	*Discoaster kugleri*	
	14.0		*Coccolithus miopelagicus*	
	15.0	*Sphenolithus heteromorphus*		
	17.0	*Helicopontosphaera ampliaperta*		
	18.0	*Sphenolithus belemnos*		
	21.0	*Triquetrorhabdulus carinatus*	*Discoaster drugii*	3580-3730
	23.0		*Discoaster deflandrei*	3580-3730
Oligocene	24.0		*Cyclicargolithus abisectus*	
	25.0	*Sphenolithus ciperoensis*	*Dictyococcites bisectus*	3790-4050
	26.5		*Cyclicargolithus floridanus*	3790-4050
	30.0	*Sphenolithus distentus*		
	34.0	*Sphenolithus predistentus*		
	34.5	*Helicopontosphaera reticulata*	*Reticulofenestra hillae*	
	37.0		*Coccolithus formosus*	
	38.0		*Coccolithus subdistichus*	4080-4320
Eocene	41.0	*Discoaster barbadiensis*	*Isthmolithus recurvus*	
	42.0		*Chiasmolithus oamaruensis*	
	44.0	*Reticulofenestra umbilica*	*Discoaster saipanensis*	4500-4620
	45.0		*Discoaster bifax*	4500-4620
	46.5	*Nannotetrina quadrata*	*Coccolithus staurion*	
	47.0		*Chiasmolithus gigas*	
	48.0		*Discoaster strictus*	
	49.0	*Discoaster sublodoensis*	*Rhabdosphaera inflata*	
	49.5		*Discoasteroides kuepperi*	4900-4910
	50.0	*Discoaster lodoensis*		
	52.0	*Tribrachiatus orthostylus*		
	52.8	*Discoaster diastypus*	*Discoaster binodosus*	5000-5020
	53.5		*Tribrachiatus contortus*	5000-5020
Paleocene	54.0	*Discoaster multiradiatus*	*Campylosphaera eodela*	5000-5020
	55.0		*Chiasmolithus bidens*	5000-5020
	55.5	*Discoaster nobilis*		
	57.0	*Discoaster mohleri*		
	58.0	*Heliolithus kleinpellii*		
	60.0	*Fasciculithus tympaniformis*		
	63.0	*Cruciplacolithus tenuis*		

Age	(m.y.)	Age	COST No. B-2 well (depth in feet)
Cretaceous	71	Maestrichtian	
	80	Campanian	5110-6010
	82	Santonian	
	86	Coniacian	
	91	Turonian	7300-7610
	95	Cenomanian	7900-8210
	106	Albian	8500-8810

◄TABLE 8.—*Preliminary age determinations of COST No. B-2 samples on the basis of calcareous nannofossils*

[Samples below 8,810 feet were barren. Depths are in feet below Kelly Bushing. Calcareous nannofossil zones and subzones and estimated time relations are taken from Bukry (1975, fig. 3 and table 2). Black bars indicate range of determinations for given sample depths.]

thina spp., *Helicosphaera compacta, Isthmolithus recurvus, Lanternithus minutus, Neococcolithes dubius, Reticulofenestra hillae, R. reticulata, R.* cf. *R. scissurus* of Bramlette and Wilcoxon (1967), *R. umbilica, Transversopontis obliquipons,* and *T. zigzag.*

EOCENE (≅4,500 FEET TO ≅4,910 FEET)

Two samples (from 4,500 to 4,530 ft and 4,590 to 4,620 ft) contain calcareous sediments of middle to late Eocene age. The assemblage identified in these samples is characteristic of the *Reticulofenestra umbilica* Zone of Bukry (1973, 1975): *Chiasmolithus grandis, C. solitus, C. titus, Coccolithus eopelagicus, C. pelagicus, Cyclicargolithus floridanus, Cyclococcolithina formosa, Discoaster barbadiensis, Helicosphaera lophota, H. seminulum, Neococcolithes dubius, Reticulofenestra hillae, R. reticulata, R. samodurovi, R. umbilica, Sphenolithus moriformis,* and *Zygrhablithus bijugatus.*

The sample from 4,900 to 4,910 feet, also calcareous, yielded an assemblage of early to middle Eocene age; it is placed in the *Discoaster lodensis* Zone and *Discoasteroides kuepperi* Subzone of Bukry (1973, 1975): *Blackites creber, Campylosphaera dela, Chiasmolithus grandis, Coccolithus crassus* (abundant), *C. pelagicus, Cyclococcolithina kingii, Discoaster lodoensis, D. binodosus, Discoasteroides kuepperi, Helicosphaera seminulum, Lophodolithus mochlophorus, L. nascens, Markalius inversus, Marthasterites tribrachiatus, Neococcolithes dubius, N. protenus, Prinsius bisulcus, Sphenolithus radians, Transversopontis obliquipons,* and *T. pulcher.*

EOCENE THROUGH PALEOCENE (≅5,000 FEET TO ≅5,020 FEET)

The interval bounded by the samples from 5,000–5,010 feet and from 5,010–5,020 feet is composed of calcareous sediments of earliest Eocene to latest Paleocene age. On the basis of the following assemblage, these strata are placed in the *Discoaster multiradiatus* and *Discoaster diastypus* Zones of Bukry (1973, 1975): *Campylosphaera dela, Cepekiella lumina, Chiasmolithus solitus, Coccolithus jugatus* of Proto Decima and others (1975), *C. pelagicus, C. petrinus, Cyclococcolithina formosa, C. gammation, Discoaster barbadiensis, D. binodosus, D. distinctus, D. elegans, D. lenticularis, D. multiradiatus, Discoasteroides kuepperi, Ellipsolithus distichus, Fasciculithus involutus, Helicosphaera lophota, H. seminulum, Markalius inversus, Neococcolithes dubius, Transversopontis fimbriatus, T. obliquipons, T. pulcher,* and *Zygrhablithus bijugatus.*

The Eocene section in the COST No. B-2 well, is considered to be 1,000 feet or more thick. Future, more detailed investigations may reveal the existence of a fairly complete record of the Eocene in this well.

CRETACEOUS (FROM ≅5,110 FEET)

The Tertiary-Upper Cretaceous boundary is at approximately 5,110 feet in this well. In contrast to the carbonate rocks of the Paleogene sequence, the sample from 5,110 to 5,140 feet is composed of terrigenous clastic sediments containing rare but well-preserved calcareous nannofossils of Campanian Age. Other fossiliferous strata from the Cretaceous in this well are appreciably more calcareous. In general, however, these older rocks have a terrigenous aspect, and much of the section is of nonmarine origin.

The interval from 5,390 feet to 6,010 feet (samples from 5,390–5,400 feet, 5,510–5,520 feet, 5,800–5,810 feet, and 6,000–6,010 feet) contains the following assemblage, considered to represent the Campanian (*Broinsonia parca*, a Campanian and early Maestrichtian marker, was observed in samples from 5,800 to 5,810 feet and 6,000 to 6,010 feet.): *Ahmuellerella octoradiata, Arkhangelskiella cymbiformis, Biscutum blackii, Braarudosphaera bigelowii, Broinsonia parca, Chiastozygus amphipons, C. plicatus, Corollithion achylosum, C. signum, Cretarhabdus conicus, C. crenulatus, Cribrosphaerella ehrenbergii, Eiffellithus eximius, E. turriseiffeli, Gartnerago costatum, Kamptnerius magnificus, K. percivalii, K. punctatus, Lucianorhabdus cayeuxii, Manivitella pemmatoidea, Microrhabdulus decoratus, Micula staurophora, Parhabdolithus embergeri, Percivalia porosa, Podorhabdus orbiculofenestrus, Predis-*

cosphaera cretacea, P. spinosa, Tetralithus obscurus, Vagalapilla elliptica, V. imbricata, V. matalosa, Watznaueria barnesae, Zygodiscus acanthus, Z. compactus, and *Z. diplogrammus.*

The beds from 6,010 feet to 7,300 feet were examined at 300-foot intervals and were found to be barren of calcareous nannofossils.

Strata thought to be of Turonian Age are present in the interval between 7,300 feet and 7,610 feet (samples from 7,300–7,310 feet and 7,600–7,610 feet). *Kamptnerius magnificus, Lucianorhabdus cayeuxi,* and *Microrhabdulus decoratus* are not recorded from below 6,010 feet. *Eiffellithus eximius, Gartnerago costatum,* and *Micula staurophora* are not formed below the sample from 7,300 to 7,310 feet, and *Ahmuellerella octoradiata* and *Gartnerago segmentatum* are not found below the sample from 7,600 to 7,610 feet. The following assemblage was identified in this interval: *Ahmuellerella octoradiata, Arkhangelskiella cymbiformis, Braarudosphaera bigelowii, Chiastozygus amphipons, C. plicatus, Corollithion signum, Cretarhabdus conicus, C. crenulatus, Cribrosphaerella ehrenbergii, Eiffellithus eximus, E. turriseiffeli, Gartnerago costatum, G. segmentatum, Lithastrinus floralis, Manivitella pemmatoidea, Micula staurophora, Prediscosphaera cretacea, Tetralithus obscurus, Vagalapilla elliptica, Watznaueria barnesae, Zygodiscus acanthus, Z. compactus, Z. diplogrammus.*

Sediments from the interval bounded by samples from 7,900 to 7,910 feet and 8,200 to 8,210 feet contain a calcareous nannofossil assemblage characterized by long-ranging species. Many species that evolved during the Turonian and were recorded in higher samples from the COST No. B–2 well are absent. The presence of *Prediscosphaera cretacea* indicates that these sediments are no older than Albian, and they are tentatively assigned an age of Cenomanian and Albian: *Biscutum blackii, Chiastozygus amphipons, C. plicatus, Corollithion achylosum, C. signum, Cretarhabdus conicus, C. crenulatus, Eiffellithus turriseiffeli, Lithastrinus floralis, Manivitella pemmatoidea, Parhabdolithus angustus, P. asper, P. embergeri, Podorhabdus orbiculofenestrus, Prediscosphaera cretacea, Watznaueria barnesae, Zygodiscus acanthus, Z. compactus,* and *Z. diplogrammus.*

Samples from 8,500 to 8,510 feet and 8,800 to 8,810 feet also contain many long-ranging species. *Prediscosphaera cretacea* is present, a species restricted to Albian and younger strata, and the occurrence in these two samples of *Rucinolithus irregularis,* a species recorded only from the Albian and Aptian, points to an Albian Age for the sediments of this interval: *Chiastozygus plicatus, Corollithion achylosum, C. signum, Cretarhabdus conicus, Eiffellithus turriseiffeli, Lithastrinus floralis, Manivitella pemmatoidea, Markalius circumradiatus, Parhabdolithus embergeri, Prediscosphaera cretacea, Rucinolithus irregularis, Vagalapilla matalosa, Watznaueria barnesae,* and *Zygodiscus diplogrammus.*

The strata from depths below 8,810 feet, examined at 300-foot intervals, were found to be barren of calcareous nannofossils.

Palynomorph Biostratigraphy

By R. A. Scott and E. I. Robbins

Brenner (1963), Wolfe and Pakiser (1971), Sirkin (1974), Robbins and others (1975), Wolfe (1976), and Doyle and Robbins (in press) have reviewed the development of a palynological zonation for the sequence of both exposed and subsurface Cretaceous beds along the Atlantic Coastal Plain from South Carolina to Rhode Island. These informal zonations have been established primarily for the Barremian and younger strata of the emerged Coastal Plain. The striking record of the entry and evolution of the angiospermous pollen in Cretaceous strata forms the basis for clarifying many stratigraphic relationships among beds that have been difficult to separate on lithologic grounds.

Some evidence about the composition of earlier Cretaceous (Neocomian) floras of the region is furnished by spore assemblages from lower depths, for example, below 5,401 feet in the E. G. Taylor well (Accomack County, Va.) and below 5,612 feet in the J. D. Bethards well (Worcester County, Md.) (see Doyle and Robbins, in press), as well as both spore and dinoflagellate assemblages of Hauterivian to Berriasian Age in DSDP hole 105 (Habib, 1976, and in press). Palynological evaluations at the Cretaceous–Jurassic boundary have been made elsewhere in North America (Pocock, 1962; Williams, 1974; Norris and others, 1975) and in Europe (Norris, 1970).

The purposes of this preliminary report are threefold: (1) to discuss the palynomorph biostratigraphy of sediments present in the COST No. B-2 well; (2) to determine whether the hole penetrated beds older than Cretaceous; and (3) to present a broad-based paleoecological framework. Fifty-four samples were selected at intervals of approximately 300 feet. At least a few palynomorphs were present in almost every sample, although the number of forms and their preservational quality varied greatly among the samples. Although the cuttings were washed carefully, there is evidence of at least slight contamination by rare dicotyledonous pollen grains in deep levels of the well.

RESULTS

Pollen from the interval from 5,200 to 5,230 feet is regarded as Eocene in age (Norman Fredericksen, oral commun., 1976). Furthermore, F. E. May (written commun., 1976) identified the following Tertiary dinoflagellates: *Deflandrea phosphoritica, Hystrichokolpoma rigaudae, Thalassiphora delicata, T. pelagica, Wetzeliella clathrata,* and *W. symmetrica.* The age of the sample would appear to be Eocene on the basis of the presence of the two species of *Wetzeliella.* However, the interval could range as low as early Maestrichtian on the basis of the presence of the triaperturate angiospermous pollen C3B–3 (Wolfe, 1976, pl. 3) and MPD–1 (Wolfe, 1976, pl. 4).

The interval from 5,410 to 5,830 feet contains pollen indicative of a Maestrichtian to Santonian Age, as shown by the following Normapolles genera: *Plicapollis* sp., *Praebasopollis* sp., and *Pseudoplicapollis* sp. On the basis of the presence of the dinoflagellate cysts *Paleohystrichophora infusorioides* and *Phoberocysta ceratioides*, a Campanian or Santonian Age is confirmed (F. E. May, written commun., 1976). F. E. May located the Tertiary-Cretaceous boundary, on the basis of dinoflagellates, at from 5,230 to 5,410 feet.

From 6,120 to 7,330 feet, Zone V (Santonian to Turonian?) pollen is recognized on the basis of the association of Group 13, Krutzsch (1957), *Pseudoplicapollis* sp. and *Triatriopollenites* sp.

Zone IV pollen, which is present from 7,620 to 7,630 feet (lower Turonian? to middle

Cenomanian), is recognized on the basis of the occurrence of *Complexiopollis, Tricolpites vulgaris*, and many unidentified tricolporates.

Zone III is identified in the interval from 7,920 to 7,930 feet on the basis of the association of *Straitopollis* sp. B of Doyle and Robbins (in press), *Tricolporoidites bohemicus,* and *"Tricolporopollenites" distinctus.* This zone has been dated as early Cenomanian.

From 8,220 to 8,840 feet, the association is suggestive of Subzone II C (upper Albian), as indicated by the association of *Rugubivesiculites rugosus, Granulatisporites dailyi*(?), *Lycopodiumsporites triangularus,* and *"Tricolporopollenites" distinctus.* The sample is too contaminated by Late Cretaceous and Miocene pollen to yield a confident correlation.

In the interval from 8,520 to 8,530 feet, the association of *Rugubivesiculites reductus, R. rugosus, Cicatricosisporites subrotundus,* and *Taurocusporites spackmani* with the angiosperm species *Clavatipollenites tenellis, "Peromonolites" peroreticulatus, Tricolporoidites subtilis,* and *"Tricolporopollenites" triangulus* suggests that the sample is late Albian in age (Subzone II C). This assemblage also includes dinoflagellates of this age.

The sample from 8,820 to 8,830 feet contains the following Subzone II B (upper to middle Albian) species of angiosperms: *Clavatipollenites tenellis,* aff. *"Foveotricolpites" concinnus,* cf. *Liliacidites* sp. D of Doyle and Robbins (in press), two unidentified species of *Liliacidites, "Retitricolpites" prosimilis, "R." vermimurus,* and *Tricolpites georgensis.*

Varying quantities of pollen and spores in the interval from 9,120 to 11,890 feet can be correlated with Zone I (lower Albian to Barremian). Important species include: *Cicatricosisporites aralica, C. dorogensis, Concavissimisporites variverrucatus, Gleicheniidites apilobatus, Klukisporites pseudoreticulatus, Parvisaccites amplus,* as well as the angiosperms *Clavatipollenites hugesii,* aff. *C. tenellis,* and *Retimoncolpites dividuus.*

Dinoflagellates occur intermittently in the interval from 9,120 to 11,890 feet; for example, at 11,560 to 11,590 feet, 11,260 to 11,290 feet, 10,020 to 10,030 feet, and 9,720 to 9,730 feet. Study of the dinoflagellate assemblages will undoubtedly provide a record of fluctuating marine incursions. F. E. May (written commun., 1976) believes that the dinoflagellates in the interval 11,260 to 11,290 feet are of Barremian Age.

The intervals between 12,160 to 16,030 feet contain a typical pre-Zone I assemblage (pre-Barremian). Some species identified from the interval include: *Parvisaccites* sp., *Podocarpidites potomacensis, Vitreisporites pallidus, Appendicisporites* sp., *Deltoidospora* sp., *Leptolepidites* sp., *Lycopodiacidites* sp., abundant *Pilosisporites trichopapillosus, Taurocusporites* sp., *Todisporites* sp., and *Trilobosporites* sp.

In the deepest sample, from 16,020 to 16,030 feet, the following taxa were recognized: *Alisporites* sp., *Podocarpidites* sp., *Classopollis* sp., *Ephedripites multicostatus, Eucommiidites troedssonii, Cicatricosisporites* sp., and *Concavissimisporites* sp.

Although the presence of *Appendicisporites* sp. suggests an Early Cretaceous age for these basal samples, the occurrence of *Ephedripites multicostatus* in the basal sample allows a correlation with the *Ephedripites multicostatus* Zone (Hauterivian to Berriasian) of Habib (1976, and in press) from DSDP hole 105.

The presence of megaspores in several samples, including the lowest one (16,020-16,030 feet), reinforces an Early Cretaceous age for the base. The megaspores have been examined by R. H. Tschudy (oral commun., 1976), who found no taxa that have been recognized in North America below the upper Lower Cretaceous; little information is available from lower Lower Cretaceous beds. None of the megaspores described from the Upper Jurassic of Greenland (Harris, 1935) or of England (Murray, 1939) was present among forms found in this well.

Thus, there appears to be only a slight possibility, implicit in the incompleteness of the dating of assemblages from elsewhere in North America and northern Europe, that Jurassic beds are present in the COST No. B–2 well.

PALEOECOLOGY

Study of the palynomorphs, as well as plant fragments, algae and fungi, the type of sapropel, and the presence of pyrite crystals in samples prepared for sapropel studies (see section "Color Alteration of Visible Organic Matter") has also yielded paleoenvironmental information, indicating the following environmental conditions: 610 to 3,790 feet, alternating nearshore marine, brackish, and nonmarine; 3,790 to 4,880 feet, open-marine;

4,880 to 6,430 feet, nearshore; 6,430 to 8,530 feet, alternating nonmarine and marine. In the interval from 8,530 to 11,290 feet, the organic matter is largely nonmarine and primarily oxidized or degraded by bacteria. From 13,330 feet to the bottom of the well, the organic matter is largely terrestrially derived.

CONCLUSIONS

In summary, palynomorphs were obtained from most of the cuttings studied between 1,030 and 16,030 feet from the COST No. B–2 well. The Tertiary-Cretaceous boundary, determined on the basis of dinoflagellates, is found between 5,230 and 5,410 feet. Late Cretaceous dicotyledonous pollen, equivalent to Zones V, IV, and III in the Atlantic Coastal Plain informal pollen zonation, is present between 5,410 and 7,930 feet in the COST No. B–2 well. An Early Cretaceous spore assemblage equivalent to Subzones II C, II B, Zone I, as well as the *Ephedripites multicostatus* Zone of Habib (1976, and in press) extends to the lowest level sampled, 16,020 to 16,030 feet. Early Cretaceous megaspores are present in the lowest samples, including the lowest one examined. Evidence at hand indicates that the COST No. B–2 well bottoms in Lower Cretaceous beds and thus penetrates at least 9,000 feet of Cretaceous sediments. However, the possibility that some Upper Jurassic is present in the basal samples cannot be excluded.

Geothermal Gradients

By E. I. Robbins

Present-day subsurface temperatures can be used to give an approximate idea of the depth range of maximum hydrocarbon generation (liquid petroleum window) in a basin. This can be particularly useful when other studies are performed to determine whether the modern temperatures are the highest to which the section has been subjected.

For the COST No. B–2 well, 29 geothermal values have been plotted (fig. 9) using approximate equilibrium temperatures calculated from the five available temperature logs. A linear regression was computed using these points; it shows a systematic increase in temperature with depth (correlation coefficient=0.98). The geothermal gradient is calculated to be 1.3°F/100 ft with a surface intercept of 75.7°F. A geothermal gradient of 1.3°F/100 ft is rather typical for basins around the North Atlantic Ocean (table 9). An alternative method of calculating geothermal gradients, by using the present-day mean annual surface temperature (52°F) and the bottom-hole temperature, yields a thermal gradient of 1.5°F/100 ft (Smith and others, 1976).

The liquid petroleum window is based largely on empirical observation and generally is considered to have a lower limit of about 150°F and an upper limit of 270° to 300°F (Pusey, 1973; Harrison, 1976). The upper temperature limit may be significantly higher if heating times are short. Using the present geothermal gradient, the liquid petroleum window (fig. 9) would be expected to occur between 5,700 and 17,000 feet, provided these temperatures are maintained over a significant period of time. Work on vitrinite reflectance, visual analysis of color alteration of organic matter, and organic geochemistry all suggest that similar or slightly lower geothermal gradients may have prevailed in the past. However, most reconstructions of the geologic history of the area (Bott, 1971; Sleep, 1971, Falvey, 1974) would predict considerably higher geothermal gradients in the past, particularly during Triassic and Jurassic rifting events. Thus, some conflict remains between the direct thermal analyses of the COST No. B–2 well sediments and both present and inferred past geothermal history. Certainly, the thick sedimentary section that underlies the rocks penetrated by the COST No. B–2 well may have been influenced by higher geothermal gradients.

TABLE 9.—*Circum-Atlantic offshore geothermal gradients*

Basin	Gradient (°F/100 ft)	Reference
Scotian Shelf basin	1.2	Robbins and Rhodehamel, 1976.
Southern North Sea	1.7	Harper, 1971.
Baltimore Canyon basin	1.3	This paper.
Niger Delta shelf	1.4	Nwachukwu, 1976.
South Pass, La.	1.2	Pusey, 1973.
Offshore Louisiana	1.3	Jam and others, 1969.

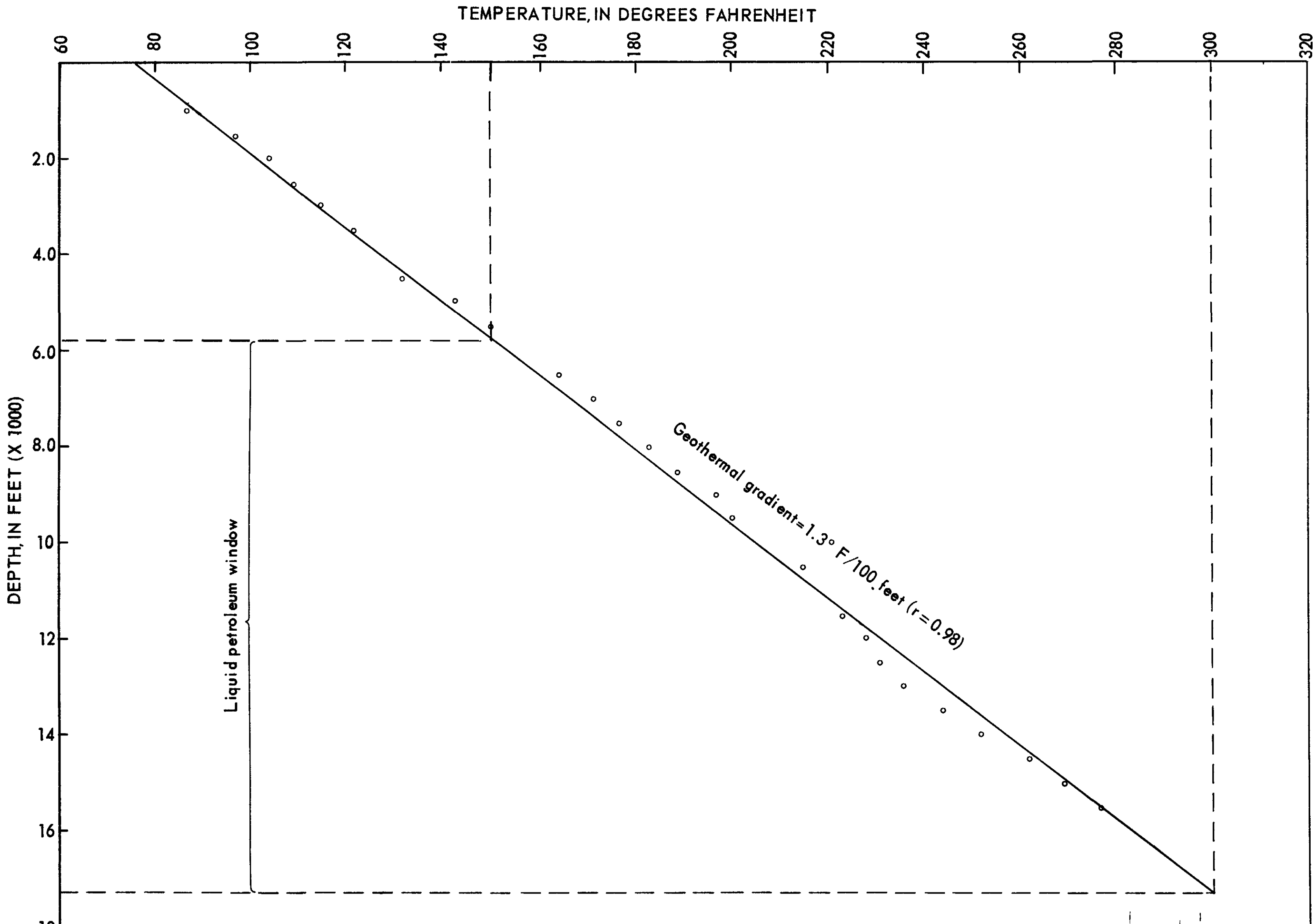


FIGURE 9.—Geothermal gradient for COST No. B-2 well. Data points are resting temperatures derived from five available temperature logs.

Organic Geochemistry

By G. E. Claypool, C. M. Lubeck, J. P. Baysinger, and T. G. Ging

Thirty-four samples of unwashed cuttings have been analyzed by combustion and thermal analysis/pyrolysis-FID techniques to evaluate petroleum source-rock potential. In addition, six of the samples were analyzed for light hydrocarbon (C_1–C_7) content, and five samples of washed, handpicked cuttings were analyzed for extractable hydrocarbons by solvent extraction, column chromatography, and gas chromatography. The thermal analysis technique was the same as that described by Claypool and Reed (1976), except that the rate of heating was 104°F/min (40°C/min) instead of 82°F/min (28°C/min). The flame-ionization response was converted to an equivalent weight of hydrocarbons by using an empirical calibration based on secondary standards analyzed by Fisher assay. The organic carbon and solvent-extraction techniques were adopted from those described by Baker and Claypool (1970).

The following criteria are used in this section to evaluate petroleum source-rock potential:

1. Organic richness—Sedimentary rocks must contain a sufficient quantity of organic matter that can be or that has been converted to petroleum hydrocarbons. Measurements used to indicate sufficient organic richness for petroleum source-rock potential are either (a) pyrolytic oil yield in excess of about 0.2 to 0.3 percent; or (b) extractable hydrocarbon concentrations in excess of about 100 to 500 ppm.
2. Maturity—The conversion of organic matter to petroleum hydrocarbons takes place by temperature-dependent chemical reactions. Sedimentary rocks that are rich in organic matter and in which the petroleum-generating reactions have not advanced to a degree sufficient to expect expulsion and accumulation of petroleum are called immature. The principal criteria used to determine the extent of petroleum-generating reactions are the molecular composition and the relative concentration of indigenous extractable hydrocarbons. When the extractable hydrocarbons are chemically indistinguishable from petroleum and are present at levels in excess of about 1 to 2 percent of the total organic carbon, the rock is mature. When a rock is known to be capable of generating petroleum hydrocarbons (for example, by pyrolysis) but contains a relatively low concentration of largely biochemically derived hydrocarbons, then the hydrocarbon-generating reactions are not sufficiently advanced, and the rock is immature.

By using these criteria of maturity and richness in organic matter, we can distinguish the following categories of petroleum source rocks:

Potential source rock—A sedimentary rock that is rich in organic matter and that is immature. This is a potential source rock in the sense that hydrocarbon generation may have taken place in laterally equivalent strata, if higher temperatures prevailed (for example, deeper burial); however, it is not practical to wait for the sedimentary section in question to realize its hydrocarbon-generating potential.

Possible source rock—A sedimentary rock that is rich in organic matter and that is mature. This rock has realized its potential for generating hydrocarbons (that is, it contains petroleumlike hydrocarbons).

Many other chemical and physical measurements relate to the interpretation of richness in organic matter and, especially, maturity. However, these properties or observations are indirectly related to petroleum occurrence or generation. For purposes of petroleum source-rock evaluation, the direct measurement of the approximate degree of completion of hydrocarbon-generating reactions (where possible) is preferable to an inference based on indirectly related properties.

RESULTS AND CONCLUSIONS

Although potential source rocks are present in the lower part of the COST No. B–2 well, the presence of fully mature oil source rocks was not confirmed. The organic matter in all samples analyzed appears to be immature in greater or lesser degree with respect to the degree of liquid-petroleum-hydrocarbon generation required for expulsion and economic occurrence of petroleum. This conclusion is based primarily on the nonpetroleum characteristics of the saturated-hydrocarbons, that is, the predominance of n-paraffins containing an odd number of carbon atoms (nC_{27} to nC_{31}) in the five samples analyzed. Additional support for this conclusion is provided by the relatively low temperatures of maximum pyrolysis yield, indicating coal rank in the subbituminous to high-volatile bituminous range. Although the deepest rocks that are rich in organic matter appear not to be fully mature, the hydrocarbon-generating reactions are definitely in progress. Moreover, the rocks below 14,000 feet in this well contain such small quantities of organic matter that geochemical methods for evaluation of maturity are of questionable applicability. If rocks of sufficient organic richness were present, they might well be fully mature at, or just below, the bottom of the well.

The results of the combustion and thermal analysis/pyrolysis FID measurements are given in table 10. The trend of increasing temperature of maximum pyrolysis yield as a func-

TABLE 10.—*Organic content of sediments from the COST No. B–2 well, obtained by combustion and thermal analysis/pyrolysis*

Depth interval (feet)	Organic carbon (weight percent)	Thermal analysis: Pyrolytic hydrocarbon yield (weight percent)	Oil content (ppm)	Temperature maximum yield (°F)	(°C)
1,120– 1,150	0.1	0.04	54	835	446
1,300– 1,330	.2	.09	81	864	462
1,480– 1,510	.1	.04	53	873	467
1,660– 1,690	<.1	.01	20	810	432
2,050– 2,080	.3	.13	67	864	462
2,330– 2,350	<.1	.02	37	849	454
2,330– 2,350	.5	.21	85	876	469
3,040– 3,070	1.4	.53	320	864	462
3,580– 3,610	2.4	1.5	200	867	464
3,850– 3,880	2.8	1.9	180	896	480
4,110– 4,140	.9	.48	100	871	466
4,690– 4,700	1.0	.41	300	871	466
4,990– 5,000	.9	.05	33	858	459
5,200– 5,300	.3	.12	43	860	460
5,410– 5,420	.5	.23	46	871	466
6,720– 6,730	.2	.10	100	878	470
8,220– 8,240	2.1	1.8	9,600	876	469
8,850– 8,860	.5	.02	30	878	470
9,720– 9,730	.6	.30	240	878	470
10,870–10,910	2.2	.50	520	842	450
11,260–11,290	2.6	2.1	1,300	867	464
12,160–12,190	6.0	2.9	3,100	874	468
12,750–12,760	2.0	.30	320	860	460
13,020–13,030	11.5	5.1	5,600	907	486
13,020–13,030 (Black shale)	6.0	1.6	1,500	891	477
13,410–13,420	2.0	.30	260	887	475
13,920–13,930	1.1	.17	66	900	482
14,520–14,530	<.1	.03	60	878	470
14,820–14,830	.6	.04	86	910	488
15,120–15,130	<.1	.11	130	896	480
15,420–15,430	<.1	.04	94	882	472
15,720–15,730	<.1	.03	72	896	480
15,840–15,850	.3	.01	10	896	480
15,900–16,030	.2	---	----	---	---
16,020–16,030	<.1	.10	110	907	486

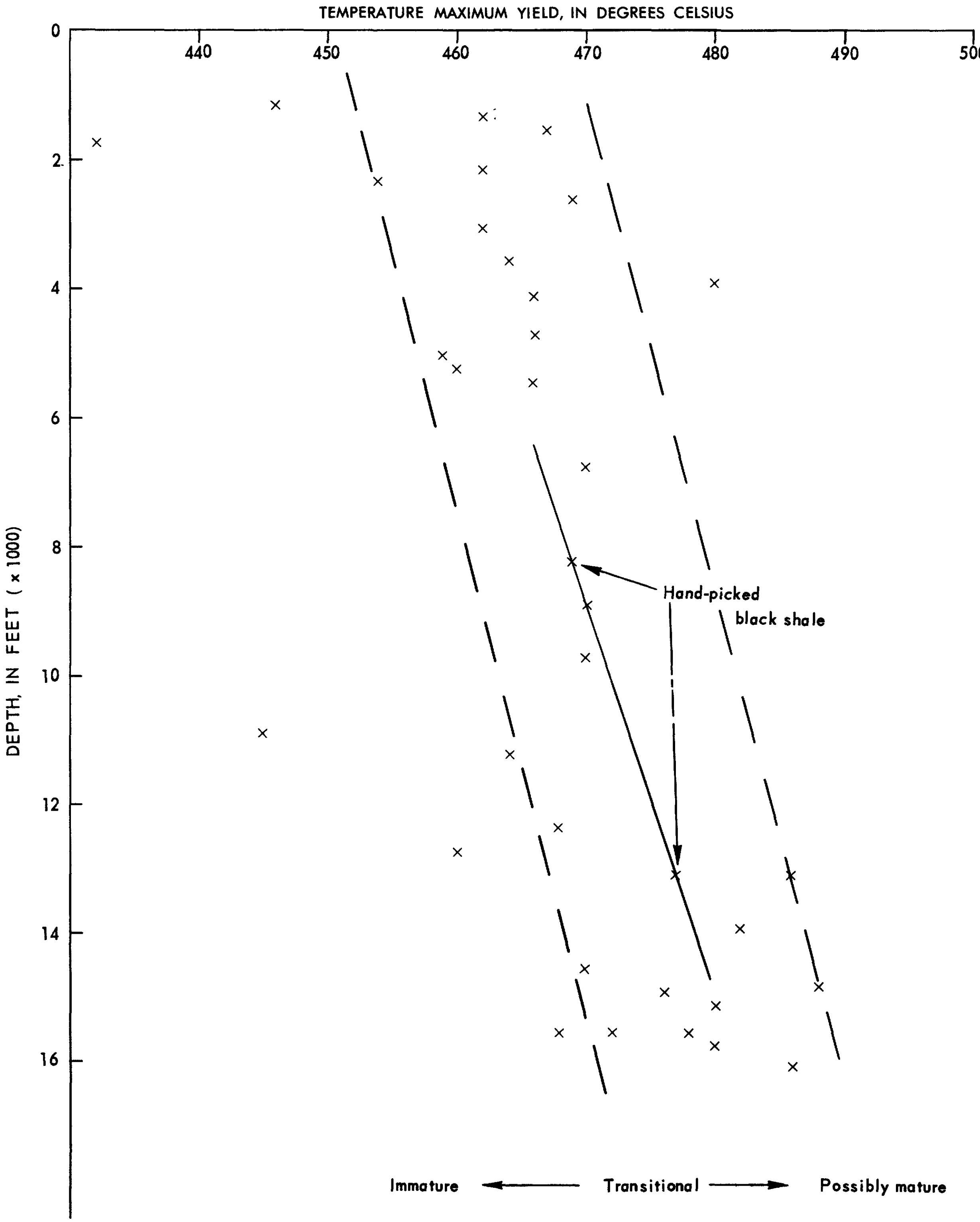


FIGURE 10.—Temperature of maximum pyrolysis yield as a function of depth.

tion of depth is shown in figure 10 for the COST No. B–2 well; it is superimposed on the tentative calibration based on analysis of standard coals, shown in figure 11.

Samples from depth intervals of about 3,000 to 4,000 feet and about 8,000 to 14,000 feet are relatively rich in organic matter (greater than 2.0 percent organic carbon). Samples from the shallowest interval (3,040–3,070 feet and 3,580–3,610 feet) contain relatively low amounts of hydrocarbons (80 to 78 ppm, respectively) and have a marked odd carbon-number predominance in the normal paraffins. These samples also show a relatively high conversion of organic matter to hydrocarbons upon pyrolysis (0.5 and 1.5 percent, where 0.3 percent is about the minimum value for rocks considered to be potential source rocks).

The samples at 8,220 to 8,240 feet and those in the range of 10,000 to 14,000 feet contain large amounts of volatile or thermally extractable organic matter, in addition to high contents of total organic carbon. In the sample from 8,220 to 8,240 feet, the material appears to be nonindigenous (oil staining or possible contamination) because the quantity of volatile organic matter is out of proportion to the total organic carbon content of the sample. However, the samples analyzed from 10,000 to 14,000 feet, especially the sample from 12,160 to 12,190 feet, contain high concentrations of apparently indigenous, solvent-extractable organic matter. The high concentrations of hydrocarbons are probably related to abundant coaly material in this part of the section, and the richness-in-organic-matter criteria for petroleum source-rock evaluation of shales are not strictly applicable.

More detailed analyses were performed to determine whether the section rich in organic matter between approximately 10,800 and 14,000 feet contains an assemblage of indigenous, petroleumlike hydrocarbons generated from the solid organic matter (that is, to determine whether the section is mature with respect to liquid-petroleum hydrocarbon generation). The results of the solvent-extraction analyses are summarized in table 11. The sample from 12,160 to 12,190 feet has 2,680 ppm hydrocarbons and 6.0 percent organic carbon for a hydrocarbon-to-organic-carbon ratio of 4.5 percent. The other two samples from the deeper part of the section have hydrocarbon-to-organic-carbon ratios of 1.7 percent (11,260–11,290 feet) and 1.3 percent (15,900–16,030 feet). These ratios are in contrast to values of 0.6 and 0.3 percent for the shallower samples (3,040–3,070 feet and 3,580–3,510 feet, respectively). Ratios in excess of 1 percent usually suggest that hydrocarbon generation has taken place. However, the more important question is whether or not this process is sufficiently advanced in the sections of this well that are rich in organic matter for expulsion and accumulation of liquid petroleum to have taken place.

The results of detailed analyses of the saturated hydrocarbons by gas chromatography are summarized in figures 12–16. The tendency for the odd-numbered n-paraffins to predominate over the neighboring even-numbered n-paraffins is summarized by the carbon preference index (CPI). A definite trend of CPI values approaches 1 as depth in the hole increases. This trend also indicates that some degree of hydrocarbon generation has taken place. However, the deepest samples analyzed that contain sufficient organic matter to be considered a potential petroleum source rock (12,160–12,190 feet, fig. 15) have a CPI

TABLE 11.—*Summary of chloroform extraction-yields, column chromatographic separation of C_{15+} hydrocarbon fractions, and estimate of carbon preference index (CPI) by gas chromatography from COST No. B–2 well samples*

Depth interval (feet)	$CHCl_3$-soluble bitumen (ppm)	Extractable hydrocarbons: Saturated (heptane eluate) (ppm)	Aromatic (benzene eluate) (ppm)	Total (sum) (ppm)	CPI[1]	Hydrocarbons total organic C
3,040– 3,070	311	21	60	81	3.4	0.6
3,580– 3,610	272	30	48	78	~3.4	0.3
11,260–11,290	893	115	315	430	1.5	1.7
12,160–12,190	5,747	710	1,970	2,680	1.2	4.5
15,900–16,030	77	9	16	25	1.2	1.2

[1] $CPI = \frac{nC_{25}+nC_{27}+nC_{29}+nC_{31}}{nC_{26}+nC_{28}+nC_{30}+nC_{32}} + \frac{nC_{25}+nC_{27}+nC_{29}+nC_{31}}{nC_{24}+nC_{26}+nC_{28}+nC_{30}}$

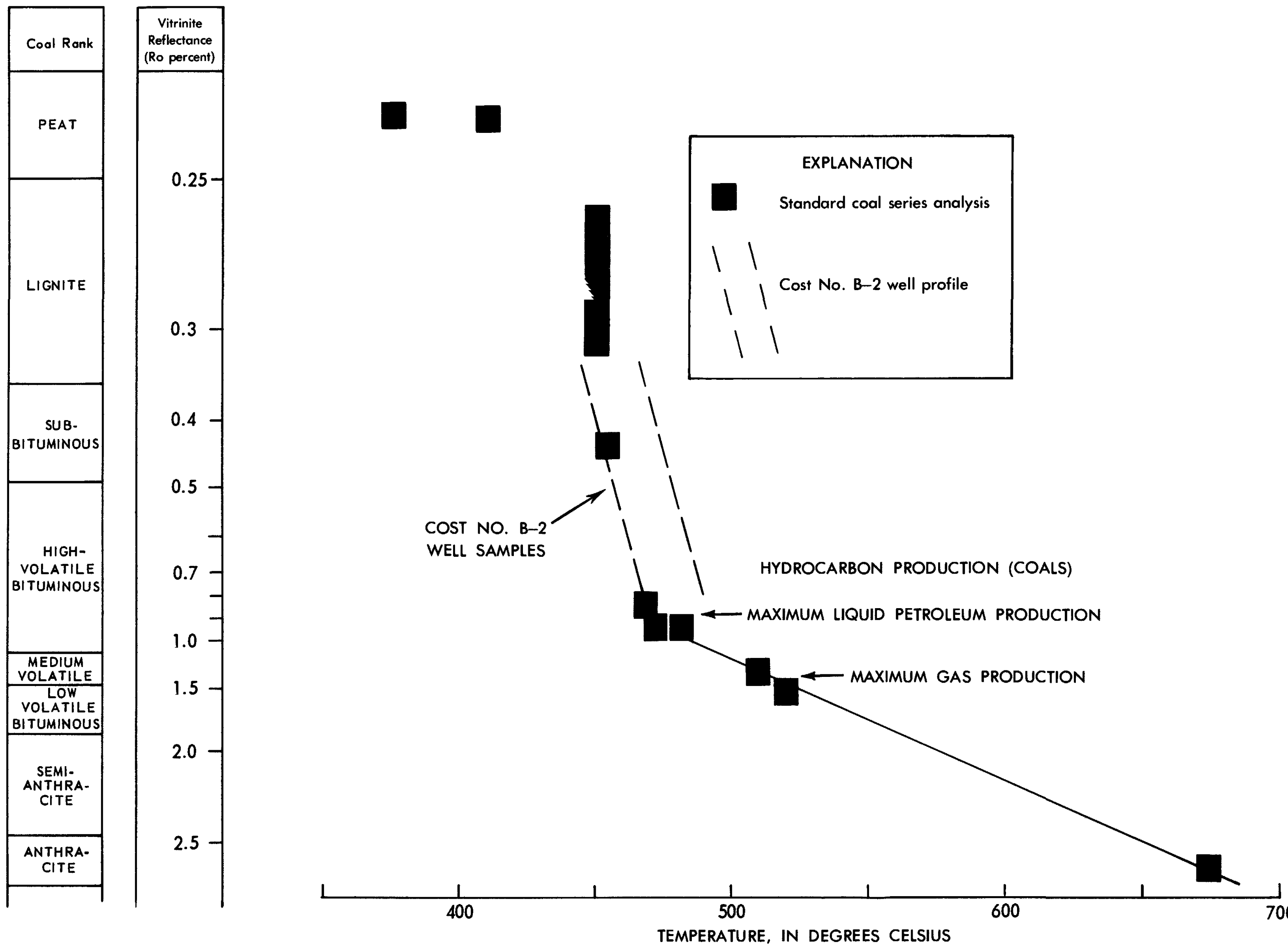


FIGURE 11.—Calibration of temperature of maximum pyrolysis yield with respect to coal rank, based on analysis of standard humic coal samples. Position of COST No. B–2 samples determined by range of maximum pyrolysis yields, temperatures, and average values of vitrinite reflectance, reported by Superior Oil (written commun., 1976).

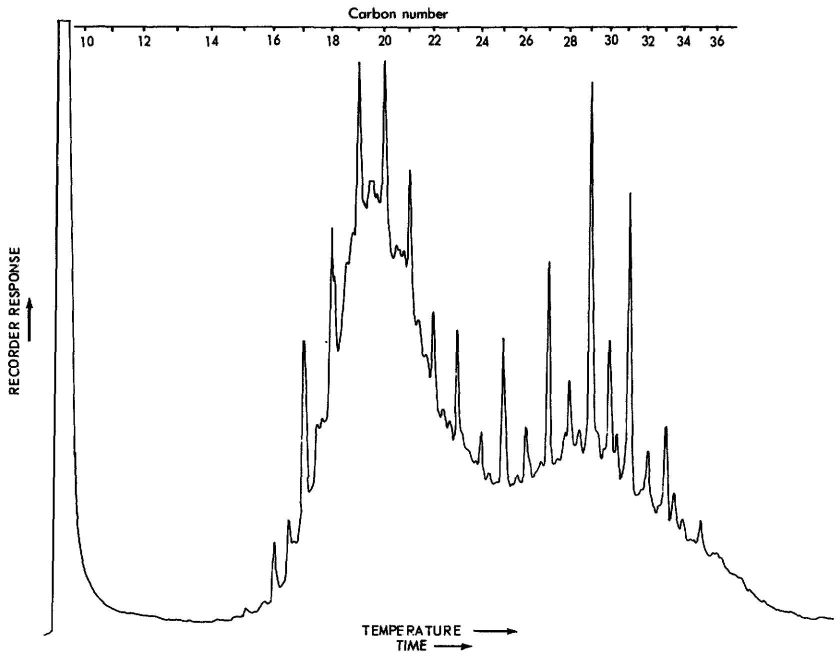


FIGURE 12.—Gas-chromatographic analysis of saturated hydrocarbons, COST No. B–2 well, sample from 3,040 to 3,070 feet. Analysis on 20-mm × 1.8-m columns packed with 3.0-percent GCSE–30 on 100–120-mesh Gas Chrom Q; the flow was 40mL/min. Column temperature was 80°C at injection and was programmed to rise 12°C/min for 10 min, then 10°C/min for 12 min to a final temperature of 320°C.

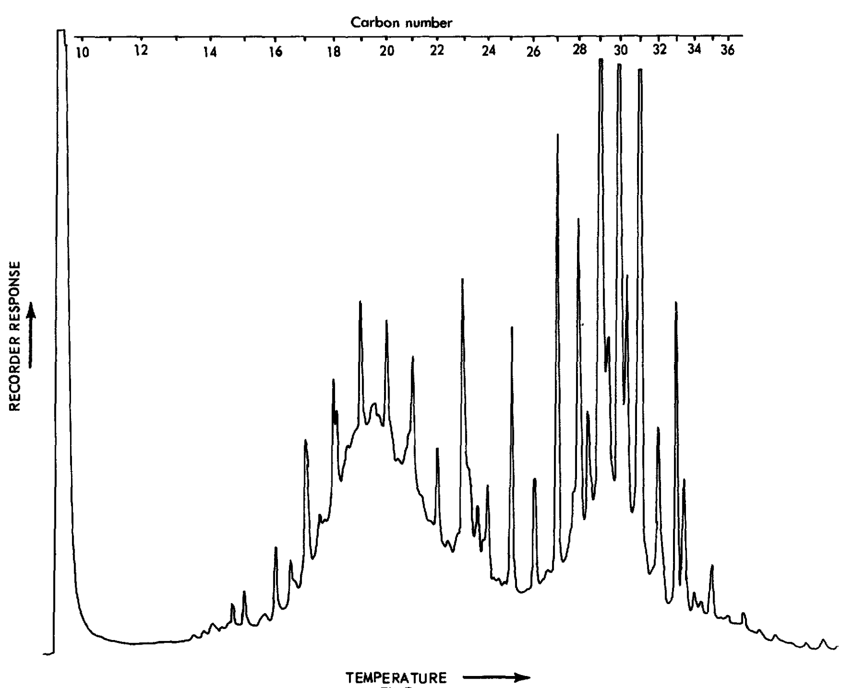


FIGURE 13.—Gas-chromatographic analysis of saturated hydrocarbons, COST No. B–2 well, sample from 3,580 to 3,610 feet. Conditions same as analysis shown in figure 12.

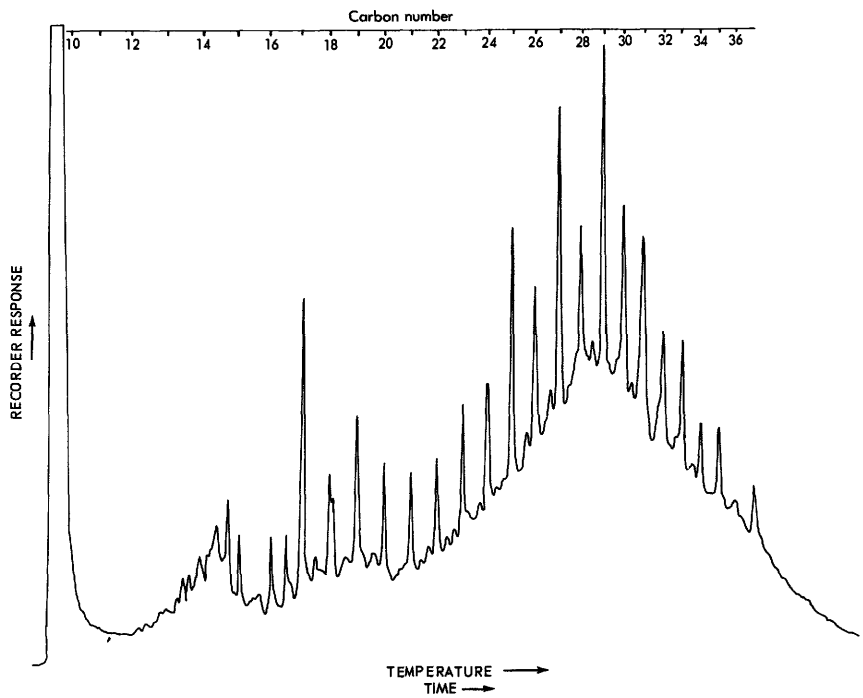


FIGURE 14.—Gas-chromatographic analysis of saturated hydrocarbons, COST No. B–2 well, sample from 11,260 to 11,290 feet. Conditions same as analysis shown in figure 12.

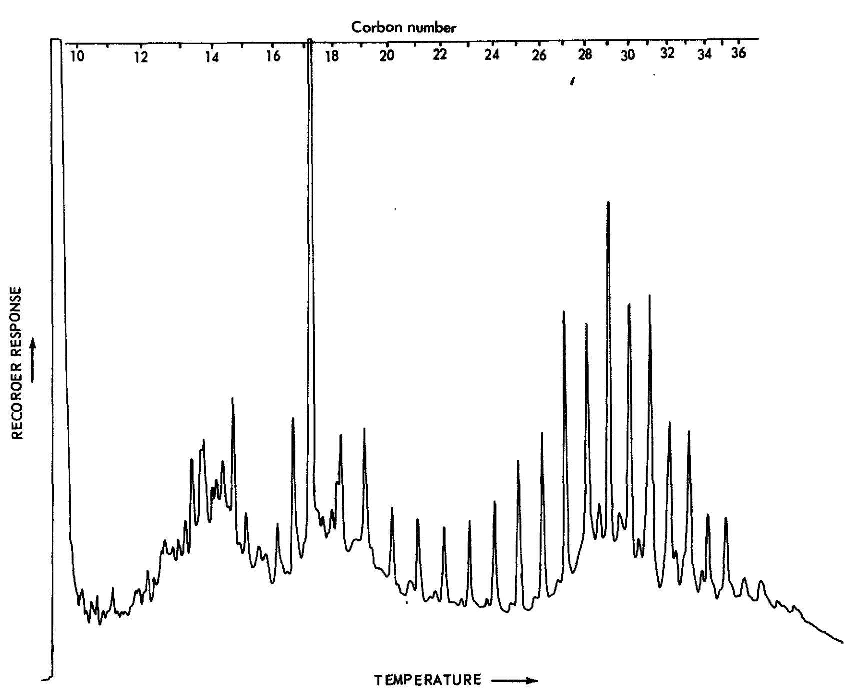


FIGURE 15.—Gas-chromatographic analysis of saturated hydrocarbons, COST No. B–2 well, sample from 12,160 to 12,190 feet. Conditions same as analysis shown in figure 12.

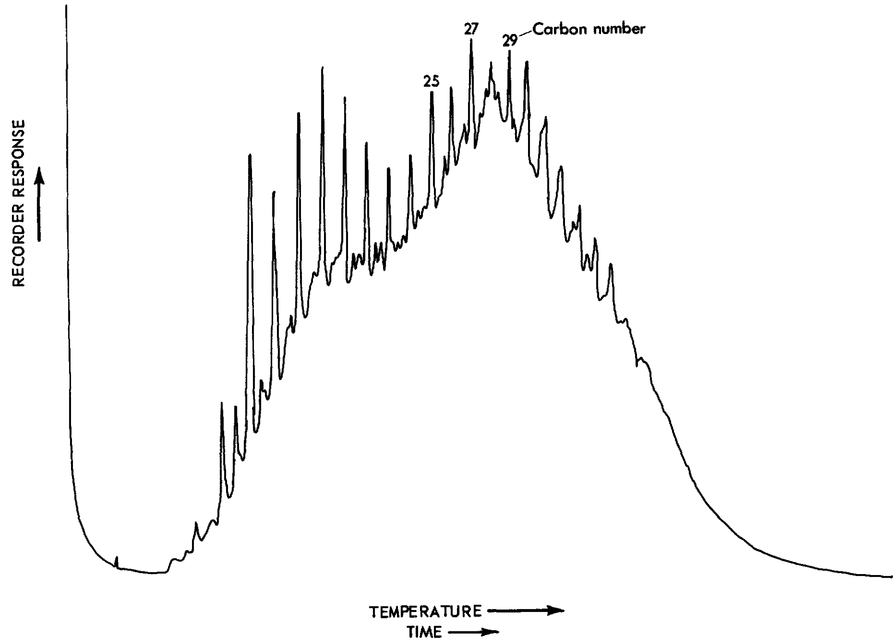


FIGURE 16.—Gas-chromatographic analysis of saturated hydrocarbons, COST No. B–2 well, sample from 15,900 to 16,030 feet. Conditions same as in the analysis shown in figure 12.

value of 1.5; pristane is the most abundant single compound in the mixture. These are still the chemical characteristics of subbituminous coals (Brooks and Smith, 1967), whereas the principal phase of oil formation takes place at the high-volatile bituminous stage (Vassoyevich and others, 1970). At this latter stage, the mixture of saturated hydrocarbons resembles mature petroleum in having little or no odd-carbon-predominant n-paraffins and much smaller predominance of pristane in the total mixture.

Another analysis was performed on pieces of black shale handpicked from the interval 13,020 to 13,030 feet. The sample was heated in two stages—from room temperature to 680°F (360°C) and then from room temperature to 1,382°F (750°C)—and the volatile and pyrolysis products produced during the two separate heating periods were analyzed by gas chromatography. Two different hydrocarbon mixtures are evident, indicating that the volatile organic matter was not produced by thermal alteration of the solid organic matter. In addition, the gas-chromatographic analysis of the pyrolysis products indicates liquid-hydrocarbon-generating potential (as opposed to gas only).

Six samples from the interval 8,850 to 15,850 feet were analyzed for light hydrocarbons in the headspace gas of a blender containing the cuttings and distilled water at 198°F (92°C). The results are shown in table 12. The cyclic isomers in the C_6 to C_7 range are predominant, which is consistent with immaturity. The measured quantity of C_1 to C_7 hydrocarbons was in the range of 10^{-6} to 10^{-5} grams per gram of organic carbon. In mature petroleum-generating sediments, the corresponding range is 10^{-3} to 10^{-2}. However, these samples were bagged cuttings that had been opened prior to analysis so that the quantities of gaseous and gasoline-range hydrocarbons measured are minimum values. Sample 13,410 to 13,420 feet had the highest content of C_1 to C_7 hydrocarbons and a significant proportion (51 volume percent) of permanent gases (methane, ethane, propane). As these samples were not collected and handled in a manner that would insure retention of dissolved or absorbed gases, this gas was probably released from the rock when the cuttings were disaggregated in the blender.

Although experimental evidence suggests that virtually the same temperatures are needed for gas- or liquid-hydrocarbon formation, an extensive body of empirical evidence shows that wet or dry gas is present and may form before crude oil, probably at temperatures starting

TABLE 12.—C_1 *to* C_7 *hydrocarbon analyses of selected samples from the COST No. B-2 well*

[Values in volume percent of C_1 to C_7 hydrocarbons normalized to 100 percent]

Hydrocarbons	Depth interval (in feet)					
	8,850–8,860	10,870–10,910	12,750–12,760	13,410–13,420	14,820–14,830	15,840–15,850
Methane+ethane	0.0	2.6	2.8	25.8	7.1	37.5
Propane	.0	9.5	24.9	25.4	7.1	8.0
Isobutane	.0	5.2	9.1	4.7	.0	4.0
n-Butane	.0	6.2	2.7	12.7	3.6	4.7
Isopentane	.0	8.5	12.9	4.8	.9	.0
n-Pentane	.0	4.8	10.7	3.8	1.8	2.2
2,2-Dimethybutane	.0	.0	.0	.0	.0	.0
Cyclopentane	.0	1.2	1.8	.4	.0	.0
2,3-Dimethylbutane	.0	.6	.4	.1	5.3	.0
2-Methylpentane	.0	6.5	3.5	2.0	.0	4.5
3-Methylpentane	.0	2.6	2.3	.8	.0	.0
n-Hexane	.0	1.9	2.3	.8	.0	.0
Methylcyclopentane	.0	9.3	6.8	1.8	.0	.0
2,2-Dimethylpentane	.0	.0	.0	.0	.0	.0
Benzene	55.0	6.6	.9	4.8	21.1	12.5
2,4-Dimethylpentane	.0	.0	.0	.0	.0	.0
2,2,3-Trimethylbutane	.0	.0	.0	.0	.0	.0
Cyclohexane	45.0	9.9	4.7	6.5	53.1	26.6
3,3-Dimethylpentane	.0	.0	.0	.0	.0	.0
1,1-Dimethylcyclopentane	.0	.0	.1	.0	.0	.0
2-Methylhexane	.0	.9	.5	.2	.0	.0
2,3-Dimethylpentane	.0	.7	.2	.0	.0	.0
1,Cis-3-dimethylcyclopentane	.0	1.6	.8	.3	.0	.0
3-Methylhexane	.0	.8	.6	.3	.0	.0
1,Trans-3-dimethylcyclopentane	.0	1.2	.8	.4	.0	.0
1,Trans-2-dimethylcyclopentane	.0	2.9	1.4	.5	.0	.0
3-Ethylpentane	.0	.0	.1	.0	.0	.0
2,2,4-Trimethylpentane	.0	.0	.0	.0	.0	.0
n-Heptane	.0	1.4	.6	.4	.0	.0
1,Cis-2-dimethylcyclopentane	.0	.0	.1	.0	.0	.0
Methylcyclohexane	.0	15.1	8.8	3.5	.0	.0
C_1 to C_7 hydrocarbons, total:						
g/g sediment	6×10^{-9}	7×10^{-8}	2×10^{-6}	1×10^{-6}	3×10^{-8}	4×10^{-9}
g/g organic carbon	1×10^{-6}	3×10^{-6}	8×10^{-5}	5×10^{-5}	5×10^{-6}	1×10^{-6}

about 125°F (Evans and Staplin, 1970). Biogenically generated dry gas can form only at low temperatures (Claypool and Kaplan, 1974). Thus, the types of sediments in the COST No. B-2 well, although still somewhat immature with respect to liquid-hydrocarbon generation, may have been significant sources of dry and possibly wet gas.

The data also do not rule out generation of gas or oil in deeper, more thermally mature horizons, coupled with lateral and (or) vertical migration into favorable traps.

GEOCHEMICAL MEASUREMENT AND INTERPRETATION—A COMPARISON

The samples from the COST No. B-2 well were analyzed by a contract service-research laboratory (Geochem Laboratories) and by research laboratories of some participating major oil companies (including Superior, Amoco, and Phillips) prior to and in addition to the analyses done by the USGS. The reports of these private companies are on file for public inspection at the offices of the USGS, Washington, D.C. It is interesting to compare the results and interpretations of different laboratories on samples from this well.

These analyses are compared with respect to the properties of the sedimentary organic matter they are intended to measure: richness, type (oil versus gas potential), and degree of maturity. These analyses are summarized for comparison in figures 17, 18, and 19.

In figure 17, organic-carbon measurements done by Geochem Laboratories (1976) are compared with those done by the USGS. In general, the agreement on these analyses are excellent. Both sets of measurements, performed on independently selected samples, clearly show that the main intervals that contain rocks rich in organic carbon (>1 percent) are from about 3,000 to 6,000 feet and from about 10,000 to 14,000 feet. The USGS data show a sample containing 2.1 percent organic carbon at 8,220 to 8,240 feet, whereas all the samples analyzed by Geochem Laboratories in this same general interval are less than 1 percent.

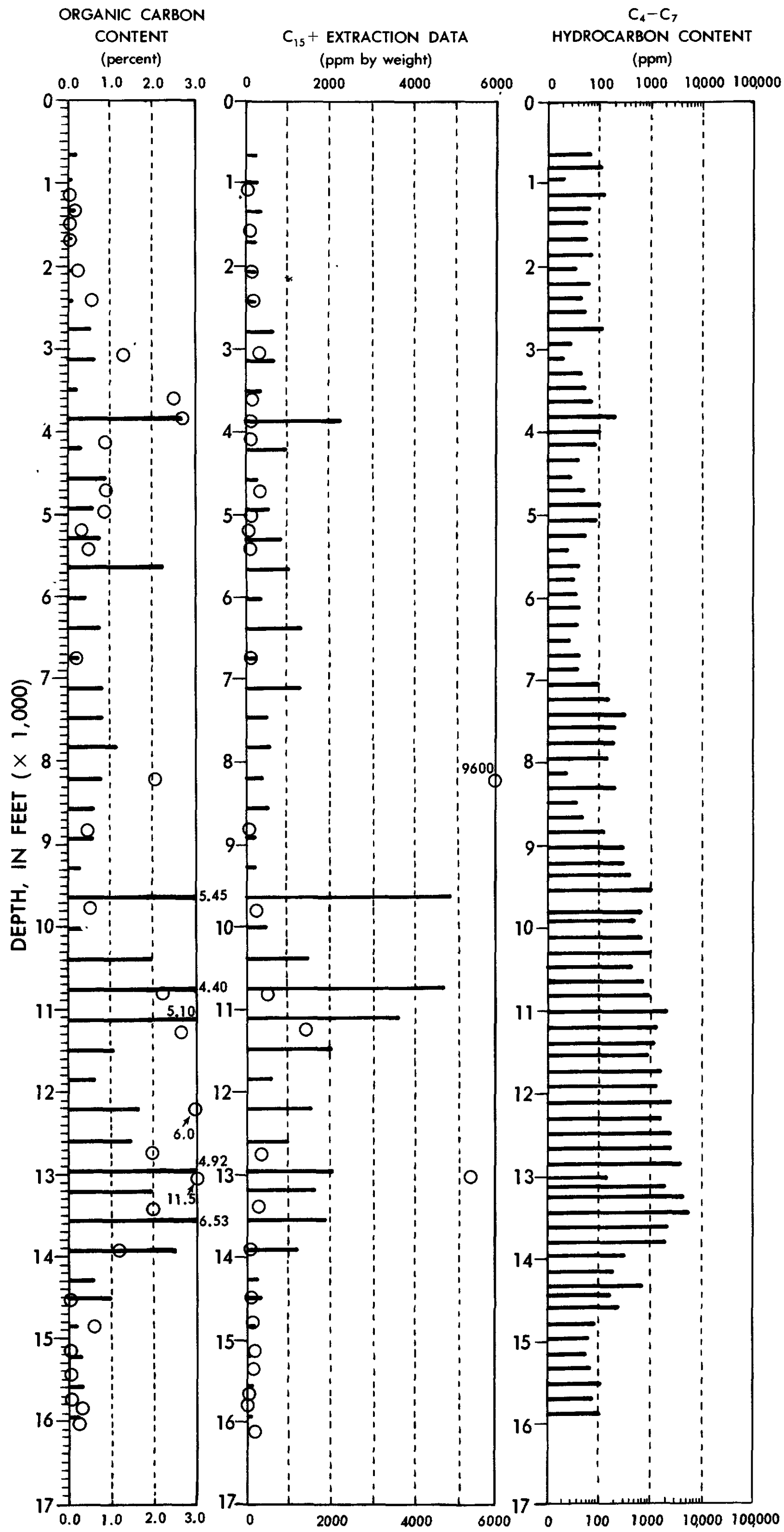


FIGURE 17.—Summary and comparison of analyses of richness of sediments in the COST No. B–2 well. Geochem Laboratories (1976) data are shown as bars, whereas USGS data are shown as circles.

In figure 17, a comparison also is shown between the $C_{15}+$ extraction data of Geochem Laboratories (1976) and organic compounds volatilized at less than 680°F (360°C) during thermal analysis by the USGS; both are expressed in parts per million by weight basis. These two different methods for estimating richness of organic matter are in fair agreement. The differences present are probably partly due to the effect of the different analytical techniques used, although both are inferred to measure the same constituents. The extraction technique depends on volatility to remove organic compounds from the rock. The thermal-analysis technique will detect light hydrocarbons that are lost in the isolation and gravimetric $C_{15}+$-extractable determination. The solvent-extraction technique will remove very heavy (mostly asphaltic) compounds that are either nonvolatile or that are not transported from the furnace to the detector through lines maintained at 482°F (250°C). Where the $C_{15}+$-extraction yields are significantly higher than the 86° to 680°F (30°–360°C) thermal-analysis yield, it is generally for samples that have especially high NSO+ asphaltine content. The 86° to 680°F (30°–360°C) thermal-analysis yields are higher than extraction yields for the interval (12,000–14,000 feet) where the highest C_4 to C_7 hydrocarbon contents were detected by Geochem Laboratories (1976) in a separate analysis, (fig. 17).

The extractable organic matter present at relatively high concentrations in the interval of about 9,000 to 14,000 feet was concluded by the USGS to be unlike petroleum, on the basis of gas-chromatographic analysis of the saturated hydrocarbons and by comparison of thermally extracted material with that generated by pyrolysis. Geochem Laboratories (1976, p. 2) had earlier arrived at the same conclusion, that is, that "· · · this interval *has only generated methane gas and C_2–C_4 'wet gas' hydrocarbons.* This facies *has not generated* any petroleum-related liquids and it is unlikely that any oil will be found in the immediate area of this well."

Four measurements that are sensitive to the type of organic matter in the COST No. B–2 well are summarized for comparison in figure 18. The first column shows a direct measurement of kerogen type and relative abundance, as determined in microscopic examination. The next three columns of figure 18 show the yield of pyrolytic hydrocarbons as a percentage of organic carbon, the atomic ratio of hydrogen to carbon in the kerogen, and the stable carbon isotopic composition of various fractions of the organic matter. These latter three techniques give an indirect indication of the type of organic matter and are also influenced by the state of diagenesis or degree of thermal maturation. The pyrolytic hydrocarbon yield as a percentage of organic carbon and the atomic hydrogen-carbon ratio of the kerogen are both related to the structure and liquid-hydrocarbon-generating potential of the kerogen. A fairly good correlation exists between these two measurements in the COST No. B–2 well, as shown in columns two and three of figure 18.

The stable carbon-isotope ratio, $^{13}C/^{12}C$, is shown in figure 18 as parts per thousand (per mil) deviations from the $^{13}C/^{12}C$ ratio of the PDB marine carbonate standard. $\delta^{13}C$ values are reported for kerogen (the fraction of the organic matter insoluble in benzene-methanol) for the total extract (the soluble fraction), and for the saturated or paraffin-napthene hydrocarbons that are separated from the total extract. The carbon-isotope ratio primarily reflects the nature of the source material or the environment in which the organic matter was generated by photosynthesis. In addition, the difference in $\delta^{13}C$ between the kerogen and total-hydrocarbon extract may indicate the extent to which possible petroleumlike constituents have been generated from the solid organic matter.

In the COST No. B–2 well, the $\delta^{13}C$ values of the kerogen appear to reflect the zonation seen on the basis of other organic geochemical characteristics, as described by Geochem Laboratories (1976). This fact probably reflects the abundant coaly material in Zone B. In general, a spread of about 2.5 per mil or more is found between the saturated hydrocarbon (or the extract) and the kerogen. This spread indicates that the materials probably have largely unrelated origins and that these lipid materials have not been generated from the kerogen by thermal diagenesis.

Figure 19 shows five different indicators of organic metamorphism or maturation—the numerical index (CPI) of the predominance of odd-numbered n-paraffin in the saturated hydrocarbons, the visual kerogen thermal-alteration index, vitrinite reflectance, temperature of maximum pyrolysis yield, and percent carbon

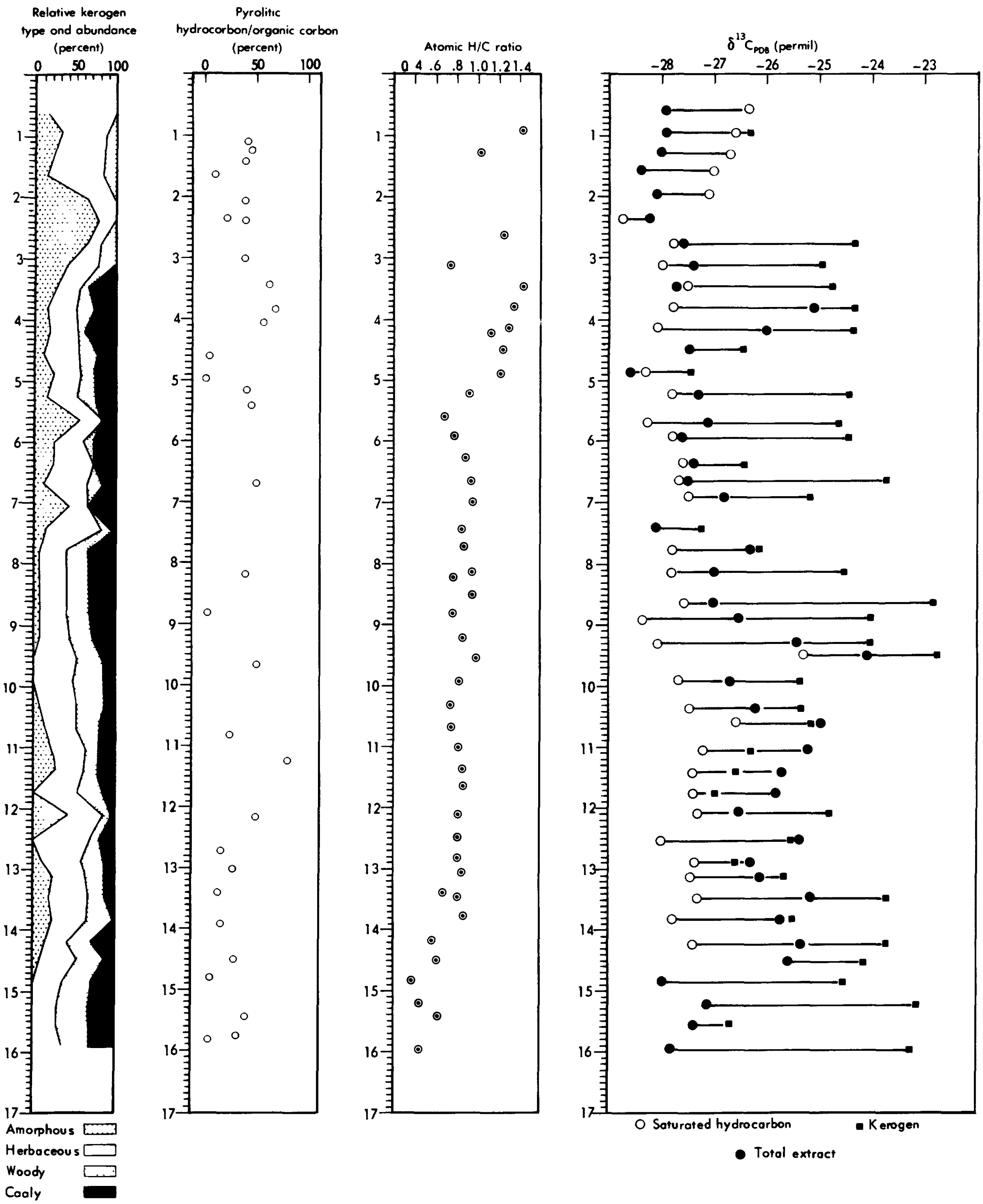


FIGURE 18.—Summary and comparison of analyses of type of organic matter in COST No. B-2 well samples. Data in the first column are from Geochem Laboratories (1976); second column, from this volume; third column, from Amoco Production Company (J. A. Momper, written commun., 1976); and the last column, from Phillips Petroleum Company (J. G. Erdman, written commun., 1976).

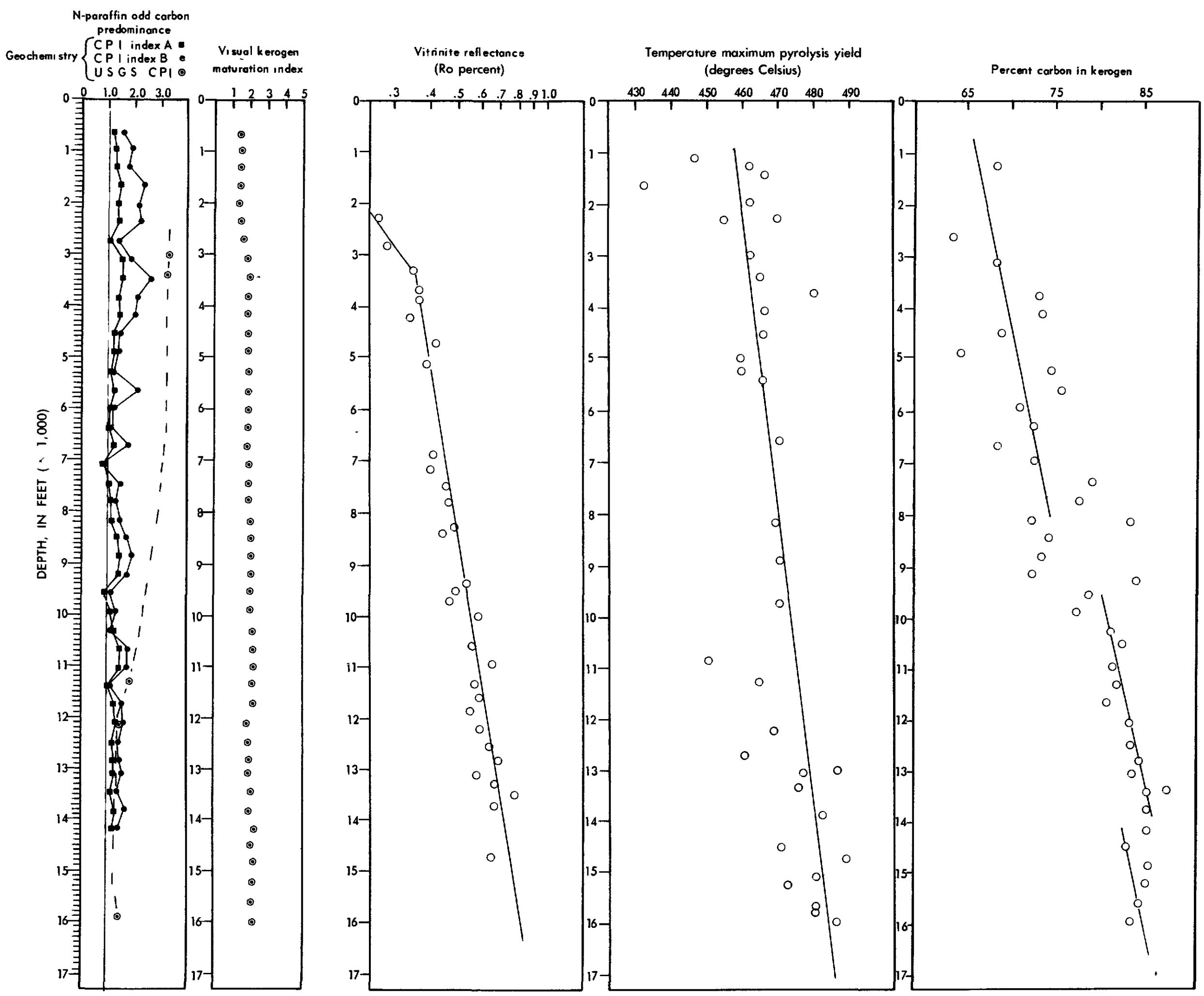


FIGURE 19.—Summary and comparison of analyses of maturity of organic matter in the COST No. B–2 well. Data in first column are from Geochem Laboratories (1976) and Claypool (this volume); in second column, from Geochem Laboratories (1976); in third column, from Superior Oil Co. (W. G. Dow, written commun., 1976); in fourth column, from Claypool (this volume); in fifth column, from Amoco Production Company (J. A. Momper, written commun., 1976).

in the kerogen. All these indicators show significant change as depth increases in the COST No. B–2 well. Although agreement is excellent among the different measurements, there are some apparent differences in interpretation of the significance of these measurements with respect to the generation of hydrocarbons. The interpretation of the vitrinite reflectance data by Superior Oil Company (W. G. Dow, written commun., 1976) stated that, "Although both oil and gas begin to be formed at maturities of about 0.45 R_0 (6,800 feet in the subject well), maximum generation and expulsion occur only below the top of the peak generation zones. On the basis of these criteria, effective oil source rocks (those which have both generated and expelled oil) could be present below 11,300 feet if organic matter capable of conversion to oil is present." The diagram accompanying this report shows "peak generation" at R_0 value of 0.6 percent, which takes place at 11,300 feet in this well.

The report on elemental analyses by Amoco Production Company (J. A. Momper, written commun., 1976), referring to the degree of carbonization of the kerogen, stated that, "The diagenesis level below 10,000 feet is equivalent to the peak stage for oil generation." This report also emphasized that the elemental data must be considered with the geochemical data of Geochem Laboratories (1976) and the vitrinite reflectance data of Superior Oil Company (W. G. Dow, written commun., 1976).

These reports of "peak generation" in the lower part of the section penetrated in the COST No. B–2 well seem to many observers to be in conflict with the interpretation by Geochem Laboratories (1976, p. ii) that, "These sediments (9,500±feet to 14,000±feet) have experienced an insufficient geothermal (time-temperature) history to have generated any petroleum-related liquids in the immediate vicinity of the COST No. B–2 well," or our interpretation that the organic matter in all samples analyzed appears to be immature in greater or lesser degree with respect to the degree of liquid-petroleum-hydrocarbon generation required for expulsion and economic occurrence of petroleum.

These apparent inconsistencies are due to the difficulty of inferring the extent of hydrocarbon-generating reactions from the nature of the solid organic matter. The decrease in CPI with depth shows that hydrocarbon generation began as depth increased in the COST No. B–2 well. A greater change is shown for the USGS CPI data because the gas-chromatographic analysis was performed on SE–30-packed columns rather than on eutectic-salt-packed columns. The odd-carbon predominance is usually most pronounced in the n-C_{29} region, and these compounds are partially oxidized during analysis on the eutectic column. This means that the CPI values given by Geochem Laboratories (1976) are minimum values and in particular do not reflect the degree of immaturity at shallow depths (less than 6,000 feet) in the COST No. B–2 well. Regardless of differences in the analytical technique, CPI decreases significantly between 3,000 feet and 12,000 feet. This undoubtedly reflects some degree of hydrocarbon generation. However, both the molecular composition of the saturated hydrocarbons in samples at 12,000 feet and the remaining hydrocarbon-generating potential shown by pyrolysis of samples at 13,000 feet indicate that the "principal phase of oil formation" has not yet taken place in this well.

The terms "peak generation" or "the top of the peak generation zone," as indicated by vitrinite reflectance and kerogen carbonization, are apparently used to designate upper depth limits, below which effective oil source rocks may occur and above which they cannot occur. Therefore, additional evidence is required before rocks at a specific depth in a well can be properly considered effective or possible oil-source rocks.

Another apparent contradiction lies in the interpretation of the geochemical data with regard to the gas- or wet-gas-source capabilities of the sediments penetrated in the COST No. B–2 well. Geochem Laboratories (1976), on the basis of measurement of C_1 to C_7 hydrocarbons, indicated that the interval from 9,500 to 14,000 feet has undergone good to excellent gas and wet-gas generation. However, the report by Superior Oil Company (W. G. Dow, written commun., 1976) concluded that "If only wet-gas source beds are present, they would be effective only below about 19,000 feet. . . ." The report by Amoco Production Company (J. A. Momper, written commun.,1976) implied a similar interpretation, in that a diagenesis level equivalent to peak generation for oil was considered early generation to early peak generation in sediments containing kerogen with potential only for wet-gas or gas generation. This interpretation is probably based on the fact that the main stage of gas production during coalification is after the stage of maximum liquid-hydrocarbon production (Teichmüller and Teichmüller, 1968). Sediments having an unusually high organic carbon content might be effective source rocks at a level of maturation less than the standard "peak generation" for either gas or oil. This may be the case for gas generation from the 9,500-to-14,000-foot interval of the COST No. B–2 well.

Color Alteration of Visible Organic Matter

By E. I. Robbins

Color alteration of visible organic matter as a function of burial depth, especially when used in conjunction with vitrinite reflectance and organic geochemistry, can provide an indication of the probable maximum burial temperatures reached by the sediments and has strong bearing on the potential for hydrocarbon generation.

The sapropel fraction of organic matter is the amorphous breakdown product of living tissue. If the definition of Staplin and others (written commun., 1974) is used, this sapropel fraction is any amorphous matter present in aquatic sediments (in soil it is named humus) that has been created in relatively anoxic environments of deposition. Microscopically, it is seen as two forms: wispy, which was believed by Staplin and others (written commun., 1974) to form in higher energy environments; and fluffy, which accumulates in low-energy and more reducing environments.

The type of sapropel, as well as total organic matter, is important from the viewpoint of the type of hydrocarbon that will be generated (McIver, 1967; Burgess, 1974). The endpoint of the disseminated wispy sapropel and terrestrial organic matter is predominantly methane. The endpoint of the oil-shale type, the fluffy sapropel, can be liquid petroleum.

Most of the organic matter responds to temperature increases in the following manner: As volatile matter and oxygen are driven off, carbon is enriched, and the organic matter and its breakdown products become darker. On the basis of this response, a thermal-alteration scale has been prepared (Staplin, 1969; Evans and Staplin, 1970; Burgess, 1974). Because the petroleum-generating stage (the onset of browns) and the end of petroleum generation (black) are clearly recognizable, the technique is useful for determining the interval of probable liquid-petroleum generation.

The method of treatment is important as it determines the final interpretation of the organic matter (Bostick, 1971). Samples for the study of the sapropel fraction were composed of 100-foot composited intervals every 500 feet. Sample preparation included treatment in 10-percent HCl (overnight) to eliminate carbonates and 50-percent HF (24 hours) to eliminate silicates.

DATA

Figures 6 and 20 are compilations of data collected on the degree of thermal alteration of the organic matter, relative sapropel abundance, and maturity. The terms for the degree of maturation in figure 20 have been taken from Evans and Staplin (1970) and refer to the maturity of the hydrocarbons. Immature sediments should contain yellow sapropel, mainly C_1 gas, few gasoline-range hydrocarbons, and abundant heavy nonhydrocarbon compounds (mainly containing N, S, and O). Mature facies should contain orange to brown sapropel, significant C_2 to C_4 gases, and abundant gasoline-range and heavy hydrocarbons.

Figure 20, shows an overall systematic increase in maturity of the sapropel as depth increases. However, from 5,510 to 6,090 feet, an anomalously sharp increase in maturity is indicated. From 14,510 to 15,600 feet there is a slight anomalous decrease in maturity.

Reworking, bacterial degradation, and oxidation are important processes that can be recognized and that must be differentiated from thermal alteration. Reworking is indicated by samples containing organic matter that has the whole spectrum of natural and alteration colors

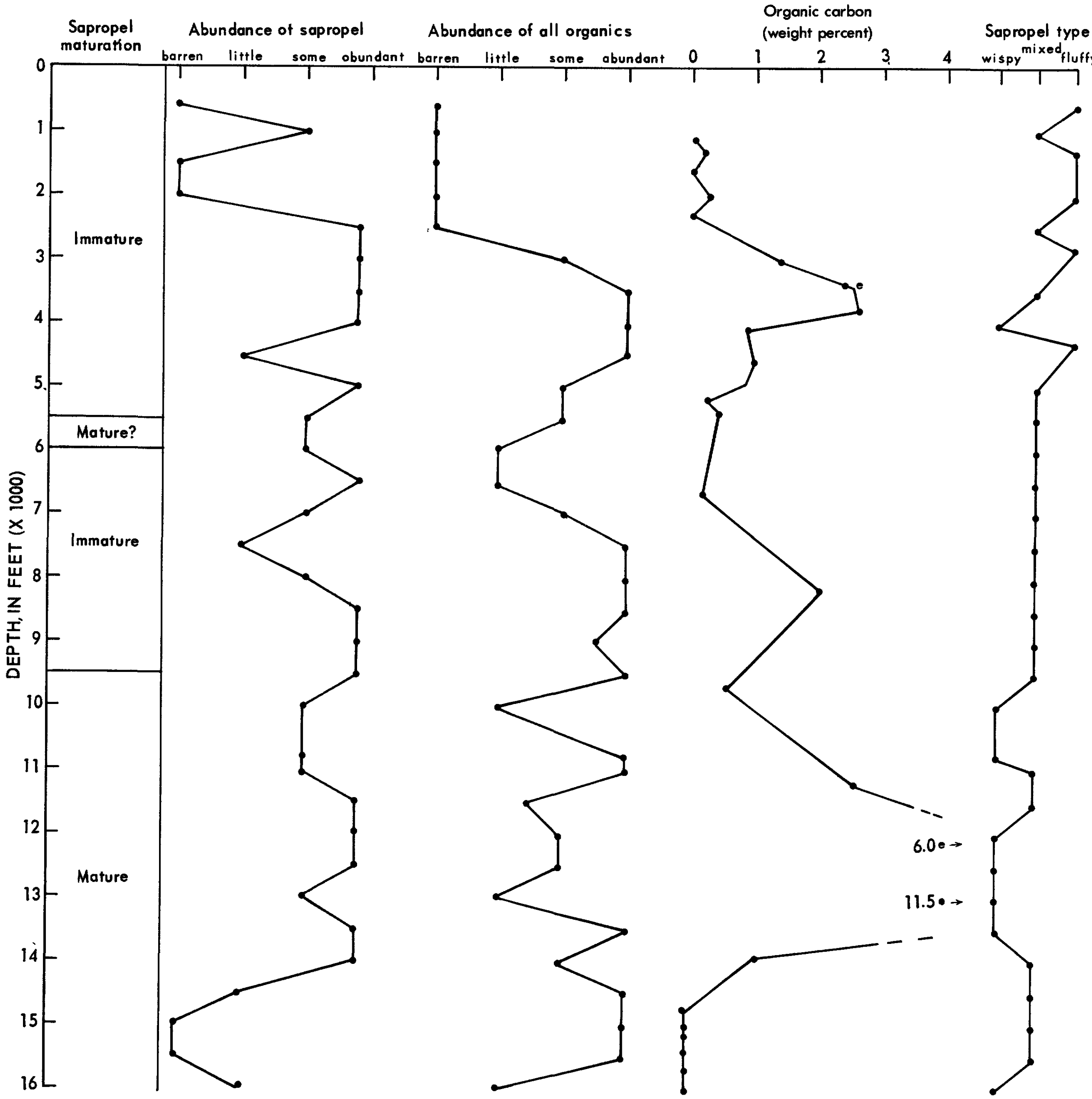


Figure 20.—Maturation, abundance, and types of sapropel, abundance of organic matter, and weight percent organic carbon as a function of depth. Weight percent organic carbon taken from report by Claypool and others (this volume).

—black, orange, brown, and yellow. Reworked organic grains are present in COST No. B-2 well samples from 1,600 to 1,630 feet, 6,420 to 6,430 feet, 6,320 to 6,330 feet, and 14,510 to 14,580 feet. Degraded organic matter, which suggests bacterial breakdown, is found in the following intervals (in feet): 4,290 to 4.320, 6,000 to 6,090, 7,010 to 7,100, 7,500 to 7,590, 8,220 to 8,240, 9,100 to 9,130, (9,430 to 9,440?), (10,960 to 10,990?), 11,260 to 11,290, 11,560 to 11,590, 11,860 to 11,890, 12,160 to 12,190, 12,-460 to 12,490, 13,010 to 13,080, 13,300 to 13,330, 15,120 to 15,130, and 15,720 to 15,730. Oxidized zones are common from 9,500 to 15,730 feet but also are found from 3,010 to 3,100 feet, 3,520 to 3,610 feet, 4,000 to 4,100 feet, and 4,500 to 4,620 feet.

The part of the stratigraphic section that has reached thermal maturity and that has the highest weight-percent organic carbon also contains dominantly wispy sapropel (fig. 20). This type generates mainly methane and not liquid petroleum. Thus, the potential of these lower intervals in the COST No. B–2 well is highest for gas generation, a conclusion substantiated by the organic geochemical data presented in this report.

CONCLUSIONS

The organic matter in the COST No. B–2 well shows an overall systematic increase in maturity with depth. In the depth range from 9,300 feet to the bottom of the well, temperatures apparently have been sufficient for generation of hydrocarbons. However, in the intervals with high weight-percent organic carbon, the sapropel is of the type more likely to yield natural gas than liquid petroleum. Deeper parts of the section, not penetrated by the COST No. B–2 well, are likely to be even more thermally mature and could have acted as gas or liquid-hydrocarbon sources, depending on the type and amount of organic matter they contain.

Geophysical Studies

By D. J. Taylor, R. E. Mattick, and K. C. Bayer

Figure 3, an interpretive profile of seismic-reflection data from USGS Line 2, summarizes much of the geophysical data obtained in the Baltimore Canyon trough. Line 2, a 12-fold, common-depth-point (CDP), stacked section, was shot and processed by Digicon, Inc., in 1973. The location of the seismic line on the New Jersey shelf is shown in figure 1; the COST No. B–2 well and the onshore USGS Island Beach No. 1 well are projected into the line of section. Correlation of seismic reflectors with geologic units in the COST No. B–2 well is based on the work discussed earlier in this report together with velocity data derived from sonic logs recorded in the B–2 well (fig. 21). The correlation with the Island Beach well is based on the stratigraphic work of Perry and others (1975), pollen analyses of Doyle (written commun., 1974), and velocity analysis of the seismic-reflection data of Line 2.

SEISMIC STRATIGRAPHY

The age horizons determined from the COST No. B–2 well are illustrated in figure 3 to show their subsurface configuration. Previous determinations of the Neogene-Paleogene and Teritary-Cretaceous boundaries (Mattick and others, 1974) are in reasonable agreement with the revised interpretations made using COST No. B–2 well data.

The foreset bedding seen in the upper Tertiary section of seismic Line 2 has been interpreted by Garrison (1970) to represent a seaward progradation of deltaic sediments across the shelf during Tertiary time. As shown in figure 3, sediments from the base of the Pleistocene to the top of the Eocene thicken in a seaward direction from the Island Beach well, whereas Eocene and Paleocene beds remain relatively uniform in thickness across the seismic record section. According to Smith and others (1976), the lower Tertiary rocks produce strong seismic reflections having reflection coefficients +0.3 and −03.

Upper Cretaceous strata are rather uniform in thickness from the USGS Island Beach No. 1 well to the edge of the Continental Shelf along Line 2. Again, however, thinning is evident over the intrusion. The COST No. B–2 well data have significantly raised the Upper Cretaceous-Lower Cretaceous boundary relative to earlier estimates by Mattick and others, (1974). Previously, Lower Cretaceous sediments were thought to begin at 2.4 seconds at shotpoint 1203 (where the COST No. B–2 well is projected into the section). This determination was based on extrapolation of onshore well data into the regional dip.

Lower Cretaceous rocks clearly thicken significantly from the Island Beach well to the northwest flank of the basement intrusion (shotpoint 900). Seaward of the intrusion, the Lower Cretaceous is again thought to be thick, although perhaps thinning seaward over possible reefs in Jurassic strata under the present-day Continental Slope. A seismic horizon slightly below the top of the Lower Cretaceous represents a prominent unconformity where at least 1,300 feet of sediment was removed by erosion. Jurassic strata apparently were not found in either the Island Beach well or the COST No. B–2 well; thus, correlation of the top of the Jurassic is difficult.

Near shotpoint 600, strong reflectors appear on the seismic record section at a depth of 4.0 seconds. Interval velocities in the seismic time section between 4 and 5 seconds in this area may range from 16,000 ft/sec to more than 20,000 ft/sec. These high interval velocities are

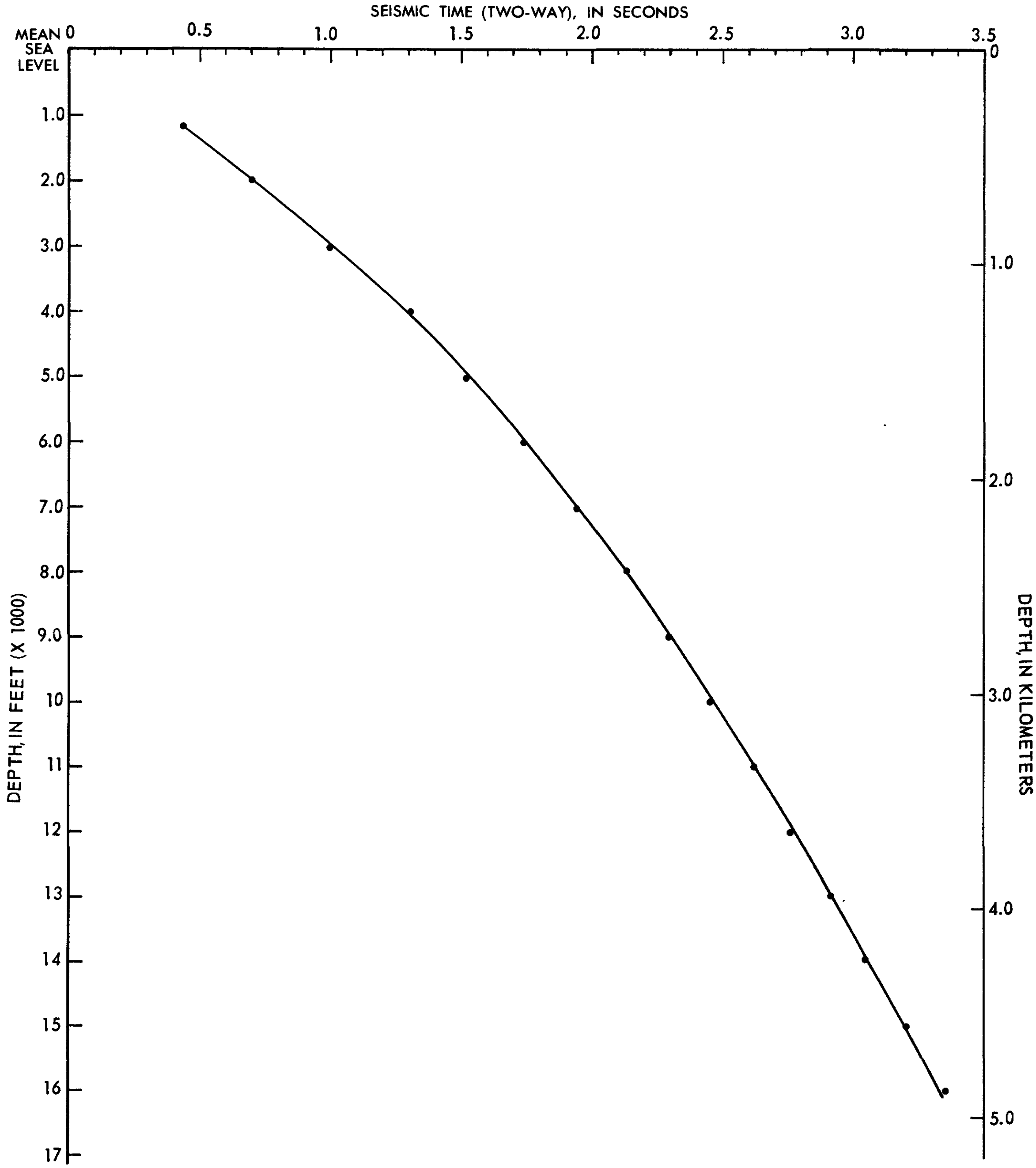


FIGURE 21.—Seismic travel time (two-way) as a function of depth from the COST No. B–2 well sonic logs.

interpreted to represent a thick Jurassic and (or) Triassic sedimentary section.

Acoustic basement is thought to appear as a distinctive diffraction pattern at a depth of 1.65 seconds on the northwest end of Line 2, which correlates with crystalline basement rocks in the Island Beach well. According to Mattick and others (1975) and Schlee and others (1976), this horizon deepens to more than 45,000 feet and appears at approximately 7 seconds (reflection time) in the vicinity of shotpoint 800. Near shotpoint 500, the basement horizon is underlain by a series of more steeply dipping reflectors. These have been interpreted by Mattick and others (1976) as representing Triassic or Paleozoic marine sediments. According to Schlee and others (1976), these reflectors may indicate layering within metasedimentary rocks thought to underlie the Baltimore Canyon trough.

Between shotpoints 900 and 1,100, sedimentary rocks, which are otherwise gently dipping, are warped upward. In this area, Taylor and others (1968) have mapped a 500-gamma magnetic high interpreted as a basement intrusion that may be in a zone of weakness near the intersection of two fault systems, one parallel to the Continental Shelf and a second oblique to the shelf edge. Although depth to basement in the vicinity of the intrusion cannot be determined from the seismic record section, John C. Behrendt (written commun., 1976), has indicated that the depth to magnetic basement at shotpoint 1,000 is between 12,000 and 13,000 feet.

Another smaller piercement structure is seen in the vicinity of shotpoint 725. As reflectors seem to continue through the structure, we assume it to be out of the plane of section.

LITHOLOGIC INFORMATION

The sedimentary section in the Baltimore Canyon trough, previously inferred from seismic response and now confirmed by COST No. B–2 well information is composed primarily of sand and shale. The relative percentages of each lithology and their degree of diagenetic alteration have been unknown until now.

As evident from the COST No. B–2 well, the upper Tertiary, from the upper Pliocene to about the middle Eocene, consists mainly of sandstone, shale, and mudstone that have been compacted to varying degrees. Seismic evidence suggests that this is true throughout the basin, the degree of compaction increasing below the lower Miocene. Relatively low interval velocities, computed along seismic-reflection Line 2 indicate that upper Tertiary rocks may remain relatively unconsolidated across the entire shelf. From middle Eocene to Late Cretaceous time, COST No. B–2 well information reveals a relatively dense, calcareous shale and sandstone sequence. These calcareous units are apparently limited to the seaward part of the basin, as indicated by a decrease in velocity in this interval as one moves toward shore. Velocity in this interval increases significantly over the basement intrusion perhaps because of increased compaction over this feature or higher sand content in the sediments.

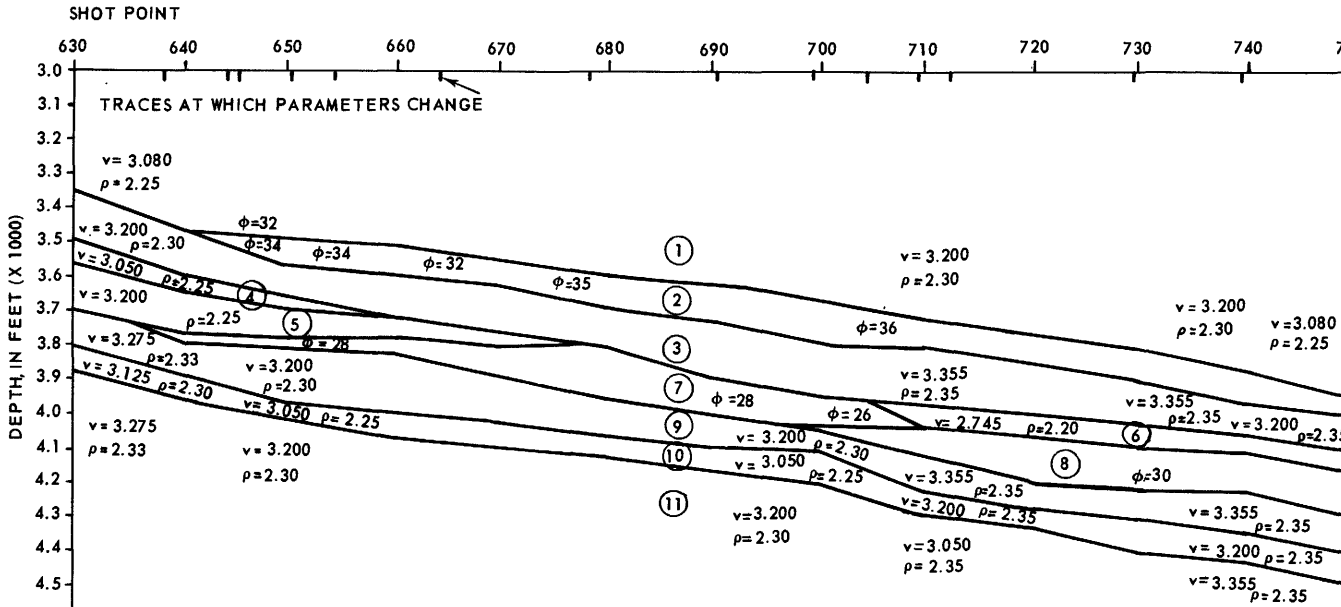
In the Upper Cretaceous strata, the seismic signals and the velocity data suggest a predominantly sandstone and shale section. COST No. B–2 well data substantiate this and show that some limestone beds are also present in this interval. Interval velocities decrease in a shoreward direction, suggesting a decrease in the carbonate content in nearshore areas.

The seismic-reflection signatures and velocity information suggest that the lithologies found in the Lower Cretaceous section in the B–2 well (mainly sandstone and shale) extend throughout much of the basin. Increases in velocity in the basal Lower Cretaceous sediments seaward of the COST No. B–2 well suggest an increase in the amount of interbedded limestone. Velocities in the Lower Cretaceous interval over the intrusion (and above the unconformtiy) do not indicate a strong increase in compaction.

Although Jurassic strata apparently were not penetrated in the COST No. B–2 well, a significant thickness of Jurassic sediments is thought to exist in the deeper parts of the basin. Seismic evidence suggests a more calcareous lithology for the Jurassic(?) section than for the overlying section. According to Maher (1971), a 100-foot carbonate sequence was found in the Esso Hatteras Light No. 1 well (North Carolina) at the top of the Jurassic or base of the Cretaceous. The interval contains oolitic limestone, porous granular dolomite, and anhydrite. Dip rates projected from onshore well data suggest that Jurassic beds thicken in an offshore direction. On the basis of a refraction survey shot by Hersey and others (1959), Gibson (1970) suggested that a thick layer of rocks, which appears to onlap crystalline basement, offshore from the Hatteras well, represents a seaward extension of the Jurassic limestone, dolomite, and anhydrite.

Carbonate rocks of Jurassic age (Abenaki Formation) have also been reported beneath the Scotian Shelf off Canada (McIver, 1972). In addition, information from DSDP hole 105 indicates that east of the Baltimore Canyon trough, near the base of the Continental Rise, about 2,000 feet of Neocomian, Tithonian, Kimmeridgian, and Oxfordian limestone overlies oceanic basement (Hollister and others, 1972).

On the basis of a velocity inversion below 40,000 feet, Mattick and others (1976) have speculated that Lower Jurassic evaporites may overlie basement rocks in the Baltimore Canyon trough area. Other evidence of evaporites on the Atlantic margin comes from well data on



Layer	Lithalagy	Fluid	Vm	ρm	Vw	ρw	Vhc	ρhc	Sw	Shc
1	Shale	—	—	—	—	—	—	—	—	—
2	Sand	Wet	5.085	2.65	1.615	1.0	—	—	100	—
3	Shale	—	—	—	—	—	—	—	—	—
4	Shale	—	—	—	—	—	—	—	—	—
5	Shale	—	—	—	—	—	—	—	—	—
6	Shale	—	—	—	—	—	—	—	—	—
7	Gas sand	Gas zone	5.085	2.65	1.615	1.0	0.610	.2	70	30
8	Gas sand	Wet zone	5.085	2.65	1.615	1.0	0.610	.2	100	—
9	Shale	—	—	—	—	—	—	—	—	—
10	Shale	—	—	—	—	—	—	—	—	—
11	Shale	—	—	—	—	—	—	—	—	—

SHALE VELOCITY AND DENSITY VARIATIONS AS INDICATED

FIGURE 22.—A computer model of possible lithologies and physical parameters determined from amplitude anomaly or "bright spot" on seismic-reflection profile (fig. 3) between shot points 630 and 750. Modeling was done by Brad Pitney of Digicon, Inc. The symbols used are as follows: V_m, matrix velocity in ft/sec; ρ_m, matrix density in g/cm^3; V_w, water velocity in ft/sec; ρ_w, water density in g/cm^3; V_{hc}, hydrocarbon velocity in ft/sec; ρ_{hc}, hydrocarbon density in g/cm^3; S_w, percent water saturation; S_{hc}, percent hydrocarbon saturation; dash, value not estimated; ϕ, porosity in percent; V, velocity in ft/sec, disregarding fluid and gas content; ρ, density in g/cm^3, disregarding fluid and gas content. Note layer 7—gas saturation is estimated to be 30 percent.

the Canadian shelf. The Shell Argo F–38 well, on the south flank of the Orpheus basin north of Nova Scotia, drilled through approximately 2,600 feet of relatively pure halite. In addition, on the basis of seismic data, Emery and others (1970) have suggested that diapiric salt structures are present along the Continental Slope and Rise off Nova Scotia. Similar structures may exist in the Baltimore Canyon trough area.

Jurassic strata are not thought to be present over the intrusion along Line 2; whether or not Jurassic is present seaward of this feature is speculative. If present, its lithology is inferred to be mainly carbonate rocks containing little salt.

AMPLITUDE ANOMALIES

True amplitude processing of Line 2 revealed an amplitude anomaly between shotpoints 640 and 760. Depth to the anomaly is 0.75 to 0.80 seconds, corresponding roughly to 3,700 to 3,800 feet. Projection from the COST No. B–2 well and from the Island Beach No. 1 well indicates that these sediments are of late Oligocene age and are composed predominantly of shale and claystone containing a few beds of coarse-grained sandstone.

Seismic modeling or "bright-spot" analyses indicates that the amplitude anomaly could be caused by a gas sand trapped between shale beds. As modeled (fig. 22), the sand is in a foreset sequence; updip migration of gas is blocked by an impermeable shale barrier. A water drive is indicated on the low side of the sand body. Maximum reservoir-sand thickness is calculated to be about 100 feet near shotpoint 680. Porosity in the gas sand was modeled as ranging from 26 percent to 28 percent. Saturation of water and gas were calculated as 70 percent and 30 percent, respectively.

Conclusions

1. The COST No. B–2 well penetrated nearly 16,000 feet of sediment in the Baltimore Canyon trough of the AOCS. The age of the sediments (determined through the examination of Foraminifera, calcareous nannofossils, and palynomorphs) is Cenozoic down to about 5,000 feet. From 5,000 to 8,100 feet, the sediments are Late Cretaceous in age, and from 8100 feet to the base of the well, they are Early Cretaceous. Although no positive indications of Jurassic sediments were found in this well, a Jurassic age cannot be ruled out for the basal 1,000 to 2,000 feet of section.
2. Early Cretaceous depositional environments in the B–2 area were apparently primarily nonmarine; occasional shallow marine incursions took place. The Late Cretaceous environments were generally shallow marine, with the exception of a nonmarine interval during the Coniacian and Santonian. During the Eocene, water depths were similar to those found on present continental slopes; later Tertiary sediments were deposited in outer- to inner-shelf environments.
3. The dominant lithologies found were sandstone and shale and minor limestone, coal, and lignite. Sand-shale ratios vary with depth but generally are 25 to 65 percent.
4. Porosities and permeabilities in the sandstone and shale section decrease rapidly as depth increases, so that below 12,000 feet, most sandstones have less than 15 percent porosity and 1 millidarcy permeability.
5. Petrographic analysis indicates that most of the sandstone is feldspathic. Much of the porosity loss seen at depth is due to breakdown of feldspar and the generation of authigenic clay and silica cement. Calcite cement is also very important, especially in zones having primary calcareous components.
6. The present geothermal gradient in the COST No. B–2 well is 1.3°F/100 feet.
7. Organic geochemistry and color alteration of visible organic matter, in conjunction with vitrinite reflectance, indicate either immaturity or low thermal maturity for most of the section down to at least 12,000 feet. Furthermore, although many units have very high organic carbon contents (as much as 12 percent), most of the sediments in the most thermally mature zones have terrestrially derived organic matter.
8. The combination of all the above factors indicates a relatively low potential for liquid-hydrocarbon generation and a relatively high potential for natural-gas generation. Deeper parts of the section (below 16,000 feet) or other parts of the Baltimore Canyon trough may have the potential to generate oil or gas, depending on the amount and character of their contained organic matter.

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