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Geological Studies of the COST GE–1 Well, United States South Atlantic Outer Continental Shelf Area

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By Peter A. Scholle, *Editor*

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By Peter A. Scholle, Editor

ABSTRACT

The COST No. GE-1 well is the first deep stratigraphic test to be drilled in the southern part of the U.S. Atlantic Outer Continental Shelf (AOCS) area. The well was drilled within the Southeast Georgia Embayment to a total depth of 13,254 ft (4,040 m). It penetrated a section composed largely of chalky limestones to a depth of about 3,300 ft (1,000 m) below the drill platform. Limestones and calcareous shales with some dolomite predominate between 3,300 and 7,200 ft (1,000 and 2,200 m), whereas interbedded sandstones and shales are dominant from 7,200 to 11,000 ft (2,200 to 3,350 m). From 11,000 ft (3,350 m) to the bottom, the section consists of highly indurated to weakly metamorphosed pelitic sedimentary rocks and meta-igneous flows or intrusives. Biostratigraphic examination has shown that the section down to approximately 3,500 ft (1,060 m) is Tertiary, the interval from 3,500 to 5,900 ft (1,060 to 1,800 m) is Upper Cretaceous, and the section from 5,900 to 11,000 ft (1,800 to 3,350 m) is apparently Lower Cretaceous. The indurated to weakly metamorphosed section below 11,000 ft (3,350 m) is barren of fauna or flora but is presumed to be Paleozoic based on radiometric age determinations. Rocks deposited at upper-slope water depths were encountered in the Upper Cretaceous, Oligocene, and Miocene parts of the section. All other units were deposited in outer-shelf to terrestrial environments.

Examination of cores, well cuttings, and electric logs shows that potential hydrocarbon-reservoir units are present within the chalks in the uppermost part of the section as well as in sandstone beds to a depth of at least 10,000 ft (3,000 m). Sandstones below that depth, and the metamorphic section between 11,000 and 13,250 ft (3,350 and 4,040 m), have extremely low permeabilities and are unlikely to contain potential reservoir rock.

Studies of organic geochemistry, vitrinite reflectance, and color alteration of visible organic matter indicate that the chalk section down to approximately 3,600 ft (1,100 m) contains low concentrations of indigenous hydrocarbons, is thermally immature, and has a very poor source-rock potential. The interval from 3,600 to 5,900 ft (1,100 to 1,800 m) has a high content of marine organic matter but appears to be thermally immature. Where buried more deeply, this interval may have significant potential as an oil source. The section from 5,900 to 8,850 ft (1,800 to 2,700 m) has geochemical characteristics indicative of a poor oil source rock and is thermally immature. Rocks below this depth, although they may be marginally to fully mature, are virtually barren of organic matter and thus have little or no source-rock potential. Therefore, despite the thermal immaturity of the overall section, the upper half of the sedimentary section penetrated in the well shows the greatest petroleum source potential.

INTRODUCTION

Until the completion of the COST No. GE-1 well, all information on the stratigraphic framework of the Southeast Georgia Embayment had come from onshore wells, offshore bottom sampling or shallow coring, geophysical surveys, or extrapolation from the COST No. B-2 well (Scholle, 1977b) located more than 750 mi (1,200 km) north of the GE-1 drill site. Between February 22 and May 31, 1977, however, the first deep stratigraphic test was drilled in the southern portion of the U.S. Atlantic Outer Continental Shelf (AOCS) by the Ocean Production Company acting as operator for a group of 25 original participating companies, the Continental Offshore Stratigraphic Test (COST) Group. This hole, designated the COST No. GE-1 well, was drilled on the outer part of the Continental Shelf about 74 mi (119 km) east of Jacksonville, Fla., at lat 30° 37′ 07.6892" N. long 80° 17′ 59.1451" W. (fig. 1). The well was drilled using the ODECO jack-up drill barge, the "Ocean Star." Water depth at the site is 136 ft (41.5 m), and drilling continued to a depth of 13,254 ft (4,040 m) below the Kelly Bushing (KB) or to 13,175 ft (4,016 m) below sea level. The well is located off-structure but directly adjacent to the area offered for leasing on March 28, 1978, as part of Lease Sale No. 43

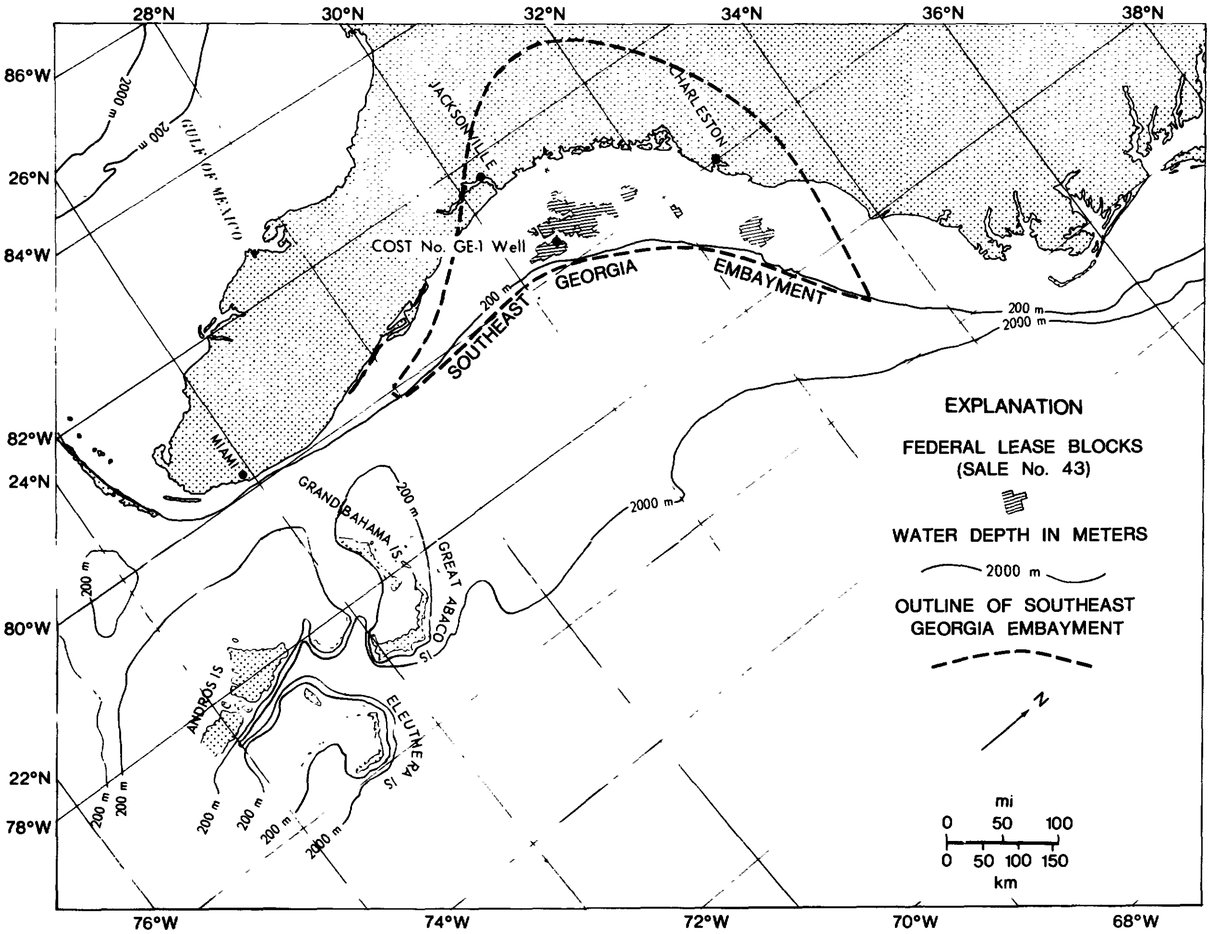


Figure 1.--Locality map showing site of COST No. GE-1 well in relation to the Southeast Georgia Embayment, Lease Sale No. 43 blocks, and coastal cities.

(fig. 1). The granting of Federal leases within 50 mi (80 km) of the GE-1 drill site on May 1, 1978, has made possible the publication of detailed information about the geological findings from the COST No. GE-1 well. Leasing stipulations provide for public disclosure by the U.S. Geological Survey (USGS) of all geological information of the well 60 days after such leasing.

Considerable basic lithologic, stratigraphic, and geochemical data, most of it derived from industry reports, have been released previously (Amato and Bebout, 1978). This Circular summarizes some of that data and adds information from other studies conducted by the USGS. It is by no means an exhaustive or completed program, but because the COST No. GE-1 well has such immediate interest for both the petroleum industry and academic workers, we believe that publication of such 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 Amato and Bebout (1978). A brief synthesis of all available data is presented in this paper in the section "Data Summary and Petroleum Potential." Much of the basic data will also be available in chart form (Scholle and others, in press).

All work reported in this paper has been done using rotary-drill cuttings 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 commonly 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 KB, which is 98 ft (30 m) above mean sea level and 234 ft (71 m) above the sediment-water interface.

ACKNOWLEDGMENTS

Technical assistance in sample preparation was provided by Patricia Brady, W. D. Marks, and Frederick Zihlman. Other technical help came from Helen Colburn, Patricia Forrestel, J. L. Hennessy, Kim Schwab, and Linda Sylvester. Discussions with Page Valentine, Wylie Poag, Kim Klitgord, John Grow, and John Schlee were very valuable in the completion of the geophysical sections. Parts or all of the manuscript was reviewed at various stages of preparation by L. M. Bybell, R. A. Christopher, O. W. Girard, Jr., R. E. Mattick, Peter Popenoe, and C. C. Smith. We are indebted to them for their many helpful suggestions.

GEOLOGIC SETTING

William P. Dillon, Kim D. Klitgord,
and Charles K. Paull

The COST No. GE-1 drill site is located on the Outer Continental Shelf, east of Jacksonville, Fla. (fig. 2). The Continental Margin off the Southeastern United States does not consist of a simple shelf, slope, and rise as it does farther north. Instead, the abyssal depths are separated from the shelf by a wide intermediate surface, the Blake Plateau (fig. 2). The gently sloping transitional surface between shelf and plateau is called the Florida-Hatteras Slope. Seaward of the Blake Plateau, south of lat 30 N., the ocean floor drops abruptly to form the Blake Escarpment, whereas, to the north, the transition to abyssal depths is less abrupt.

The main zones of basement subsidence (fig. 2) are the Blake Plateau Basin, Carolina Trough, and Southeast Georgia Embayment. The Blake Plateau Basin and Carolina Trough (fig. 2) are regions of major subsidence, amounting to more than 40,000 ft (12 km), and are believed to be floored by transitional basement (Klitgord and Behrendt, 1979). Transitional basement, as defined here, indicates a modified oceanic basement, formed of mantle-derived intrusive and extrusive mafic rocks mixed with considerable quantities of sediments and fragments of continental basement. We estimate that the COST No. GE-1 well was drilled on continental basement, but close to the western boundary of transitional basement underlying the Blake Plateau Basin.

The COST No. GE-1 well was drilled above a basement high at the seaward margin of the Southeast Georgia Embayment, a gently subsided, eastward-plunging depression recessed into the continent between two platform areas, the Carolina Platform on the north (Klitgord and Behrendt, 1979) and the Florida Platform on the south (Eardley, 1951); the embayment is probably floored by continental basement. The Paleozoic and Precambrian basement of the platforms exposed in the Piedmont is formed of igneous and metamorphic rocks (Overstreet and Bell, 1965), whereas pre-Cretaceous "basement" beneath the Coastal Plain of Georgia and northern Florida is sandstone and shale of Ordovician to Devonian age (Applin, 1951; Rainwater, 1971). However, much of the onshore part of the Southeast Georgia Embayment apparently is underlain by undeformed tuffaceous clastic deposits intermixed with basaltic and rhyolitic flows (Milton and Hurst, 1965; Milton, 1972; Barnett, 1975; Popenoe and Zietz, 1977; Gohn and others, 1978; T. M. Chowns, West Georgia College, written commun., 1976). Some of these volcanic rocks are associated with continental terrigenous deposits, presumably of Triassic age, which may have been deposited in grabens or half grabens produced during the early rifting stage of the opening of the Atlantic Ocean.

Rocks of Jurassic age do not crop out in the Southeastern United States. Upper Jurassic or Lower Cretaceous deposits may have been encountered at depth below Cape Hatteras (ESSO-Hatteras Light 1 well) and consist of finely crystalline, partly oolitic limestone and gray shale beds that grade downward into conglomerate and sandstone of possible continental origin (Spangler, 1950; Maher, 1971; Brown and others, 1972). The Lower Cretaceous-Jurassic section drilled in Florida and the Bahamas consists of shallow-marine, organic-rich carbonate rocks and, in the Bahamas (for example, in the Chevron Great Isaac 1 well), has increasing amounts of evaporite deposits at depth (Tator and Hatfield, 1975; Jacobs, 1977). An onlapping wedge of sedimentary rocks, inferred from regional stratigraphy and geophysical studies to be of Jurassic age, thickens rapidly seaward and in the Blake Plateau Basin and Carolina Trough, its thicknesses reaches 20,000-23,000 ft (7-8 km). These inferred Jurassic deposits, however, probably do not extend landward into the Southeast Georgia Embayment nor even to the COST No. GE-1 drill site (Dillon and others, 1979).

The Cretaceous and Cenozoic sedimentary rocks of the southeastern U.S. Continental Margin occur in a transitional zone between a predominantly clastic depositional province north of Cape Hatteras and a carbonate province to the south that includes Florida and the Bahamas. More than 400 wells have been drilled in Georgia and Florida, some of which reached

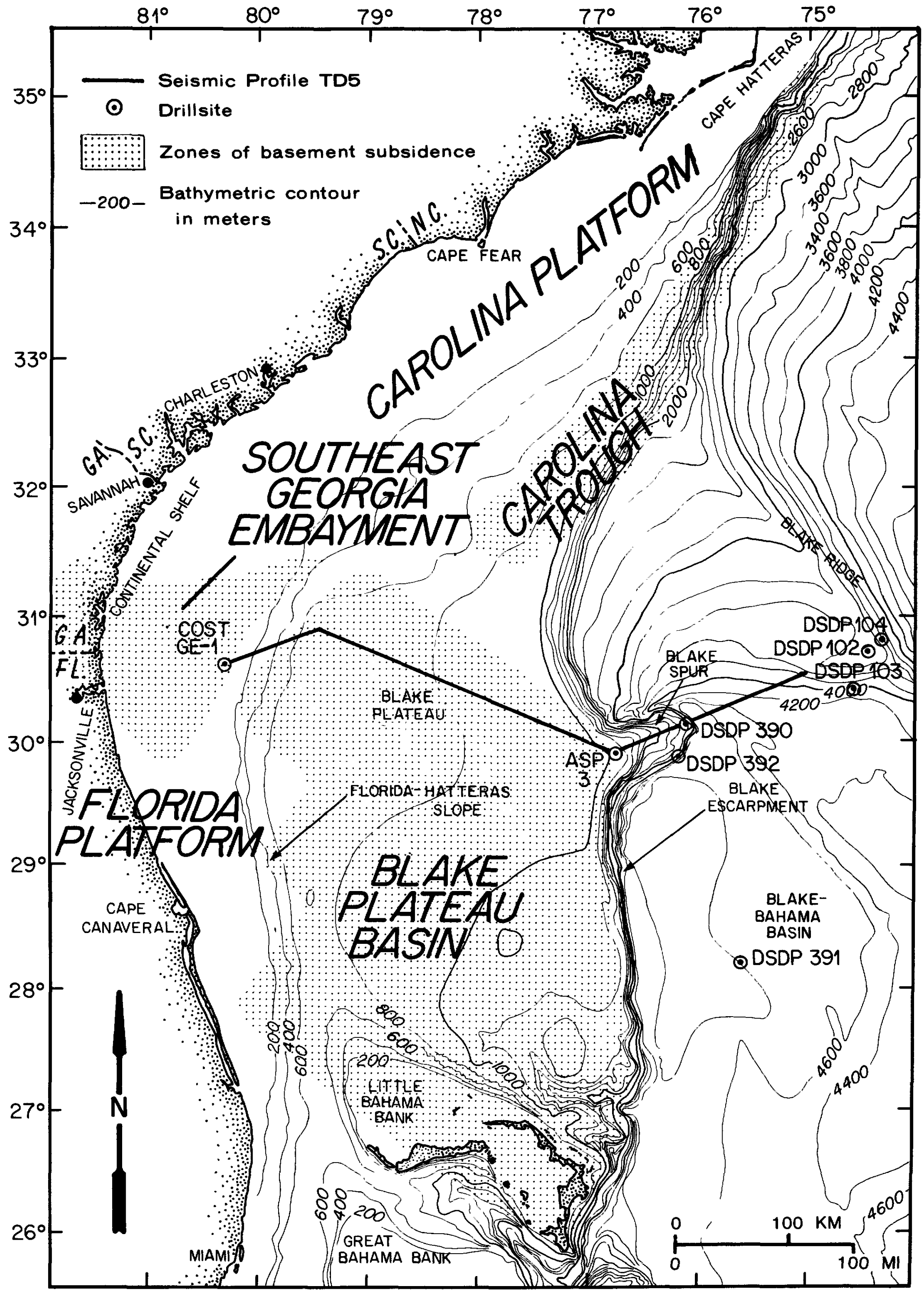


Figure 2.--Regional geologic and bathymetric features in relation to the COST No. GE-1 well, other wells, and USGS seismic line TD-5.

basement rocks. The stratigraphy and structure, therefore, are fairly well known for the onshore area (regional stratigraphy and structure are discussed by Valentine, this volume). On the other hand, only a few wells have been drilled offshore (Bunce and others, 1965; Hathaway and others, 1976; Benson and others, 1976). Cretaceous rocks were penetrated in one of these wells located on the Florida-Hatteras Slope off Charleston (USGS 6004, Hathaway and others, 1976) and in two of the wells located on the Blake Spur (DSDP 390 and 392, Benson and others, 1976). Rocks inferred to be of Cretaceous and Paleocene age underlie the Continental Margin and Coastal Plain in a broad blanket thickening to over 13,000 ft (4 km) in the Blake Plateau Basin and Carolina Trough (Dillon and others, 1979). Because these sediments are inferred to be of shallow-marine origin, the Cretaceous-Paleocene shelf apparently was very wide, extending from the present Coastal Plain to the Blake Escarpment. The COST No. GE-1 well was drilled off the Suwannee Saddle, a depression in the Cretaceous top, where Maestrichtian deposits are thinned or absent (Toulmin, 1955; Chen, 1965; Applin and Applin, 1967).

Post-Paleocene deposition was concentrated on the present Continental Shelf, probably restricted on the seaward side by the development of Gulf Stream flow across the inner Blake Plateau. The Gulf Stream not only limited shelf development and caused complicated cut-and-fill deposition against its western flank at the Florida-Hatteras Slope, but also scoured and eroded the sea floor of the inner Blake Plateau. Seaward of the Gulf Stream, a slightly thickened pod of Cenozoic deposits is present. The COST No. GE-1 well was drilled at the center of a lens of Eocene deposits which fill the seaward extension of the Southeast Georgia Embayment and account for most of the upbuilding and outbuilding of the shelf off the Georgia Coast (Paull and others, 1978; Paull, 1978).

REGIONAL STRATIGRAPHY AND STRUCTURE OF THE SOUTHEAST GEORGIA EMBAYMENT

Page C. Valentine

The stratigraphy and structure of the Southeast Georgia Embayment are relatively well known beneath the Coastal Plain from studies of the many wells drilled in Georgia and northern Florida during the last 40 years. Strata in the basin, however, dip and thicken seaward, and the basin's offshore extent is not well delineated. Until 1977, offshore drilling in the embayment had been limited to eight sites (maximum penetration of 1,000 ft (305 m)) on the Continental Shelf and inner Blake Plateau; and, until recently, deep-penetration seismic-reflection profiling in this region also had not been extensive. The COST No. GE-1 well penetrated Paleozoic basement beneath the shelf in a deep part of the Southeast Georgia Embayment, and study of this section now allows the offshore stratigraphy of the basin to be outlined. Four stratigraphic sections have been constructed across the basin to illustrate its shape, to identify the distribution of carbonate and clastic lithofacies, and to interpret the geologic development of the region (fig. 3).

The axis of subsidence of the Southeast Georgia Embayment dips seaward beneath the Georgia Coastal Plain and adjacent Continental Shelf. At the GE-1 site, on the outer part of the Continental Shelf, approximately 11,000 ft (3,350 m) of Cretaceous and Cenozoic sedimentary strata have accumulated on Paleozoic basement. The basin opens seaward beneath the Blake Plateau into a larger and deeper trough, the Blake Plateau Basin, a north-south-trending feature that contains at least 40,000 ft (12 km) of post-Paleozoic strata (Dillon, Paul, Dahl, and Patterson, this volume). The landward margins of the embayment are bounded by structural highs: the Cape Fear Arch on the northeast, the Georgia and Carolina Piedmont province on the northwest, and the Peninsular Arch on the southwest. The Cape Fear Arch extends far to seaward and is expressed in the basement and overlying rocks beyond the shelf edge (fig. 3; Popenoe and Zietz, 1977, fig. 2). Between the Peninsular Arch and the Piedmont, a minor low, the Suwanee Saddle, separates the more deeply subsided Southeast Georgia Embayment from the Southwest Georgia Embayment, a structurally similar depression that dips seaward beneath the Florida panhandle and the Gulf of Mexico (Applin and Applin, 1967, pls. 2, 4, and 6). The Upper Cretaceous and Cenozoic strata that fill the Southeast Georgia Embayment are exposed southeast of the Fall Line along the northwestern margin of the Georgia and South Carolina Coastal Plain. The outcrop pattern of the Upper Cretaceous is illustrated in figure 3.

The stratigraphic and lithofacies relationships depicted in the cross sections (figs. 4-6) draw heavily on the following investigations, outlined below by area. In some cases, a drill hole treated in more than one study may not bear the same numerical designation in each report, and a cross-check of the driller and landowner is necessary to identify the well. In this study, the designations of Florida wells are those of Applin and Applin (1967); other sources of information on these wells include Applin and Applin (1965), Goodell and Yon (1960), Puri and Vernon (1964), Chen (1965), and Maher (1971).

Georgia wells bear Georgia Geological Survey (GGS) numbers, and interpretations are based on reports by Herrick (1961), Herrick and Vorhis (1963), Chen (1965), Applin and Applin (1967), Marsalis (1970; with paleontology by S. M Herrick and E. R. Applin), Maher (1971, with paleontology by E. R. Applin), Cramer (1974), Vorhis (1974), and USGS unpublished information, 1978 (for GGS 1197).

South Carolina well sections are from Zupan and Abbott (1976) and, in the case of the Plantersville well, W. H. Abbott (South Carolina Division of Geology, oral commun., 1977). The Upper Cretaceous stratigraphy of the Fripp Island well (fig. 5) is based on unpublished studies of calcareous nannofossils by the author. Well designations are as follows: Savannah (S), Hilton Head Island (HH), Fripp Island (FI), Kiawah Island (KI), Plantersville (PV), and Myrtle Beach (MB). In North Carolina, the Calabash (C) well section, located south of Cape Fear, is from Zupan and Abbott (1976), and well NC-NH-OT-15, located north of Cape Fear, is from Brown and others (1972).

Offshore, subsurface stratigraphic information is comparatively meager and is based

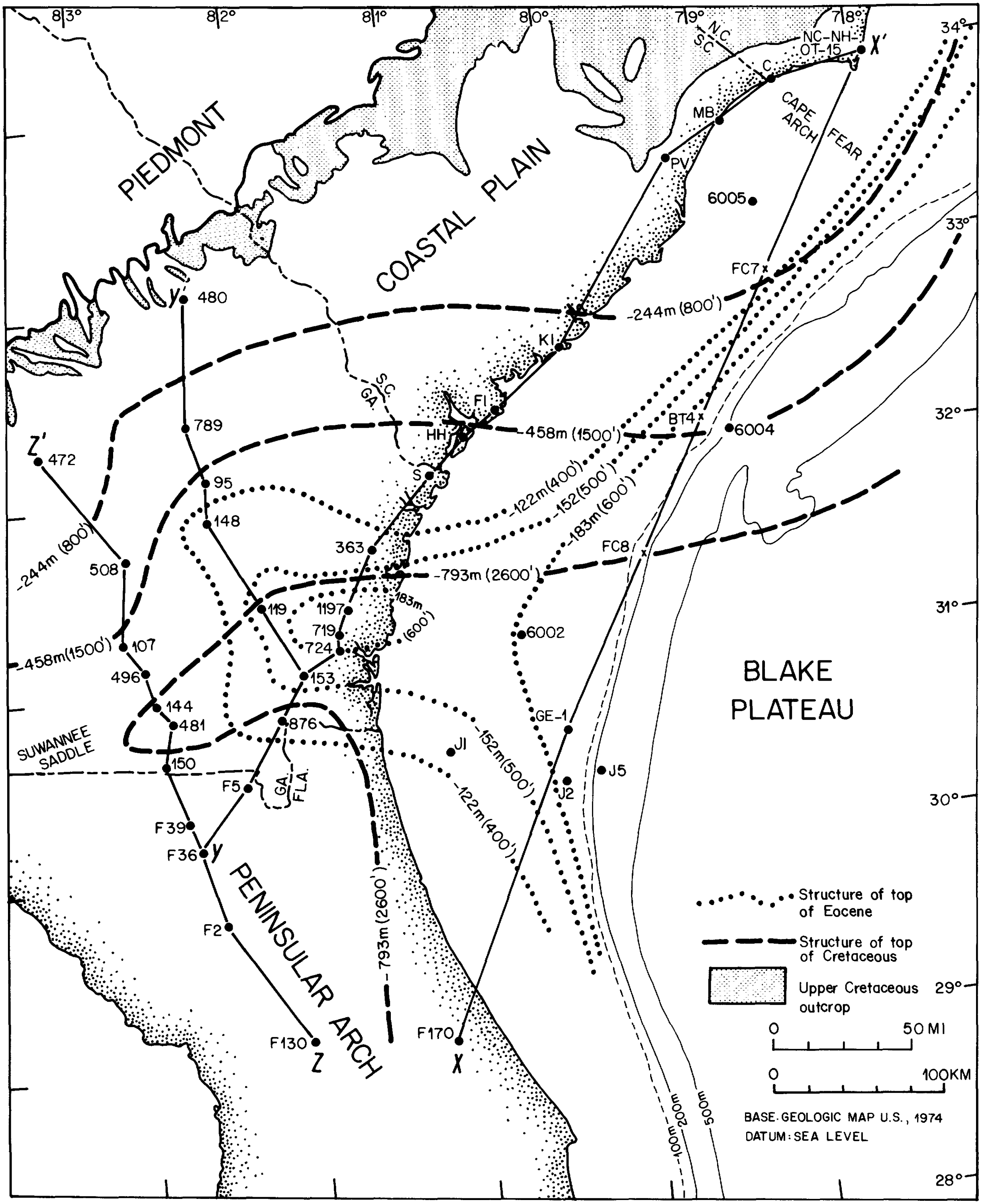


Figure 3.--Map of the Continental Margin showing locations of wells and cross sections, and structural features related to the Southeast Georgia Embayment. FC7, BT4, and FC8 indicate intersections of seismic profiles with cross section. Data base for structure contours also includes onshore wells not shown here (Herrick and Vorhis, 1963; Applin and Applin, 1967; Maher, 1971; Cramer, 1974). Well designations are as follows: Savannah (S), Hilton Head Island (HH), Fripp Island (FI), Kiawah Island (KI), Plantersville (PV), Myrtle Beach (MB), and Calabash (C).

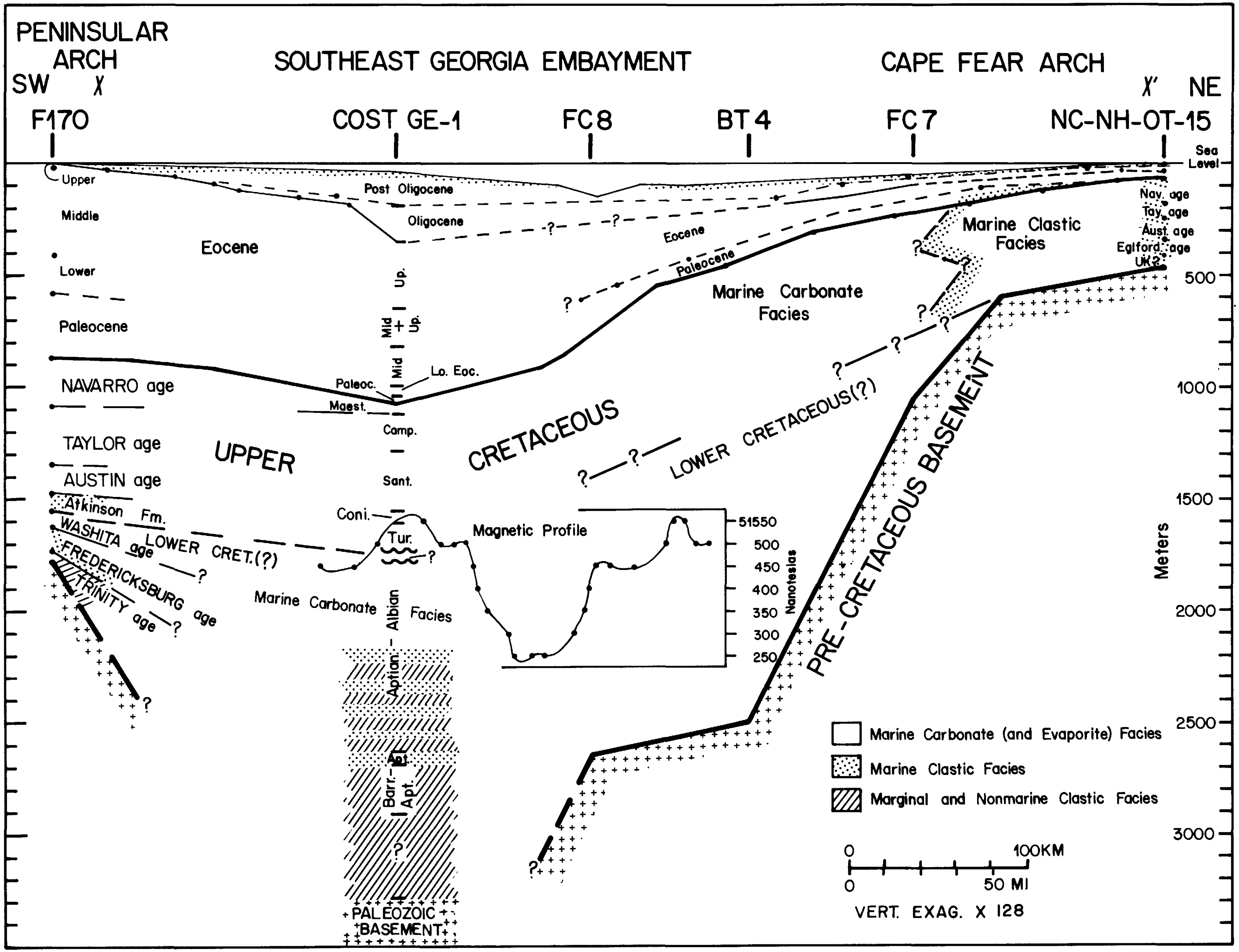


Figure 4.--Section XX' through offshore Southeast Georgia Embayment, from F170 in northeastern Florida through the COST No. GE-1 well to the NC-NH-OT-15 well at Cape Fear, N.C. FC8, BT4, and FC7 represent intersections with seismic profiles, a source of basement depths (Dillon and Paull, 1978). Magnetic profile is from Klitgord and Behrendt (1977). Datum is sea level. Well designations are as follows: Savannah (S), Hilton Head Island (HH), Fripp Island (FI), Kiawah Island (KI), Plantersville (PV), Myrtle Beach (MB), and Calabash (C).

primarily on core holes at JOIDES sites J1, J2, and J5 (Bunce and others, 1965; Charm and others, 1969; Schlee, 1977) and core holes at sites 6002, 6004, and 6005 drilled by the USGS (Hathaway and others, 1976). The locations of these drill holes are shown in figure 3.

Depth to basement, where not known from drilling, has been determined from a structure-contour map of the basement surface compiled by Popenoe and Zietz (1977) and also from interpretations of offshore seismic reflection profiles (Dillon and Paull, 1978) that intersect stratigraphic section XX′ (figs. 3, 4). The composition of basement rocks varies widely throughout this region and includes felsic and mafic igneous rocks, metamorphic and metasedimentary rocks, and in some cases clastic sedimentary strata of Triassic(?) age (Popenoe and Zietz, 1977, their table 1, and references therein).

SECTION XX′: This section (figs. 3, 4) is drawn from Cape Fear south-westward across the Continental Shelf through the COST No. GE-1 well to eastern Florida. It depicts the configuration of the southern flank of the Cape Fear Arch and the Southeast Georgia Embayment beneath the shelf edge off Georgia. The eastern flank of the Peninsular Arch appears at well F170 on the Florida coast. Pre-Cretaceous basement dips steeply into the basin from the northeast and southwest and lies approximately 10,800 ft (3,300 m) below sea level at GE-1. The shape of the basement surface must be regarded as schematic, as it is based on the drilling records of three wells and on interpretations of three seismic reflection profiles (FC7, BT4, and FC8) that cross the section (Dillon and Paull, 1978); one point is derived from the basement map of Popenoe and Zietz (1977). The pre-Cretaceous basement in the vicinity of GE-1 appears in seismic records to be an irregular, block-faulted surface containing local sedimentary basins of probable Jurassic and Triassic age (Dillon, Paull, Dahl, and Patterson, this volume). The COST No. GE-1 well was drilled on an isolated magnetic high (fig. 4) that correlates with a faulted basement block. Seismic-reflection evidence indicates that, in fact, acoustic basement drops down between GE-1 and the coast. The magnetic profile in figure 4 is from a recently published aeromagnetic study of the Atlantic Continental Margin by Klitgord and Behrendt (1977). The prominent magnetic low northeast of the GE-1 site is part of a linear magnetic high and low pair (Brunswick Anomaly) that trends southwestward from the East Coast Magnetic Anomaly and intersects the coast near Brunswick, Ga. The Brunswick Anomaly is believed to originate in a susceptibility contrast within the pre-Cretaceous basement rocks of the Southeast Georgia Embayment and to reflect a probable intrusive complex onshore and a Mesozoic structural edge offshore (Taylor and others, 1968; Pickering and others, 1977; P. Popenoe, written commun., 1978).

Lower Cretaceous rocks are well represented beneath Florida and the outer part of the Continental Shelf, but they thin toward the Cape Fear Arch and may be absent altogether at the crest. Approximately 184 ft (56 m) of Lower to Upper Cretaceous rocks, chiefly marine clastics, have been reported to overlie basement at well NC-NH-OT-15 (Brown and others, 1972; unit F, Washita and Fredericksburg age equivalents). The stratigraphic units of Brown and others (1972) that represent strata at or just above the Lower-Upper Cretaceous boundary, however, are not yet firmly dated and are presently under study (J. E. Hazel, USGS, written commun., 1976). There is some evidence that the Lower Cretaceous may be absent beneath the South Carolina Coastal Plain (Gohn and others, 1978) and, herein, the lowermost beds in NC-NH-OT-15 are questionably assigned to the Upper Cretaceous. In the south, beneath Florida, the Lower Cretaceous rocks of the Comanchean Series (Trinity, Fredericksburg, and Washita age) in well F170 represent a transgressive sequence culminating in a shallow-marine carbonate interval. A lithologically similar sequence of equivalent age occurs in the GE-1 well.

An almost complete sequence of Upper Cretaceous strata is present in the Southeast Georgia Embayment and Peninsular Arch region. In the COST No. GE-1 well, Turonian through Maestrichtian units are represented; the Cenomanian, however, is not well developed; and a poorly dated, thin, shallow-marine interval below the Turonian may mark an unconformity between the Cenomanian (or underlying Albian) and the Turonian.

On the Cape Fear Arch, the Upper Cretaceous is thinner than it is in the basin, and there are probably some hiatuses in the rock record there. A major unconformity is thought to exist in coastal South Carolina where the oldest Late Cretaceous beds, dated as Cenomanian, underlie strata of Santonian age; rocks of Turonian and Coniacian Age have not been recognized in this region (Hazel and others, 1977; Gohn and others, 1978). However, a recent unpublished study by this author of the Late Cretaceous calcareous nannofossils in the Fripp Island, S.C. well indicates that the "Cenomanian" beds in this region are at least in part Turonian (fig. 5). Offshore at GE-1, Turonian beds are well represented in the section, and the Cenomanian may be absent. The "Cenomanian" strata beneath the South Carolina Coastal Plain have been dated chiefly on the occurrences of spores and pollen, whereas the ages of the offshore units are based on marine calcareous nannofossils and planktic foraminifers. Inconsistencies in stratigraphic interpretation will persist until the zonation schemes of marine fossils and palynomorphs can be more precisely correlated. The configuration of the Upper Cretaceous surface in figure 4 is based on four wells and on an unpublished structure-contour map, part of which is illustrated in figure 3.

The entire Upper Cretaceous sequence in the Southeast Georgia Embayment and beneath Florida is composed of marine carbonate strata, excepting a short interval of marine clastics in the upper part of the Atkinson Formation in well F170. Strata on the Peninsular Arch are shallow-water, carbonate-platform deposits characteristically composed of limestone and chalk associated with evaporites. In the Southeast Georgia Embayment, at GE-1, argillaceous chalks that have a deeper-water aspect indicative of modern outer-shelf and upper-slope environments persist throughout the Upper Cretaceous section. Dark-gray carbonate silts of Maestrichtian and Campanian Age, representing a similar environment, have been cored at site 6004 (fig. 3) on the south flank of the Cape Fear Arch. In contrast, the section on the Cape Fear Arch at NC-NH-OT-15 is a marine clastic sequence containing several thin limestone beds. The location of the transition from carbonate to clastic sedimentary facies has not yet been determined and is therefore illustrated schematically in figure 4.

Cenozoic sedimentary strata vary greatly in thickness from Florida to the Cape Fear Arch along line XX′ (fig. 4). A fairly constant thickness is maintained from the Peninsular Arch into the Southeast Georgia Embayment, but unlike beds of the Upper Cretaceous, which remain relatively thick over the Cape Fear Arch, Cenozoic beds become very thin and hiatuses and overlaps are present in the section. The distribution of Tertiary units in the offshore region is not well known in detail, and unpublished structure-contour maps have been used to construct the interpretation presented in figure 4. Cenozoic strata along XX′ are carbonates, except for some Paleocene marine clastic beds cored near the coast at site 6005 on the south flank of the Cape Fear Arch, and post-Miocene carbonate and quartzose sands that are present throughout the region. The strata beneath Florida are shallow-water limestones and dolomites, whereas shelf limestones dominate the Cenozoic interval at GE-1 beneath the Continental Shelf and also at NC-NH-OT-15 on the Cape Fear Arch. Eocene limestones are by far the thickest and most widespread of the Cenozoic units. The presence of middle Eocene limestones on the Cape Fear Arch, a region of predominantly mmarine clastic deposition, indicates the unusually broad influence of the climatic regime that promoted deposition on the Atlantic margin of marine carbonates containing fossil assemblages of Gulf Coast affinity at least as far north as Georges Bank (site 6019 of Hathaway and others, 1976).

Section XX′ depicts, then, a fractured and faulted pre-Cretaceous basement at GE-1 overlain by a thick Lower Cretaceous transgressive sequence of nonmarine to marine clastics succeeded by shallow-marine carbonate rocks. Older sedimentary rocks undoubtedly occur in local basins on the faulted basement surface. To the northeast of GE-1, on the southern flank of the Cape Fear Arch, the acoustic basement surface is smooth and probably represents a volcanic layer of Jurassic age which overlies a deeper faulted surface (Dillon and Paull, 1978; seismic reflection profiles FC8, BT4, and FC7). The Upper Cretaceous and Cenozoic sequence beneath Florida is essentially a carbonate bank, whereas the geologic section across the Southeast Georgia Embayment represents the distal portion of a thick carbonate-shelf wedge that thins both to the north against the Cape Fear Arch and seaward beneath the Florida-Hatteras Slope and the Blake Plateau.

SECTION YX′: Cross section YX′, which extends from Cape Fear southwestward along the coasts of South Carolina and Georgia and into northern Florida, is shown in figure 5 (location of section is shown in fig. 3). The overall configuration of rocks of Late Cretaceous and younger age closely resembles that observed offshore in section XX′ (fig. 4). Pre-Cretaceous basement beneath Florida and southeastern Georgia in section YX′ was drawn using information from drill holes; but the six depth points from the Savannah well north along the coast and including the Myrtle Beach well are from the basement map of Popenoe and Zietz (1977, fig. 2). The magnetic profile in figure 5 (Klitgord and Behrendt, 1977) shows that the Brunswick Anomaly, mentioned above, coincides with the deepest part of the Southeast Georgia Embayment.

A major difference between this cross section and section XX′ is the change in shape and depth of the pre-Cretaceous basement surface. Onshore, beneath the coast, the shape of the basement surface is closely reflected in the Cretaceous surface, and basement is also much shallower than it is beneath the outer part of the Continental Shelf. The basement plunges seaward from a depth of about 4,700 ft (1,430 m) below sea level in well 719 in coastal Georgia (fig. 5) to approximately 10,800 ft (3,300 m) at the GE-1 site (fig. 4). In the deepest part of the basin onshore, the base of the Atkinson Formation (in this region, the lowest recognized stratigraphic unit of the Upper Cretaceous) is less than 330 ft (100 m) above basement (fig. 5), whereas, at GE-1, more than 4,600 ft (1,400 m) of Lower Cretaceous beds are present above basement.

The unit that underlies the Atkinson Formation (fig. 5) is relatively thin (less than 330 ft (100 m) thick) throughout eastern and southern Georgia (Herrick and Vorhis, 1963, fig. 19; Cramer, 1974, fig. 3) and is composed of nonmarine, varicolored, clastic sedimentary rocks. Herrick and Vorhis (1963) referred to this unit as questionable Lower Cretaceous, chiefly on the basis of its stratigraphic equivalence with marine strata to the south in

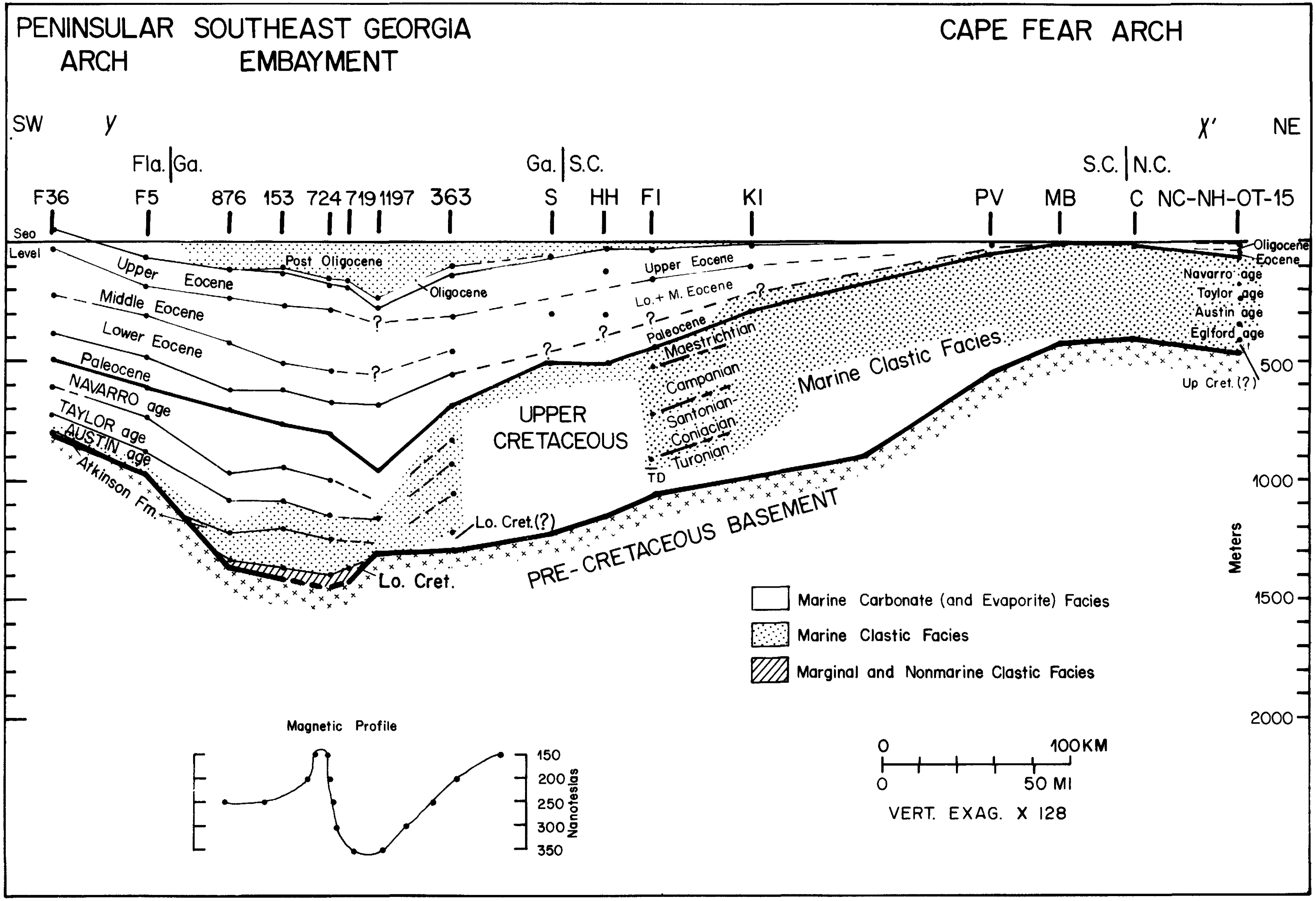


Figure 5.--Section YX′ from the Peninsular Arch in northern Florida through the Southeast Georgia Embayment in coastal Georgia and South Carolina to the Cape Fear Arch. Wells S, HH, FI, KI, PV, and MB do not reach basement; depths to basement are from Popenoe and Zietz (1977). Datum is sea level. Well designations are as follows: Savannah (S), Hilton Head Island (HH), Fripp Island (FI), Kiawah Island (KI), Plantersville (PV), Myrtle Beach (MB), and Calabash (C).

Florida; Applin and Applin (1967) placed it in the Comanchean Series. The exact age of the unit is unknown at present and it is designated Lower Cretaceous(?) in figure 5.

The Upper Cretaceous Series maintains a relatively uniform thickness along section YX′ (fig. 5). In contrast to the Upper Cretaceous marine carbonate sequence offshore, the marine clastic facies is well represented along the coast, especially in the deeper part of the Southeast Georgia Embayment and on the Cape Fear Arch. During Atkinson and early Austin time, the entire region was a marine clastic province. Subsequently, shallow-marine carbonate and evaporite beds were deposited offshore and in Florida and transgressed westward and northward into southeastern Georgia. The carbonate facies persisted here throughout the Late Cretaceous, but only the youngest unit, the Lawson Limestone of Maestrichtian Age, is present farther to the north where it grades into marine clastics between wells 1197 and 363 (fig. 5).

The Cenozoic sequence onshore in section YX′ has a configuration similar to that of equivalent strata offshore. A thick sequence of Paleocene through Oligocene beds occurs in northern Florida and southeastern Georgia but thins markedly to the north over the Cape Fear Arch. The Southeast Georgia Embayment is narrower here than offshore, and the Cretaceous-Tertiary boundary is only about 410 ft (125 m) higher beneath the coast than it is at GE-1, indicating that the floor of the embayment at this level is comparatively flat beneath the Continental Shelf. The marine clastic facies is limited to a thin interval of Paleocene age on the south flank of the Cape Fear Arch and to post-Oligocene strata that fill the uppermost part of the basin in eastern Georgia. Most of the Cenozoic strata are carbonates that include shallow-marine limestones, dolomites, and minor amounts of evaporites in Florida, and chiefly limestones of shelf origin in Georgia and South Carolina. Eocene strata are again the thickest and most widespread of the Tertiary units. Section YX′ (fig. 5) clearly illustrates the northward transgression of the marine carbonate province during the Late Cretaceous and Tertiary, as well as the pronounced buildup of the carbonate facies in Florida and southeastern Georgia.

SECTIONS YY′ and ZZ′: Two sections, YY′ and ZZ′, that extend from the interior of the Georgia Coastal Plain southward into northern Florida are presented in figure 6 (section locations shown in fig. 3). These sections exhibit stratigraphic and structural relationships that are in many respects similar to those observed along the coast in section YX′ (fig. 5), although significant differences do exist. The basement surface in the axis of the Southeast Georgia Embayment rises from approximately 4,700 ft (1,430 m) at the coast to about 3,950 ft (1,200 m) in south-central Georgia (fig. 6B). Section ZZ′ is located somewhat east of the Suwannee Saddle, where the basement becomes even shallower, about 3,600 ft (1,100 m) below sea level, before it dips into the Southwest Georgia Embayment. The Suwannee Saddle, a shallow depression terminating the Peninsular Arch on the northwest, separates the Southeast Georgia Embayment and the Southwest Georgia Embayment. The saddle can be observed in structure-contour maps at all levels from the Pre-Cretaceous basement surface (Popenoe and Zietz, 1977) through the Eocene and perhaps the Oligocene (Herrick and Vorhis, 1963; Chen, 1965; Applin and Applin, 1967). As the Southeast Georgia Embayment narrows to the west, the basement surface beneath the northern margin dips more steeply southward (figs. 5, 6).

The pattern of facies change observed in section YX′ (fig. 5) is repeated in the two profiles in figure 6. Marginal and nonmarine clastics are overlain by marine clastics that are in turn succeeded by a thick sequence of marine carbonates. It is evident that, in the western part of the basin (section ZZ′, fig. 6B), the marginal and nonmarine Lower Cretaceous(?) rocks are significantly thicker than in the east and that the thickest accumulation of Cretaceous deposits is located somewhat north of the greatest thickness of Tertiary strata. Marine clastics of the Atkinson Formation grade into the marginal and nonmarine clastic beds of the Tuscaloosa Formation updip along the northern margin of the basin. Navarro-age strata are present throughout the Southeast Georgia Embayment, but, according to Applin and Applin (1967, pl. 6A), they are absent both from the Suwannee Saddle area and also from a broad region in the Southwest Georgia Embayment. In section ZZ′, near the Suwannee Saddle, the Upper Cretaceous is markedly thinner in wells 150, 481, 144, and 496 than to the north, and beds of Navarro age are absent at well 144. Much of the thinning occurs in Navarro-age strata that lie near the transition between the marine carbonate facies in the south and the marine clastics in the north.

Synthesis of stratigraphy and structure

Beneath the Coastal Plain of North and South Carolina and central Georgia, the acoustic basement dips southeastward and strikes parallel to the Fall Line, a regional trend that is interrupted in northern Florida and in the coastal and offshore areas of the southeastern Continental Margin (Popenoe and Zietz, 1977, fig. 2). The basement is depressed in southeastern Georgia and beneath the Continental Shelf, forming a basin--the Southeast Georgia Embayment--that opens seaward into an even deeper basin beneath the Blake Plateau. The Southeast Georgia Embayment is shallow beneath the Georgia Coastal Plain (4,600-4,900 ft (1,400-1,500 m) below sea level; fig. 5), but deepens rapidly seaward to about 10,800 ft (3,300 m) beneath the outer part of the Continental Shelf at the COST No. GE-1 well (fig. 4). The basin is probably considerably deeper locally in areas of down-faulted basement blocks beneath the shelf; farther offshore, basement lies at a depth of at least 40,000 ft (12 km) beneath the Blake Plateau Basin (Dillon, Paull, Dahl, and Patterson, this volume). The wide range of pre-Cretaceous rock types

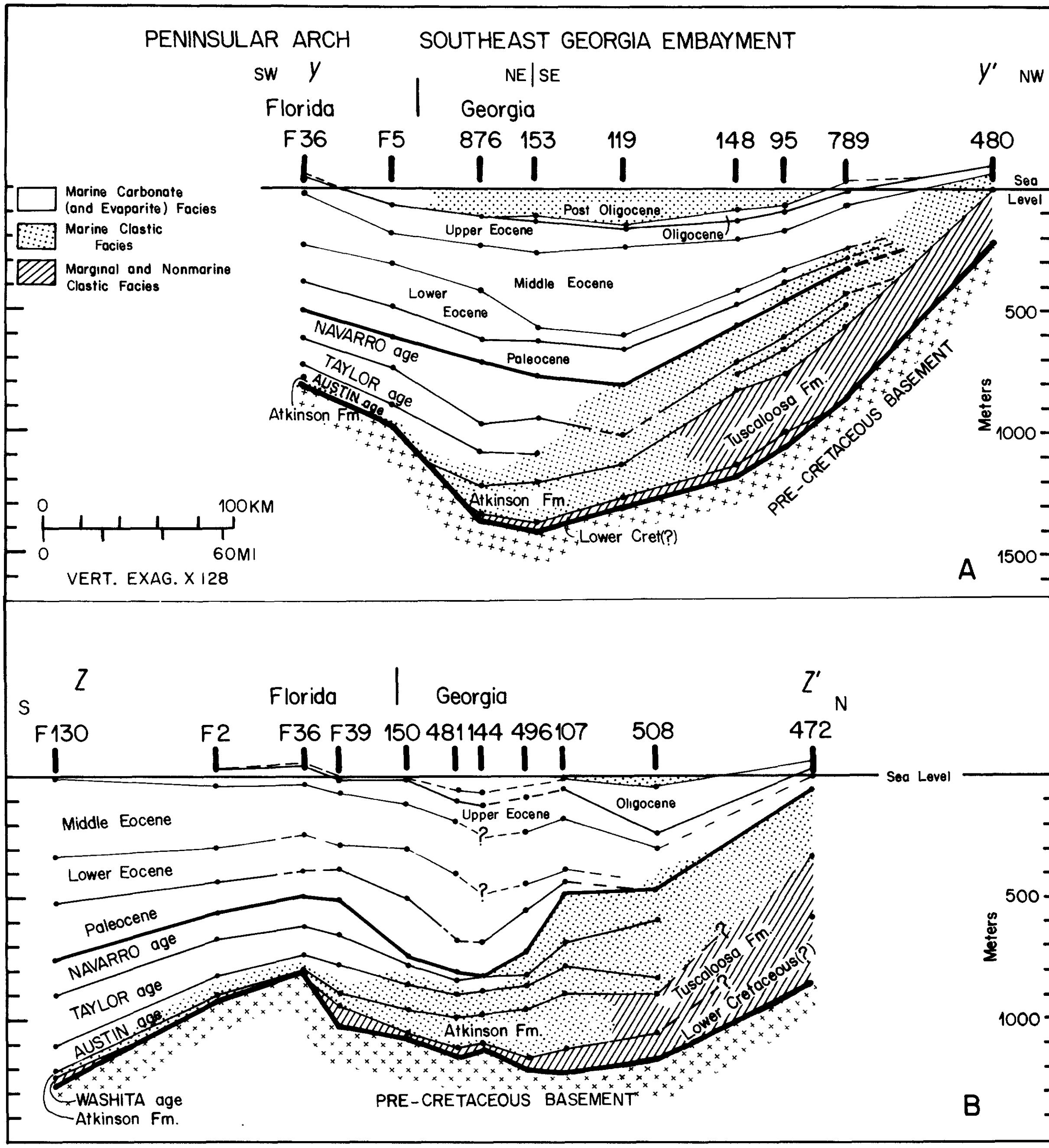


Figure 6.--Sections extending from the Peninsular Arch in northern Florida through the Southeast Georgia Embayment updip toward the Fall Line. Datum is sea level. A, Section YY'; B, Section ZZ'. Well designations are as follows: Savannah (S), Hilton Head Island (HH), Fripp Island (FI), Kiawah Island (KI), Plantersville (PV), Myrtle Beach (MB), and Calabash (C).

represented in the basement beneath the Southeast Georgia Embayment suggests that this surface has a complex developmental history (Barnett, 1975; Popenoe and Zietz, 1977). Cretaceous and younger strata have been deposited on this eroded and, in part, block-faulted surface that has subsided between two relatively stable features, the Cape Fear Arch on the northeast and the Peninsular Arch on the southwest.

The basal sedimentary units beneath the eastern Georgia Coastal Plain have not yet been dated and are designated as Lower Cretaceous(?) in figures 5 and 6. Lower Cretaceous(?) strata are poorly represented in the Southeast Georgia Embayment beneath the Coastal Plain; they are apparently absent in northeastern Georgia, are at most 330 ft (100 m) thick in eastern Georgia, and are thickest (660 ft (200 m or less)) in the western shallowest part of the basin (fig. 6; Herrick and Vorhis, 1963; Cramer, 1974). These beds are nonmarine, varicolored clastics that have been assigned an Early Cretaceous(?) age on the basis of correlations with dated rocks in northern Florida that are inferred to be stratigraphic equivalents (Herrick and Vorhis, 1963, p. 51). In South Carolina, near Charleston, a deep core hole was recently drilled by the U.S. Geological Survey (Hazel and others, 1977; Gohn and others, 1977); and the oldest sedimentary strata were found to be Cenomanian in age. However, they overlie a short interval (33 ft (10 m)) of unfossiliferous strata that rest on weathered and geochemically altered basalt (radiometric age of basalt approximately 95-105± 4 m.y., a minimum age). Gohn, Gottfried and others (1978) reported that subsequent nearby core holes penetrated the basalt (843 ft (257 m) thick; radiometric ages, Late Triassic and Early Jurassic) and drilled into underlying clastic red beds of unknown age that resemble Triassic (or Jurassic) rocks exposed in the Piedmont (Gohn and others, 1978). A recent study of a series of coastal wells in South Carolina (Gohn and others, 1978) indicates that Lower Cretaceous beds are probably absent and that, therefore, a major regional unconformity exists between the Upper Cretaceous and underlying pre-Cretaceous sedimentary rocks or crystalline basement beneath the South Carolina Coastal Plain. Even if true Lower Cretaceous is present beneath the southeastern Coastal Plain, its thinness and somewhat patchy occurrence represent the effect of a major erosional episode prior to deposition of Upper Cretaceous sediments.

Offshore, as basement dips beneath the Continental Shelf, the Lower Cretaceous becomes much thicker. It is about 5,000 ft (1,500 m) thick at GE-1 and may be even thicker in adjacent, down-faulted areas beneath the shelf. At GE-1, the Lower Cretaceous consists of nonmarine and marine clastic rocks succeeded by shallow-water marine carbonate units that are separated from overlying Upper Cretaceous shelf limestones of Turonian age by a short interval of undated shallow-water strata. There is no direct information regarding the nature of Lower Cretaceous rocks seaward beneath the Blake Plateau, but shallow-water carbonate bank and reef deposits of Early Cretaceous age are present at the outer edge of the Blake Plateau, on the Blake Spur, where they are overlain by Barremian-Albian pelagic oozes (Benson and others, 1976; site 390).

In summary, during the Early Cretaceous, the part of the present Southeast Georgia Embayment that underlies the modern Continental Shelf was a depositional area characterized in part by a smooth volcanic basement of Jurassic(?) age and also by block-faulted Paleozoic basement containing numerous basins filled with marine and nonmarine clastic sedimentary rocks. Seaward, beneath the present Blake Plateau, a shallow-water carbonate platform developed that became a pelagic province as the Continental Margin subsided during Barremian-Albian time. At GE-1, this subsidence is marked by the occurrence of shallow-marine carbonates of Aptian-Albian Age. Beneath the Coastal Plain, the western part of the present basin experienced subsidence on a much smaller scale during the Early Cretaceous. The basement is much shallower than it is offshore, and only a relatively thin interval of nonmarine clastic beds of Early Cretaceous(?) age is present. Certainly, no basin deposits developed beneath the present southeastern Georgia Coastal Plain, and the Southeast Georgia Embayment did not exist onshore; deposition was concentrated in the subsiding region beneath the modern shelf and seaward.

A comparison of the Coastal Plain cross sections (figs. 4-6) reveals that the Upper Cretaceous becomes thicker seaward and does not vary radically in thickness along the regional strike of the Continental Margin in the coastal regions of northern Florida, Georgia, South Carolina, and even over the Cape Fear Arch (section YX′, fig. 5; Applin and Applin, 1967, pl. 6B; Maher, 1971, pl. 17B; Brown and others, 1972, pl. 49; and Cramer, 1974, fig. 4). The distributional nature of the Upper Cretaceous is in marked contrast to that of Cenozoic deposits which are concentrated in the Southeast Georgia Embayment. It appears that the Upper Cretaceous strata were deposited in a sedimentary wedge on a regionally subsiding continental margin or in a broad marginal basin. Local subsidence did occur, however, northwest of the present Southeast Georgia Embayment in west-central Georgia, and the Upper Cretaceous is thicker there than it is to the southeast. This thickening can be observed at the northern end of section ZZ′ (fig. 6B, wells 508 and 472). South of this area of subsidence, the margin was apparently stable (or uplifted) over the northern end of the present Peninsular Arch; here, on the Suwannee Saddle, and to the west, Navarro-age strata are absent (fig. 6B), and their absence is attributed by Applin and Applin (1967, figs. 3, 4, pl. 5C) to lack of deposition on an area of regional uplift. Earlier studies have called upon a slow rate of deposition in a subsiding area (Hull, 1962; Chen, 1965) or on post-Cretaceous erosion (Toulmin, 1955) to explain the thinning and local absence of Navarro-age strata in this region.

In a broad sense, the Upper Cretaceous deposits represent a transgressive sequence. In Florida and Georgia, sections YY′ and ZZ′ (fig. 6) illustrate the interfingering of the marine clastic Atkinson Formation with the marginal and nonmarine clastic Tuscaloosa Formation that lies updip to the north and west. Marine clastics are transgressed from the south and east by shallow marine carbonate platform deposits of Austin, Taylor, and Navarro age that extend from Florida into southern and southeastern Georgia (figs. 4-6). Offshore, carbonate shelf deposits are represented throughout the Upper Cretaceous sequence at GE-1 (fig. 4). Interpretations of seismic-reflection profiles of the shelf and Blake Plateau imply the presence of shelf carbonates seaward beneath the Blake Plateau (Dillon, Paull, Dahl, and Patterson, this volume) that grade into pelagic oozes (Benson and others, 1976, site 390) deposited in deeper water resulting from subsidence of the margin.

The Upper Cretaceous Series, therefore, was deposited on a broad continental margin and, during the early part of the Late Cretaceous, marine shelf clastics were deposited in northern Florida and in the eastern regions of Georgia and the Carolinas. A carbonate platform soon became established in Florida and persisted throughout the Late Cretaceous. Marine clastics were transgressed by carbonates in southeastern Georgia, but they remained dominant elsewhere beneath the Georgia and South Carolina Coastal Plain and northeastward over the present Cape Fear Arch. Carbonate shelf sediments accumulated beneath the present Continental Shelf and somewhat seaward beneath the present Blake Plateau, while pelagic carbonate oozes collected in deeper water at the seaward edge of the subsiding margin.

Cenozoic sedimentary rocks in the Southeast Georgia Embayment are chiefly carbonates (figs. 4-6). In northern Florida, on the Peninsular Arch, these strata were deposited in shallow water and represent the continued buildup of the carbonate platform that developed in the Late Cretaceous. To the north, in Georgia and the Carolinas and also offshore beneath the Continental Shelf, shelf limestones predominate and transgress Tertiary clastics updip on the northern and western margins of the basin. Miocene and Quaternary clastics, chiefly calcareous quartz sands and sandy silts, occur beneath the Georgia and South Carolina Coastal Plains, but are less significant offshore beneath the Continental Shelf. Tertiary and Quaternary calcareous oozes are present beneath the Blake Plateau (Bunce and others, 1965; Charm and others, 1969, sites J3, J6; Benson and others, 1976, site 390; Schlee, 1977).

The thickest accumulation of Cenozoic beds occurs beneath the coast in southeastern Georgia and offshore beneath the Continental Shelf; the top of the Cretaceous dips very gently seaward in this region, and the Cenozoic is 2,950-3,300 ft (900-1,000 m) thick (figs. 4, 5). The section becomes somewhat thinner westward toward the Suwannee Saddle (fig. 6). And, to the south, Paleocene and Eocene strata remain rather uniform in thickness over the Peninsular Arch, whereas post-Eocene beds are considerably thinner and in part eroded away. On the northeastern margin of the basin, the Cenozoic strata thin dramatically over the Cape Fear Arch (fig. 5), and all the Tertiary units are to some extent absent and overlapped by younger strata; the stratigraphic relations are not unlike those observed among Cretaceous and Cenozoic units at the Fall Line to the west.

The Cape Fear Arch, part of the Carolina Platform (Dillon, Kiltgord, and Paull, this volume), is the dominant positive feature beneath the southeastern Coastal Plain and Continental Shelf. Maher (1971), and earlier Siple (1959) and Bonini and Woollard (1960), reviewed previous studies of the stratigraphy and structural origin of the arch. Previous authors treated the Cape Fear Arch as an uplifted basement feature associated with downwarping on the northeast and southwest; and the complex stratigraphy of the area, involving erosional hiatuses and the overlapping of strata, has been interpreted as evidence for the occurrence of mutiple movements of the basement, chiefly in the Tertiary.

The present study is an evaluation of the regional stratigraphy and structure of the southeastern Continental Margin; and detailed stratigraphic relationships, especially in the Cape Fear Arch area, are not treated. Nevertheless, it appears that a somewhat different view of the structural development of the Southeast Georgia Embayment and the Cape Fear Arch is justified, one that emphasizes subsidence in the basin rather than uplift on its margins.

It is clear from published maps portraying the basement surface (Bonini and Woollard, 1960, fig. 4; Maher, 1971, pl. 4; Popenoe and Zietz, 1977, fig. 2) that the basement bulges seaward at the Cape Fear Arch and is recessed landward in the Southeast Georgia Embayment. This configuration is expressed in the overlying units, including the Upper Cretaceous (fig. 3) and the Paleocene (P. Valentine, unpublished structure-contour map). The thickness of the Upper Cretaceous in the Southeast Georgia Embayment and over the Cape Fear Arch is more uniform than that of the overlying Tertiary (fig. 5). Upper Cretaceous beds thicken somewhat in the Southeast Georgia Embayment, but not markedly (fig. 5; Maher, 1971, pl. 17B), an indication that during the Late Cretaceous neither the embayment beneath the present Coastal Plain nor the Cape Fear Arch was active in opposing senses, but that the entire margin subsided almost uniformly. The Paleocene does thicken somewhat in the basin beneath the Georgia coast (fig. 5) and may signal the onset of localized subsidence in this region. However, the Paleocene is very thin offshore (fig. 4), and interpretations of seismic profiles show that it is thin throughout the offshore region; like the Upper Cretaceous, it evidently was deposited on a gently dipping continental margin that preceded the formation of the present Continental Shelf. As the result of subsequent subsidence, the deposition of younger rocks, and compaction, the Upper Cretaceous and the Paleocene surfaces have assumed the shape of the underlying basement surface.

The Eocene, on the other hand, exhibits a different configuration. This unit is very thick in the Southeast Georgia Embayment beneath the Coastal Plain (fig. 5) and even thicker offshore at GE-1 (fig. 4). Herrick and Vorhis (1963, p. 55) postulated a middle Eocene age for the onset of local subsidence in the Southeast Georgia Embayment, apparently because the middle Eocene is the oldest unit exhibiting local thickening in the embayment according to their isopach maps (Herrick and Vorhis, 1963, fig. 9). Evidence from offshore drilling (Bunce and others, 1965; Schlee, 1977) indicates that the modern Continental Shelf became established during the Eocene; and, in fact, the progradational nature of this unit is visible in seismic profiles across the shelf (Dillon, Paull, Dahl, and Patterson, this volume). Eocene and younger rocks, therefore, were laid down on a continental margin upon which a continental shelf was forming, and the deposits became very thick in an actively subsiding Southeast Georgia Embayment while remaining thin on the Cape Fear Arch. The structure contours on the top of the Eocene over the arch (fig. 3) do not conform to the shape of the basement surface; they cut across the structure-contour trends of the older units (the Upper Cretaceous in fig. 3) but parallel the general structural trend of the modern shelf and retain the shape of the original depositional surface. Oligocene structure contours and post-Oligocene isopachs (P. Valentine, unpublished maps) exhibit a similar configuration.

If the Cape Fear Arch had been uplifted numerous times during the Tertiary, the configuration of the Upper Cretaceous and Cenozoic beds over the arch would have been affected similarly; structure contours of these strata on the arch would have been displaced seaward, and south of the arch their angle of incidence to the coast would have increased. As shown in figure 3, Eocene structure contours are oriented subparallel to the Fall Line, the coast, and the shelf edge; they exhibit no seaward bulge attributable to uplift of the arch. Subsidence during the Tertiary has occurred mainly in the Southeast Georgia Embayment while the Cape Fear Arch has remained relatively stable, and the shape of the Upper Cretaceous surface (fig. 3) is the result of this differential downwarping. When further subsidence, deposition, and compaction occur in the area, the structure contours of the Eocene and younger beds will conform to those of the underlying older units in that region. The thinness of Tertiary beds on the arch and the erosional hiatuses within them are chiefly the result of repeated oceanic transgressions and regressions over a basement feature that is basically stable, although minor isostatic adjustments undoubtedly occurred due to sediment loading and continual upward adjustment of the Appalachian Mountains.

Offshore, the Cenozoic strata of the southeastern Continental Margin have been investigated by many workers. Most recently, Schlee (1977) studied the lithology of six offshore core holes in this region (Bunce and others, 1965); he also reviewed the work of previous authors and elucidated the Cenozoic geologic development of the Southeast Georgia Embayment and the Blake Plateau Basin. The present study supports the previous findings in most respects. The dip reversal on the Eocene surface beneath the Georgia coast and inner shelf, noted by Schlee (1977, fig. 8), is also evident in the structure-contour map in figure 3; and a similar dip reversal in the same area is present on the Oligocene surface (P. Valentine, unpublished map). The structural low on the Eocene (fig. 3) is overlain by only about 165 ft (50 m) of Oligocene beds. The Oligocene is very thin beneath the Georgia Coastal Plain (Herrick and Vorhis, 1963, fig. 4; Cramer, 1974, fig. 9) and, unlike both older and younger strata, no depocenter is discernible. This lack is the result of extensive erosion during an oceanic regression, probably in the early Miocene. The Miocene depocenter is located over the structural low on the Eocene surface (fig. 3; Cramer, 1974, fig. 10). Miocene strata thin seaward but subsequently thicken beneath the outer shelf at GE-1.

The occurrence of pelagic carbonate oozes throughout the Cenozoic section beneath the Blake Plateau indicates that subsidence of this region, initiated in the Early Cretaceous at the present Blake Escarpment, has continued to the present. The Cenozoic development of the Southeast Georgia Embayment and the Continental Shelf resulted from the deposition and progradation of Eocene and younger sediments. These sediments were laid down at a much higher rate here than they were seaward beneath the Blake Plateau, where, during this time, submarine currents inhibited deposition of sediments and even caused extensive erosion of the thin Cenozoic beds now found there.

DATA SUMMARY AND PETROLEUM POTENTIAL

Peter A. Scholle

The COST No. GE-1 well penetrated 13,039 ft (3,974 m) of Cenozoic to Paleozoic section. Lithologic, biostratigraphic, and paleoenvironmental studies, summarized in figure 7 and table 1, indicate that the section to a depth of about 3,300 ft (1,000 m) consists primarily of Eocene and Oligocene chalks deposited in middle-shelf to upper-slope environments. The Oligocene and Miocene portions of the section were deposited in the deepest waters, probably in upper-continental-slope conditions. The depth interval from 3,300 to 4,600 ft (1,000-1,400 m) consists of Upper Cretaceous, Paleocene, and lower Eocene calcareous shales and subordinate limestones. Estimates of depositional environments for these beds range from middle shelf to upper slope. From 4,600 to 7,200 ft (1,400-2,200 m), limestones and dolomites with interbedded sandstones and shales predominate. The section is Albian to Senonian in age, and estimates of depositional environments range from inner to outer shelf. Between 7,200 and 11,000 ft (2,200-3,350 m), interbedded sandstones and shales predominate, although individual beds of limestone, dolomite, anhydrite, and, in the lower part of the section, coal are common. These units, deposited in inner-shelf to terrestrial environments, are largely barren of fossils. They have been tentatively dated as Early Cretaceous, however. Below 11,000 ft (3,350 m) to the bottom of the well, the section is composed of green and gray-green, very fine grained, highly indurated to weakly metamorphosed, pelitic sedimentary rocks, with intrusive and (or) extrusive meta-igneous rocks especially abundant in the lower part of this interval. Dating of several samples of metamorphosed igneous rocks from this interval (Simonis, this volume) yielded values around 355 million years before present (m.y.B.P). This may reflect a thermal event in the Upper Devonian and puts a minimum age on the metasedimentary section.

Detailed biostratigraphic data on the GE-1 well is shown in table 1. Reasonably good agreement exists between the three studies shown. The greatest disagreement occurs in the placement of the boundaries of the Upper Cretaceous stages; even there, however, the zone of disagreement rarely exceeds 100 ft (30 m). Biostratigraphic dating of the sedimentary section below 9,000 ft (2,700 m), it should be emphasized again, is very uncertain. The section down to the metasediments at 11,000 ft (3,350 ft) is probably entirely Lower Cretaceous, but it may extend into the Jurassic. To date, no age-definitive fauna has been recovered from the 9,000- 11,000-ft (2,700- to 3,350-m) interval.

Sedimentation rates of various stratigraphic units are discussed by Poag and Hall (this volume). The highest rates of sedimentation occurred during the Albian to Senonian interval, the middle and late Eocene, and the middle Miocene. The lowest depositional rates prevailed in the Late Cretaceous (Campanian and Maestrichtian), the Oligocene, and the Pleistocene. The overall range of sedimentation rates is not great, however. Maximum rates are about 2.5 in. (6.4 cm) per 1,000 years; minimum rates are about 0.5 in. (1.3 cm) per 1,000 years.

The porosity and permeability relations of conventional and sidewall core samples from the GE-1 well are shown in figure 8. Very high porosites,in the 25-to 40-percent range, are encountered in the chalks in the 1,000- to 3,000-ft (300- to 900-m)-depth range. Corresponding permeabilities for these fine-grained limestones are, however, predictably low. Nevertheless, both oil and gas production are known from chalks of comparable petrophysical character from areas such as the North Sea, the U.S. Gulf Coast, and the U.S. Western Interior (Scholle, 1977c). Significant gas shows and potential future gas production have also been found in lithologically comparable, though older, chalks on the AOCS in the Scotian Shelf area of Canada (Scholle, 1977c). In areas where overpressuring and (or) fracturing have affected the chalks, even better reservoir character may be expected. Loss of fluid circulation in the chalk and calcareous shale interval from 2,800 to 4,900 ft (850-1,500 m) during the drilling of the GE-1 well indicates that fracturing may be significant in that part of the section.

In the interval from 5,700 to 7,200 ft (1,750-2,200 m), porosity values in the mixed assemblage of limestones, dolomites, and sandstones are varied and unsystematic. The

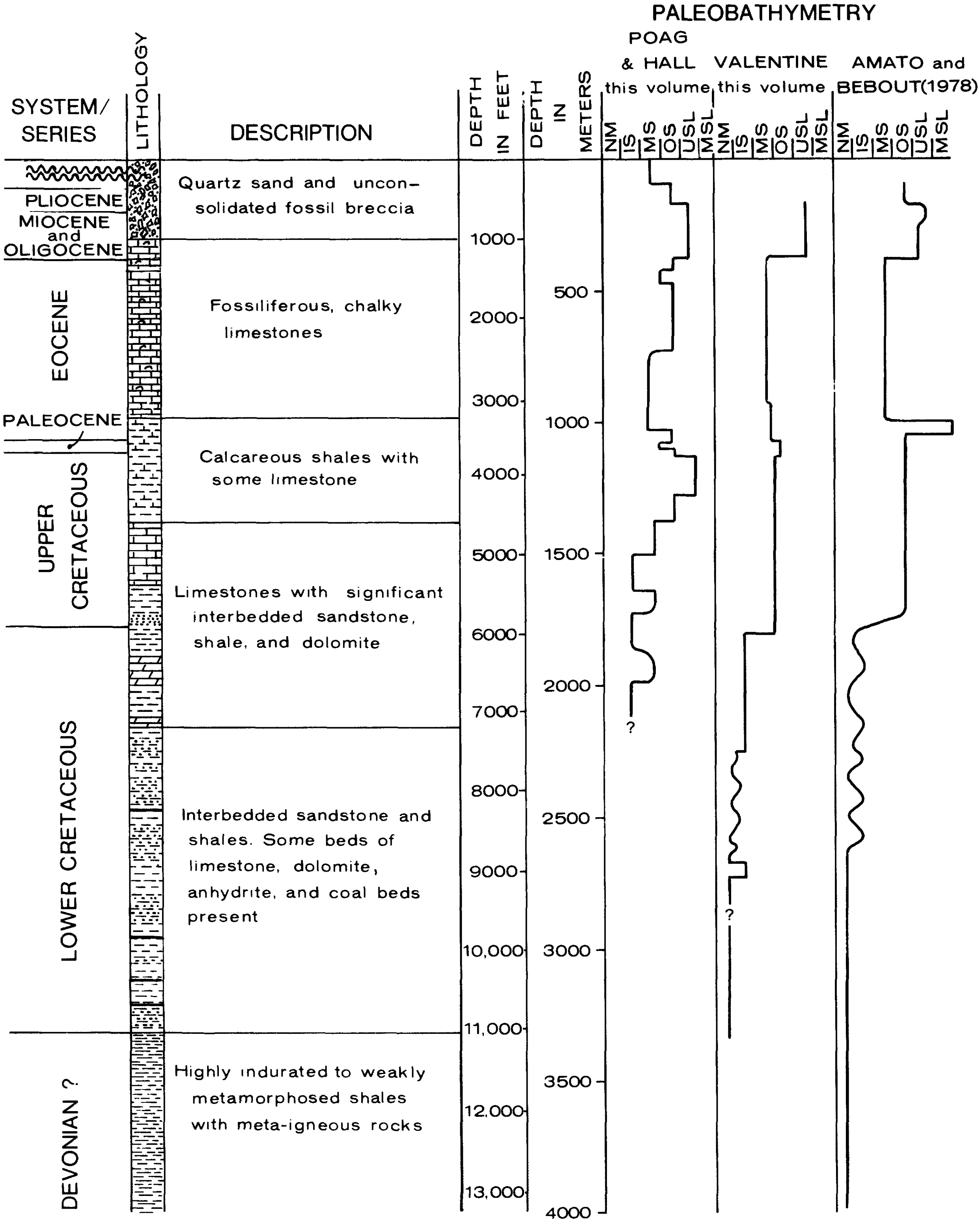
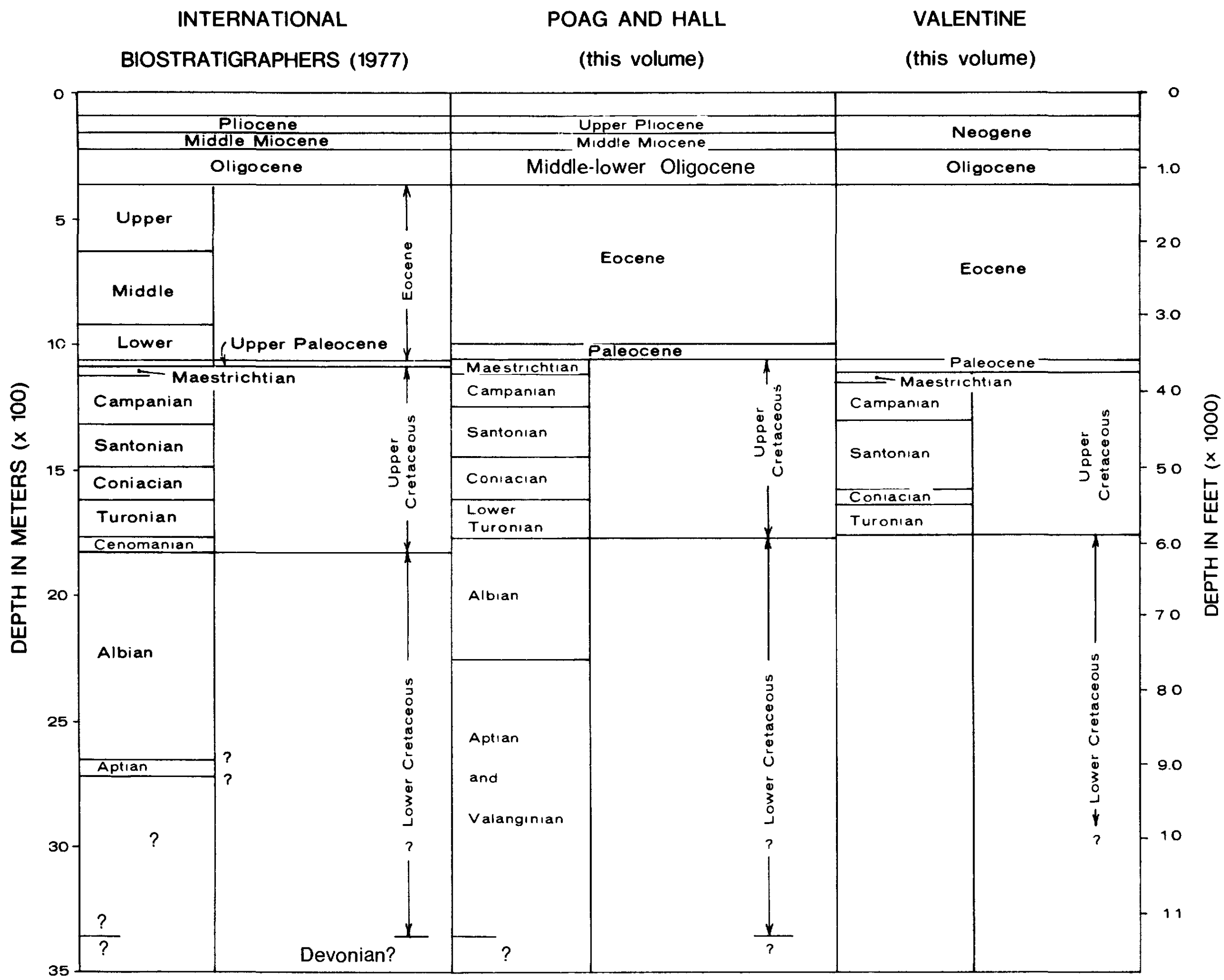


Figure 7.--Generalized plot of lithologies and depositional environments of sediments in the COST No. GE-1 well. Environmental designations are as follows: NM, nonmarine; IS, inner shelf; OS, outer shelf; USL, upper slope; and MSL, middle slope. Modified from Amato and Bebout (1978).

Table 1.—Comparison of biostratigraphic analyses from the COST No. GE-1 well



limestones contain both primary and secondary (leached) porosity; the dolomites are mostly finely crystalline and nonporous. In some carbonate units, considerable amounts of primary and secondary pore space have been obliterated by anhydrite cement.

Arkosic sandstones and siltstones provide possible reservoirs in the red-bed sequence below 7,200 ft (2,200 m). The original porosity of these rocks has been reduced by compaction, pressure solution, and cementation by silica, calcite, and anhydrite (Halley, this volume). Despite these factors, porosities in the 15- to 30-percent range are common in the 7,200- to 10,000-ft (2,200- to 3,050-m)-depth range. Corresponding permeabilities are mostly in the 1- to 100-millidarcies (md) range, although a few of the coarser sandstones have permeabilities as high as 4,100 md (averaged in with other values in fig. 8). Porosities and permeabilities of the sandstones between 10,000 and 11,000 ft (3,050-3,350 m) have been greatly reduced by diagenetic factors and no reservoir units are likely to be found in that interval. Likewise, in the slightly metamorphosed section below 11,000 ft (3,350 m), diagenetic alteration has obliterated all significant porosity and no reservoir rocks are expected.

Impermeable beds, which could act as seals for hydrocarbon entrapment, are present throughout the section. The thick shales and calcareous shales between 3,600 and 5,700 ft (1,100-1,750 m), as well as thinner shales and anhydrite beds in the deeper parts of the section, are the best potential seals.

The COST No. GE-1 well has a low geothermal gradient today (0.89°F/100 ft (16.2°C/km)), and geochemical indicators apparently show that the gradient has been that low or lower throughout Cretaceous to Holocene time. Data on color alteration of kerogen, temperature of maximum pyrolysis yield, carbon preference index, and primary vitrinite reflectance are summarized in figure 9.

In general, organic geochemical studies have shown that the section in the COST No. GE-1 well down to about 3,600 ft (1,100 m) contains small amounts of organic carbon. Furthermore, the interval shows very low concentrations of indigenous hydrocarbons, indicating a lack of significant biogenic or thermogenic generation of hydrocarbons. Vitrinite-reflectance values average about 0.2 throughout the interval and, coupled with visual-kerogen-alteration values of 1 to 1+, indicate thermal immaturity. Interpretation of C_{15}+ extractable hydrocarbons in the lower part of this Tertiary interval is greatly hampered, however, by contamination from drilling additives.

The underlying interval of Upper Cretaceous shales (3,570-5,950 ft (1,090-1,810 m)) has the highest organic carbon content of any section in the GE-1 well. Organic carbon averages 1.24 percent (by weight) through this interval, with individual beds containing in excess of 14 percent organic carbon. Visual-kerogen analyses have shown that much of this organic matter consists of hydrogen-rich, "oil-prone" kerogen types. The shales in this interval also have the highest total extractables, paraffin-

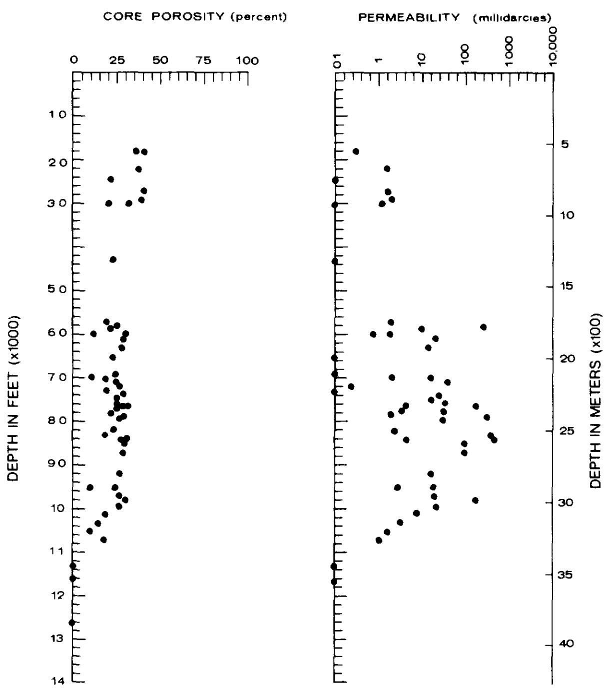


Figure 8.--Porosities and permeabilities measured on conventional and sidewall cores from the GE-1 well as a function of depth (data from Amato and Bebout, 1978). Where numerous conventional core measurements were available for short depth intervals, plotted values are averages.

napthenes, aromatics, and Nitrogen-Sulfur-Oxygen compounds (NSO's) present in the well. Although the upper half of this interval still shows signs of contamination by drilling additives, there is considerable indication that the extractable C_{15}+ hydrocarbons in this interval are, at least partly, indigenous and are derived from the abundant amorphous marine kerogen present in this section. However, vitrinite-reflectance values of 0.35 and a kerogen-maturation rank of 2- strongly imply thermal immaturity for this interval. In general, vitrinite-reflectance values of 0.45 to 0.5 and kerogen-maturation values of 2 to 2+ are taken to mark the earliest onset of significant thermogenic liquid-hydrocarbon generation (Bartenstein and Teichmüller, 1974; Hood and others, 1975; Vassoyevich and others, 1970). Such values are not encountered in the GE-1 well until depths in excess of 8,500 ft (2,600 m). The peak rate of liquid-hydrocarbon generation is apparently marked by vitrinite-reflectance values in the range of 0.6 to 0.7 (kerogen-maturation values of 2+ to 3), and such values only occur below 9,000 ft (2,750-m) in the COST No. GE-1 well.

The portion of the Lower Cretaceous section from 5,950 to 8,900 ft (1,810-2,700 m) has a considerably lower average organic carbon content than the overlying section. The kerogen in this section also appears to consist primarily of the hydrogen-deficient, "gas-prone" types. This corresponds with the low-pyrolitic-hydrocarbon-to-organic-carbon ratios found in this interval and indicates a very poor source for liquid-petroleum hydrocarbons. The deepest part of this interval, from 8,500 to 8,900 ft (2,600-2,700 m), does, however, show thermal maturity.

The Lower Cretaceous(?) and Devonian(?) sedimentary rocks in the COST No. GE-1 well below 8,900 ft (2,700 m) are largely nonmarine to coastal; and, although they are thermally mature, they must be viewed as having little or no potential as petroleum source rocks because of their very low organic carbon contents.

Essentially five major factors are involved in the origin and entrapment of hydrocarbons: (1) source rocks, (2) temperatures sufficient to generate liquid or gaseous hydrocarbons, (3) porous reservoir rocks, (4) impermeable seals, and (5) structural and (or) stratigraphic traps. Indications from the GE-1 well are that rocks of high organic carbon content and "oil-prone" kerogen types are present in the 3,570- to 5,950-ft (1,090- to 1,810-m) interval. Rocks between 5,950 and 8,900 ft (1,810-2,700 m) have a poor source potential because of low contents of organic carbon and the more terrestrial hydrogen-deficient nature of the kerogen in this interval. Sedimentary units below 8,900 ft (2,700 m) are virtually barren of organic matter and have essentially no source-rock potential.

Temperatures appear to have been sufficient for liquid-hydrocarbon generation at depths

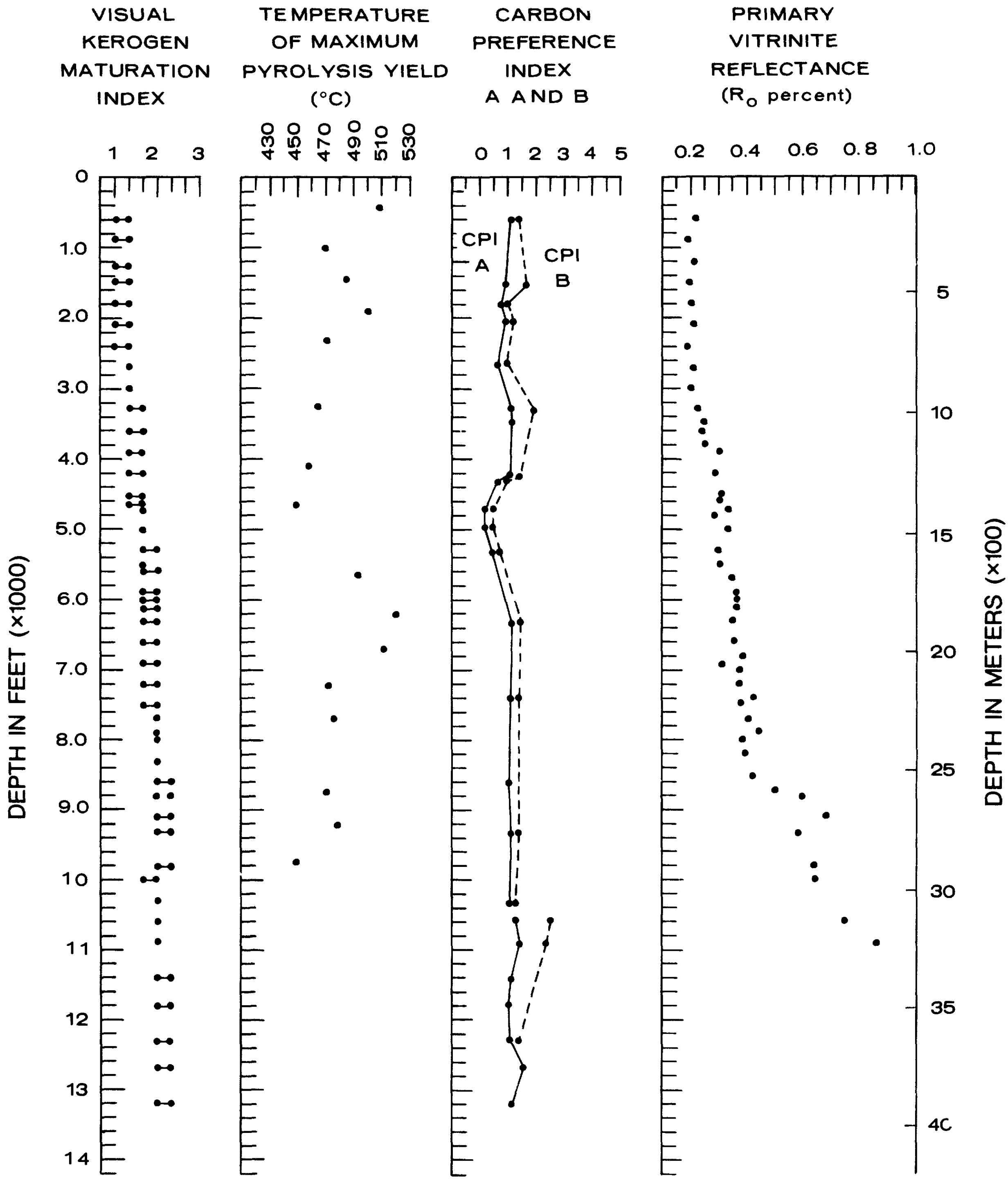


Figure 9.--Comparison of various measures of thermal maturity as a function of depth in the COST No. GE-1 well. Visual-kerogen-maturation-index and primary-vitrinite-reflectance data are from Core Laboratories, Inc. (1977); temperature of maximum pyrolysis yield is from Miller and others (this volume); carbon-preference-index data above 10,500 ft (3,200 m) are from Miller and others (this volume), whereas data below that level come from Geochem Laboratories, Inc. (1977).

below about 8,500 ft (2,600 m), although some indications of incipient generation are present at higher levels in the well. Unfortunately the source-rock potential is low in the intervals that have the optimum thermal-maturation and reservoir-rock characteristics. If the Upper Cretaceous shaly interval is encountered in areas of higher thermal gradient or deeper burial, however, it could be an excellent source rock; and this interval must be considered as the one with the highest source potential for the Southeast Georgia Embayment.

Potential reservoir rocks are available in two sections. Very low permeability (but high porosity) chalks are present in the 1,000- to 3,500-ft (330-to 1,050-m) interval. Where fractured or overpressured these could act as reservoir units, especially because of their association with the directly underlying potential-source sections. More traditional sandstone and limestone reservoirs with high porosity and permeability are present throughout the Lower Cretaceous part of the section from 5,700 ft (1,750 m) down to about 10,000 ft (3,050 m). Individual sandstone beds reach 90 ft (28 m) in thickness, and permeabilities in the hundreds of millidarcies are common. If thermally mature marine shales interfinger with these sandstones in a down-dip direction, the potential exists for excellent oil and gas reservoirs within the 5,700- to 10,000-ft (1,750- to 3,050-m) interval. Although sandstones are present below 10,000 ft (3,050 m), they are tightly cemented and, in spite of some gas shows in GE-1, must be considered as non-reservoir units in offshore hydrocarbon exploration.

Seals, in the form of shales, are present throughout the GE-1 section. In addition, anhydrite beds, which would act as seals, are present below about 6,000 ft (1,800 m).

Although the availability of structures for hydrocarbon trapping cannot be evaluated from a single well that was intentionally drilled off-structure, regional geophysical studies do not show abundant structures with significant closure in the area of the COST No. GE-1 well. Thus, stratigraphic trapping through lateral facies changes may be of greater exploration interest in this area than in other basins along the Atlantic offshore margin.

LITHOLOGIC DESCRIPTIONS

E. C. Rhodehamel

The lithologic log for the COST No. GE-1 well, shown in figure 10, is compiled from low-powered microscopic examination in reflected light of all available samples (drill cuttings) of the stratigraphic test; results of this examination, in general, are supported by interpretations from the electrical-induction, spontaneous-potential, natural-gamma-ray, sonic, density, and neutron geophysical logs. Available samples representing 30-ft (9-m) sections were taken at 90-ft (27-m) intervals from 420 to 4,020 ft (128-1,225 m); and below that depth to 13,240 ft (4,036 m), 10-ft (3-m) sample sections were taken at 30-ft (9-m) intervals to within 14 ft (4 m) of the total depth of the hole. Supplemental x-ray powder diffraction data on three samples between 12,540 and 12,670 ft (3,822-3,862 m) were supplied by Mary Mrose, USGS, Reston, Va. Charles Milton, USGS, Reston, Va., (written commun., 1978) made a petrographic examination of the altered trachyte rock noted from 12,780 to 12,790 ft (3,895-3,898 m), and the trachyte noted from 13,230 to 13,240 ft (4,033-4,036 m) was determined by Halley (this volume).

Standard USGS rock-type abbreviations, shale (sh.), siltstone (sts.), sandstone (ss.), conglomerate (cgl.), limestone (ls), dolomite (dol.), and quartzite (qtz.) are used throughout the descriptive material. Standard rock-color chart (National Research Council, 1948) colors are used. Their associated color numberings are not supplied in the lithologic description in order to reduce the description to manageable size and to facilitate readability.

Both lithologic percentages and rock-porosity evaluations are estimated from the sample material. The lithology presented is, at best, an estimate of the lithology encountered and does not truly represent a "bed-by-bed" section. As such, a brief written description of the natural lithologic units, largely interpreted from geophysical logs, is provided and is considered a valuable adjunct to the graphic lithologic log shown in figure 10.

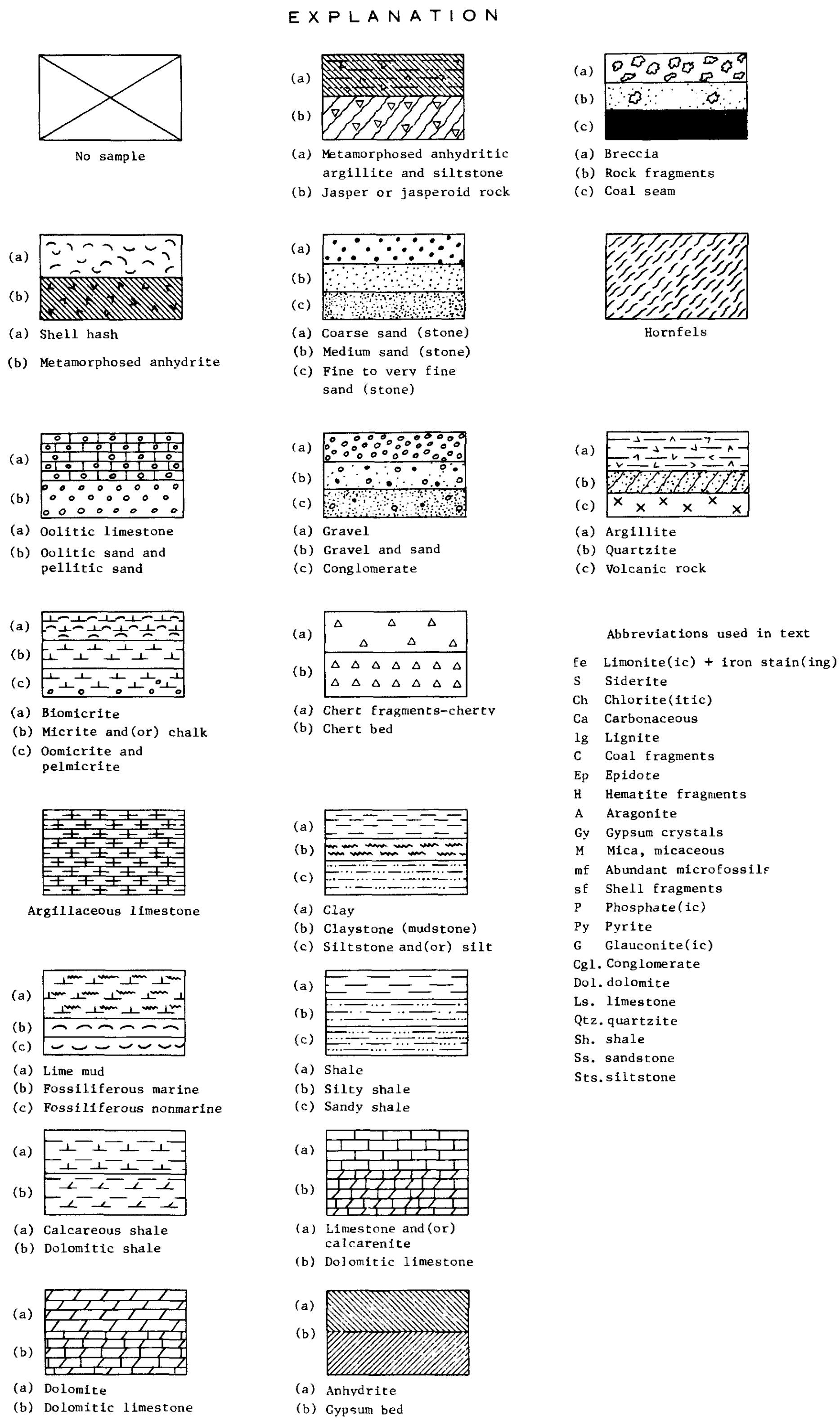


Figure 10.--Lithologic log, COST No. GE-1 well: Explanation.

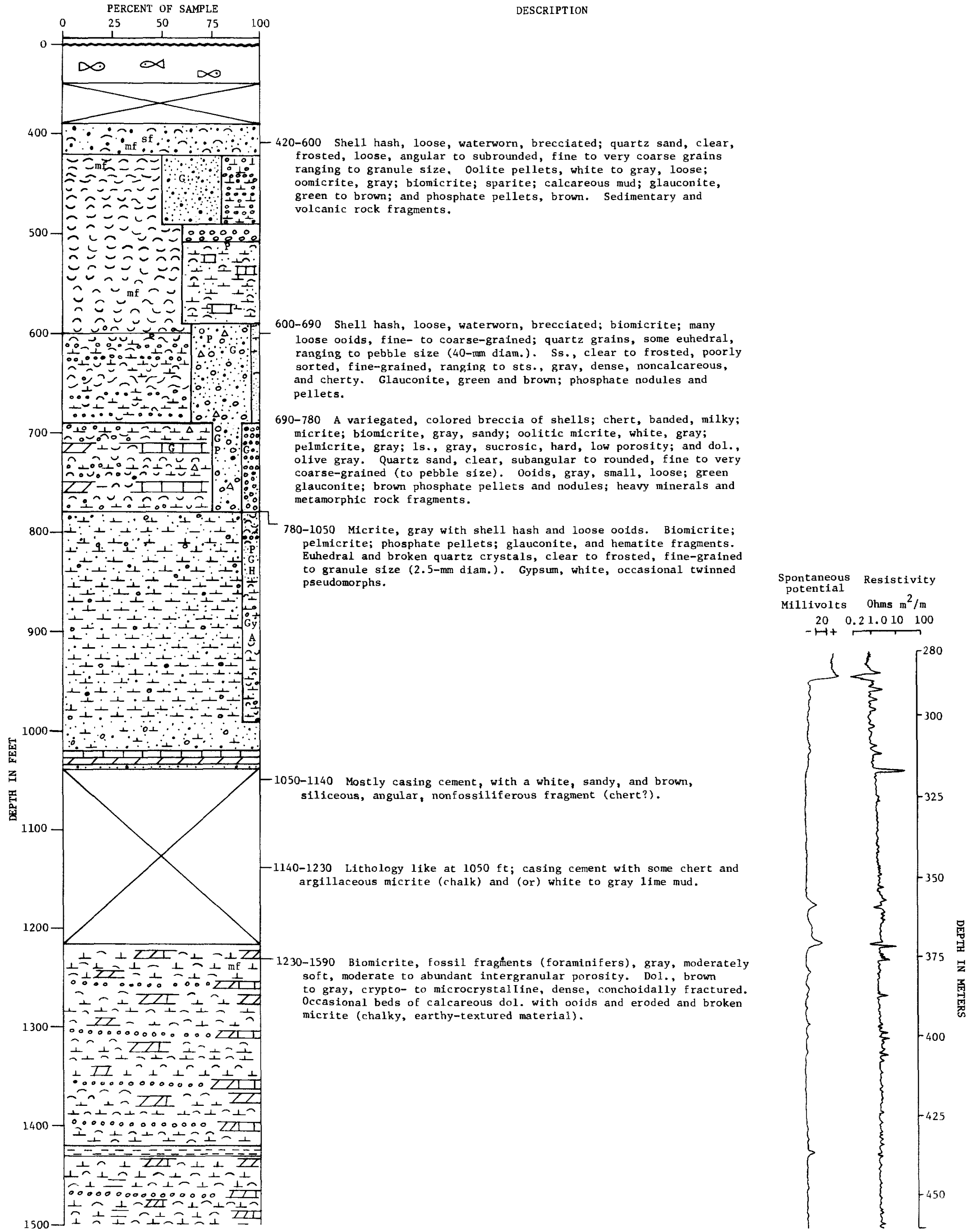


Figure 10.--Lithologic log, COST No. GE-1 well: 0-1,500 ft (0-457 m).

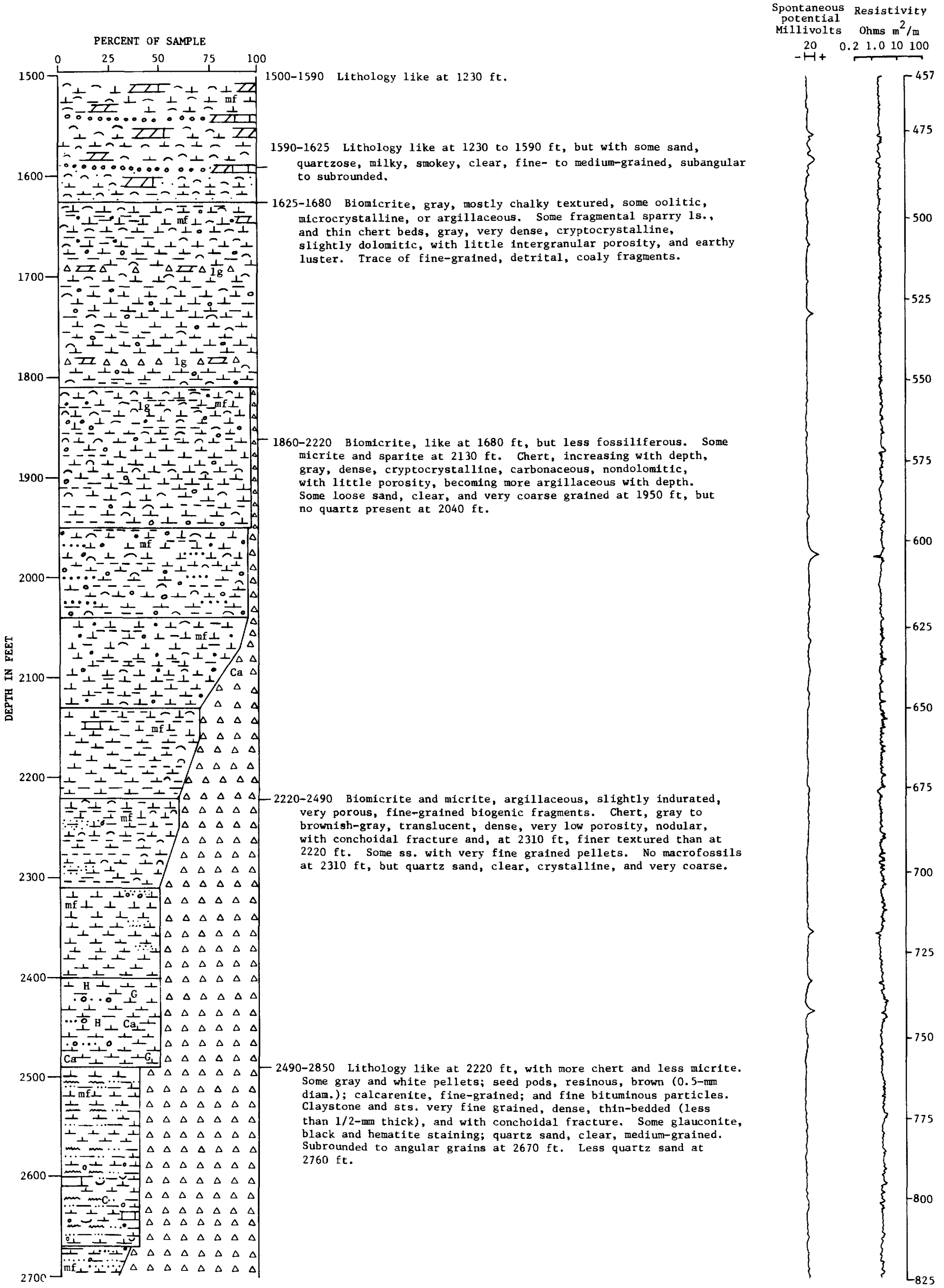
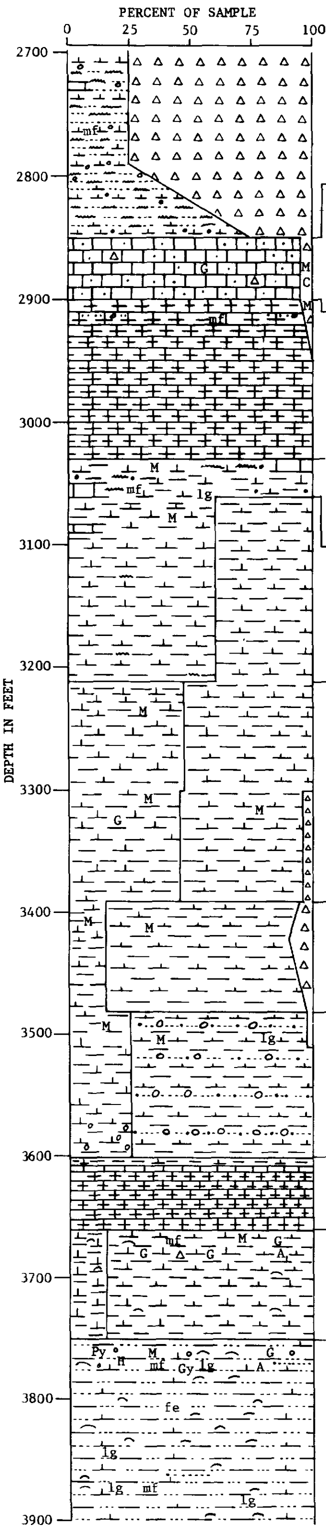


Figure 10.--Lithologic log, COST No. GE-1 well: 1,500-2,700 ft (457-823 m).



2850-2900 Calcarenite, fine- to medium-grained, somewhat sparry, nonfossiliferous, and some glauconite, green, very fine grained. Muscovite, large (3-mm diam.) flakes with smaller mica flakes of brass and gold color; some as inclusions in the calcarenite. Some milky quartz sand and chert. Walnut hull contamination.

2900-3030 Micrite and fine calcarenite, gray, argillaceous, chalky, microcrystalline, some sparry, with moderate to abundant moldic to interparticle porosity, slightly microfossiliferous, some cross-bedding, and very micaceous, like at 2850 ft. Some quartz sand, clear, broken, angular to subangular grains, and microfossils. Walnut hull contamination.

3030-3060 Micrite to fine calcarenite, gray, becoming increasingly argillaceous, more dense, and with some black lignite. Mica, like at 2850 and 2970 ft. Some quartz sand, clear, broken, angular to subangular grains, and microfossils. Walnut hull contamination.

3060-3210 Micrite, light-gray; becoming very argillaceous with depth; limy sh. at 3300 ft, thin (less than 0.2-mm), horizontally bedded, microcrystalline, soft to moderately dense, moderate to low porosity, blocky; minute mica flakes; some very fine calcarenite. Sh., light-gray, very calcareous, with wavy bedding at 3390 ft. Walnut hull contamination.

3210-3390 Lithology like at 3060 ft. Some chert, gray to brownish-gray, dense, with conchoidal fracturing beginning at 3300 ft; some green glauconite in small fractures and sparse mica.

3390-3480 Lithology like at 3060 ft, except some calcareous sh.

3480-3600 Sh., calcareous, as above at 3390 ft. Micrite, very argillaceous, with thin horizontal bedding (like at 3120 ft), and moderate to scarce intraparticle porosity, mica (both large and small flakes, like at 2850 ft) some brown pellets and ooids at 3570 ft, and chert. Some quartz sand, clear, as much as 4-mm diam., and angular. Sparry ls. and large particles of lignite.

3600-3660 Argillaceous ls., soft, and calcarenite.

3660-3750 Sh., gray, very calcareous, biomicrite, gray, and argillaceous ls., slightly oil stained. Glauconite, brown, some green, 0.5-mm-diam. pellets, weathered; and mica, two types like at 2850 ft. Walnut hull contamination.

3750-4010 Sts., gray, very fine grained, moderately indurated, fair porosity, calcareous, and microfossiliferous. Some quartz sand, clear, and angular-grained; glass beads, clear, perfectly spherical; pyroclastic grains(?), mica, two colors like at 2850 ft and iron staining. Sts., more calcareous, coarser, slightly micaceous, lignitic, and fossiliferous at the base.

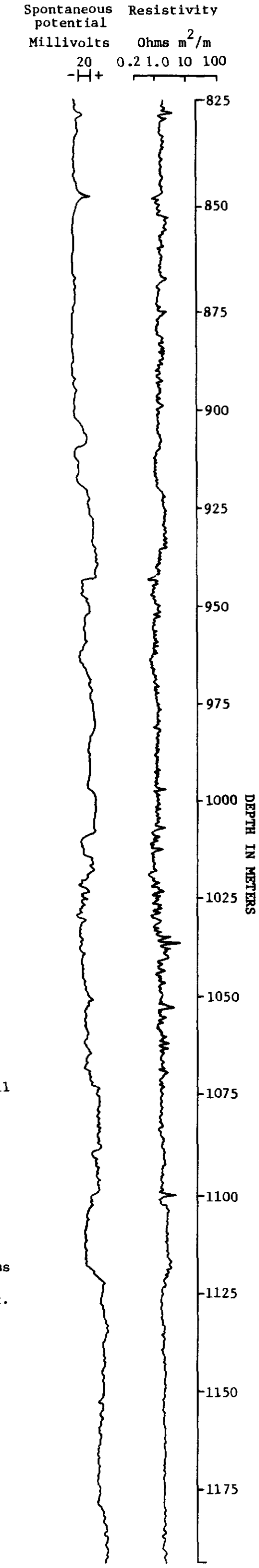
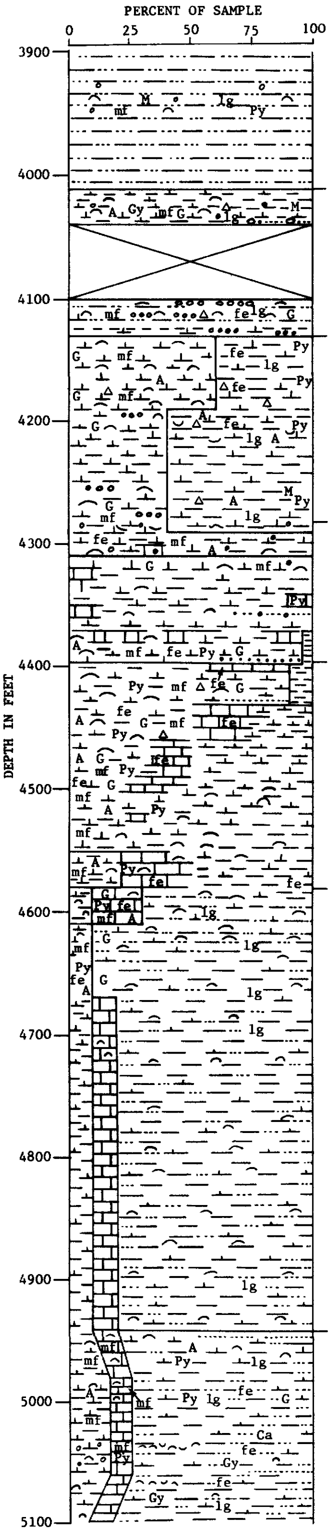


Figure 10.--Lithologic log, COST No. GE-1 well: 2,700-3,900 ft (823-1,189 m).



4010-4130 Micrite, argillaceous, and intercalated sh., calcareous, very fine (0.2-mm thick) horizontal, distinct bedding; with quartz grains, clear (to 4-mm diam.), and angular to subrounded. Small pelecypod shells, foraminifer, and broken fossils. Some chert, gray, and iron stained. Glass spheroids, numerous (like at 3750 ft). Gray sh. fragments like at 4020 ft. Quartz sand, medium-grained.

4130-4280 Micrite and biomicrite, gray; partly argillaceous calcilutite; white pellets, foraminifers, macrofossils, and calcite(?) plates. Quartz sand, loose, yellow, clear, medium-grained to as much as 2-mm diam., and angular. More biomicrite, micrite, and iron staining with less foraminifers and glauconite than at 4010 ft. Glass spheroids, like at 3750 ft. Gray sh., soft, calcareous, fossiliferous, and argillaceous. Some calcite, pinkish-gray. No loose quartz at 4230 ft. At 4200 and 4230 ft, more white calcareous pellets and calcite crystals.

4280-4395 Biomicrite, white, argillaceous, cryptocrystalline, soft, low to moderate interparticle porosity. Some loose glass spheroids, calcareous sand, pellets, and ooids. More clay and sh. at 4380 ft. Micrite; calcarenite and biomicrite, clayey, fossiliferous, and iron stained. Clay, gray. Some calcite crystals, quartz sand, loose, and coarse-grained.

4395-4580 Micrite; biomicrite; very fine calcarenite, argillaceous, white, moderate to low porosity, and fossiliferous. Sh., gray, fossiliferous, moderately hard to soft, calcareous, some open partings, and moderate inter-particle porosity. Some quartz sand, medium-grained, angular to subrounded, and glass spheroids as above. At 4410 ft, micrite with fewer fossils, iron oxide, and aragonite. More sh., increasing with depth, calcareous, and silty, and loose calcarenite. Some calcite crystals. No quartz sand. Some pyritized foraminifers at 4470 ft. At 4500 ft, some fossiliferous gray sh.

4580-4940 Sh., gray, moderately hard to soft, easily lost by sample washing, very fine bedding (0.05-mm thick), moderate to low interparticle and intergranular porosity, megafossils, calcareous, and silty. Calcarenite, and biocalcarenite, fine- to medium-grained fossiliferous; micrite and biomicrite, white to yellowish-gray, silty, very fine grained, argillaceous, and poorly consolidated. Some glass spheroids, calcite crystals, but no quartz grains. Some manganese and iron-oxide stain at 4710 ft. At 4860 ft, lithologies are especially soft and wash out easily.

4940-5150 Lithology like from 4860 to 4940 ft, except more biomicrite and sh., as above, but more calcareous. Some large, calcite fragments; quartz sand, medium-grained; and glass spheroids. Sh., gray, soft, poor to fair porosity, silty, calcareous; biomicrite, semi-indurated, with fair porosity, and a bio-calcarenite of foraminifers, aragonite crystals, and broken calcareous shell fragments. Thin soft ls. at about 5140 ft. Soft sh. as above, probably underlogged between 4370 to 5030 ft. Calcareous clay increasing; some biocalcarenite, largely of pyritized foraminifers, and iron oxide like at 4980 ft.

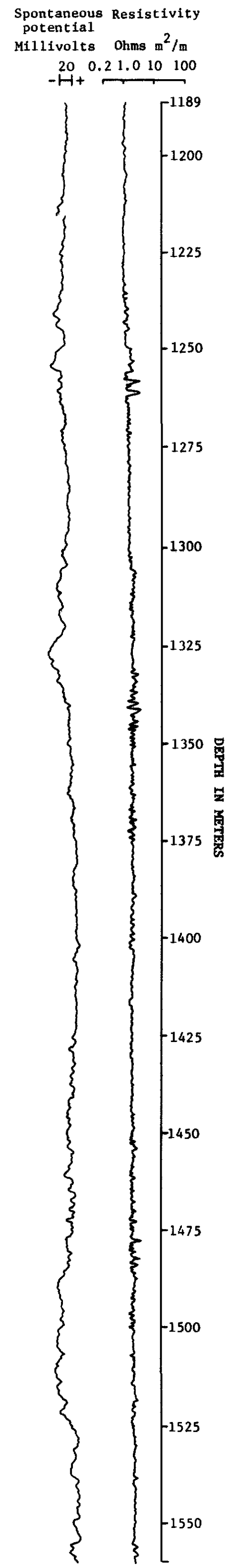
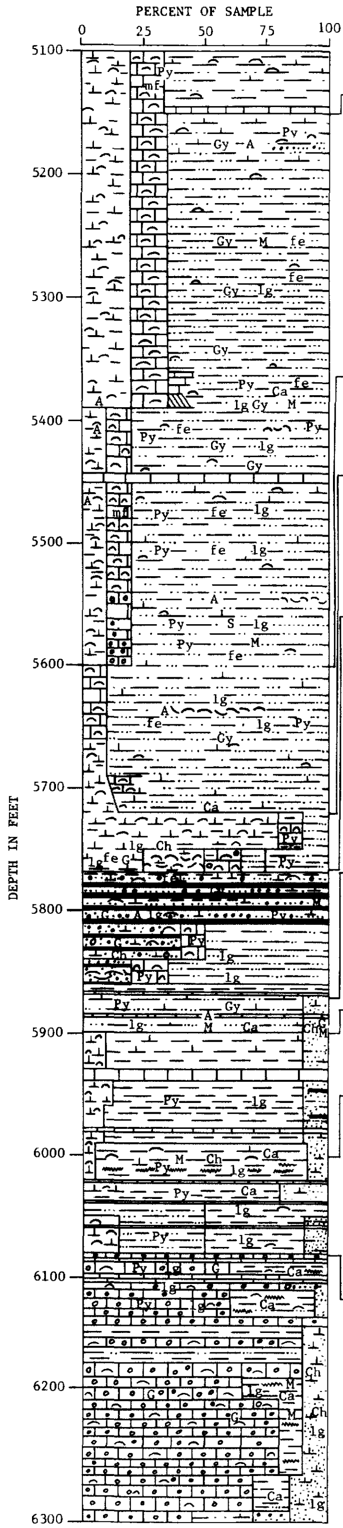


Figure 10.--Lithologic log, COST No. GE-1 well: 3,900-5,100 ft (1,189-1,554 m).



5150-5600 Sh., various shades of gray, some pyritic, soft to moderately soft, more indurated below 5430 ft, low to moderate porosity; high porosity between 5500 and 5576 and especially low porosity from 5575 to 5765 ft; fossiliferous, silty, calcareous, with siderite cement at 5550 ft; grading to micrite and biomicrite, yellowish-gray, lignitic, silty, fine-grained, moderate porosity; biocalcarenite of broken fossils, ooids, pellets, and foraminiferal tests; becoming pyritized like at 5100 ft. (becoming less so with depth). Some sucrosic ls.; and white and pink calcite fragments, large, broken, angular; and more glass spheroids like at 3750 ft, but markedly less near the base of unit, where some have small, glassy, globular volcanic(?) tails at 5580 ft. Quartz sand, clear, medium- to coarse-grained, angular to rounded, and euhedral bassanite (gypsum) crystals, especially between 5340 and 5380 ft. Ls. bed at 5440 ft.

5600-5720 Sh., gray, more fissile, brittle, dense, low porosity, with calcareous cement, much very fine to medium silt, but gradually changing to more white and gray biomicrite like at 5580 ft. Calcarenite, loose, like at 5610 ft. Some amber-colored organic shreds.

5720-5765 Biomicrite like at 5580 ft, and sparry calcite. Sh., like at 5670 to 5700 ft. Calcarenite and biocalcarenite, fine-grained, with pyrite. Quartz sand, clear, coarse, and angular; and quartzose silt, clear, fine to coarse, angular, and loose. Some ss., gray, with fine, angular grains, tightly consolidated, low porosity; much calcareous cement. Some clear to white calcite, megacrystalline (as much as 1/2-cm diam.), some stained red, and some glass spheroids.

5765-5870 Ss., subarkose to subgraywacke, gray, calcite-cemented, moderate to high porosity, poorly sorted; pyritized lignite; bedded and detrital coal and gray rock fragments. Quartzose silt, coarse, angular to subangular grains; and quartz sand, coarse to very coarse, clear, milky, some euhedral. Sh., gray like at 5670 ft, increasing with depth; and micrite, like at 5370 ft. Some ss., grayish-green, very fine grained, calcareous; and dark brown dol. At 5810 ft, lithology like at 5790 ft, except ss. is subarkosic, gray to yellowish-gray; and an orthoquartzite, white, fine- to coarse-grained, calcite-cemented, poorly sorted, very angular to angular, fossiliferous. Also a biomicrite, yellowish-gray, silty, at 5855 ft; and a thin ls. bed at 5865 ft. Some loose sand. From 5850 to 6300 ft, sh. and sts. are either calcareous, gray, or noncalcareous, greenish-gray.

5870-5900 Sh., gray, silty, calcareous, lignitic, micaceous, and dark noncalcareous sts., fine-grained, micaceous, and carbonaceous. Calcite, white, yellow, gray, some stained pink, large (2.6-mm) megascopic fragments, partly fossiliferous; and ls., white, sucrosic to sparry. Ss., orthoquartzite, subarkose to subgraywacke, white, gray, very fine- to fine-grained, dense, low porosity, poorly sorted, calcareous, angular to subangular, and nonfossiliferous.

5900-5990 Lithology similar to 5870 ft, except some biomicrite and calcite present. Much more sh., green, and noncalcareous. Ss., with coal; graywacke sts.; and a ls. bed at 5930 to 5940 ft. More sh. and sts. with increasing depth, and bassanite crystals at 5970 ft.

5990-6080 Lithology similar to 5970 ft. More sh., gray, slightly calcareous, carbonaceous, fossiliferous, micaceous; and claystone, green to greenish-gray, soft, noncalcareous. Ss., partly subarkosic to orthoquartzitic, gray, dense, very fine-grained to fine-grained, calcareous, low porosity; and thin-bedded, calcareous, green, carbonaceous, very fine to very coarse subgraywacke; and sts. with very poor porosity, poorly sorted, and angular to subrounded shapes. Micrite, gray; calcite, sparry, fossiliferous; and ls., white, yellowish-gray, megacrystalline to microcrystalline. Some yellow amber, soft, resinous masses; and loose quartz sand, clear, medium-grained, angular to subrounded.

6080-6320 Ls., yellowish-gray, with coarse to medium crystals; sparite; biosparite; pelsparite; and oosparite; sucrosic, dense, poor to fair interparticle porosity, oolitic and fossil ghosts, very vuggy, with secondary calcite growths, and weathered glauconite. Micrite; biomicrite; calcite crystals; and fossil fragments, orange colored, and stained (less at the base). Sh., gray and greenish gray like at 5940 ft; very fine sts., with calcareous to noncalcareous cement, fossiliferous, and thin-bedded; and intercalated claystone. Ss., subarkosic, subgraywacke to graywacke, gray, very fine-grained to fine-grained, calcareously cemented, poorly sorted, and having low to moderate porosity. Some loose quartz sand, clear, fine grained to very coarse grained, euhedral, and angular to subrounded.

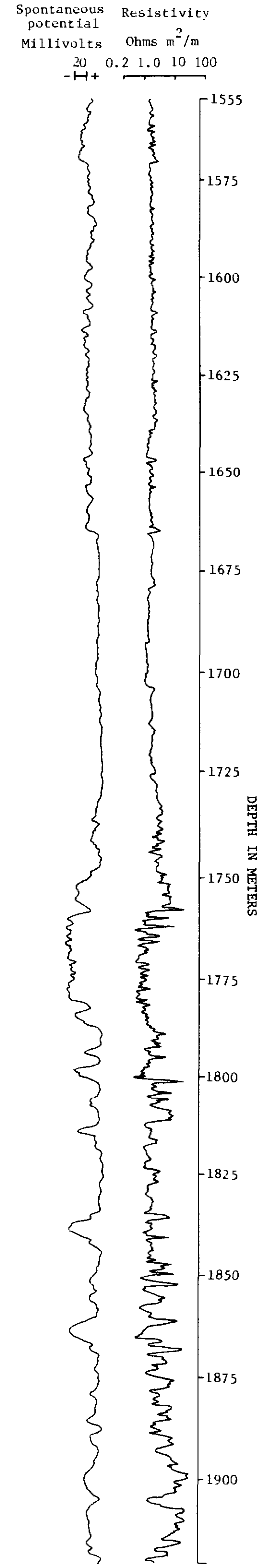
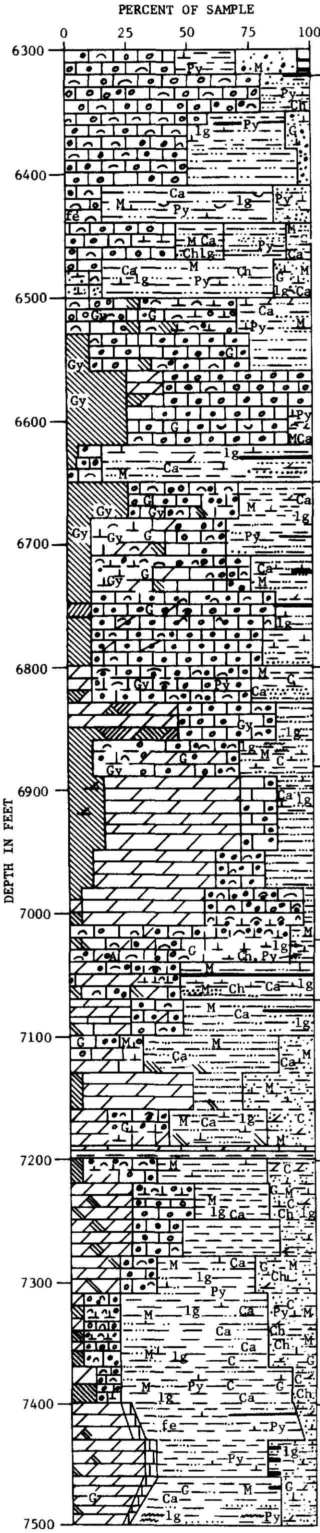


Figure 10.--Lithologic log, COST No. GE-1 well: 5,100-6,300 ft (1,554-1,920 m).



6320-6500 Ls., micrite, partly sandy; biomicrite; biosparite; oosparite; pelmicrite; and oolitic and pelsparite packstone; mottled yellowish-gray, gray, and pink, with orange-colored stain; becoming more altered (weathered) below 6500 ft and less porous at 6540 to 6610 ft, hard very dense; low to high intraparticle, interparticle, and intercrystalline porosity, with sucrosic to megacrystalline texture, and calcite recrystallization in micrite. Sh., gray, greenish-gray, dense silty, hard, somewhat calcareous to noncalcareous, micaceous, carbonaceous, low porosity; pyritized fossil plants; intercalated sts. becoming dominant at 6410 to 6440 ft; fossiliferous at 6470 to 6500 ft, and dolomitic and calcitic below 6620 ft. Some ss. (subgraywacke to subarkose), and gray, fine- to coarse-grained, calcareous sts. Ss. is gray, very fine grained, silty, noncalcareous to calcareous, dense with low to high porosity, angular to subrounded grains, very carbonaceous; interbedded with sh. and with ls. at 6360 to 6370 ft, and 6390 to 6400 ft. Quartz sand, clear, very coarse (1.3-mm diam.), well-rounded, and iron-stained. Anhydrite, white, massive, non porous; and crystalline rosettes and gypsum crystals occurring in oolitic ls. vugs. Dol., below 6500 ft, gray, vuggy, dense, sucrosic, conchoidally fractured; high intraparticle, interparticle, and intercrystalline porosity. Some white, megacrystalline calcite, and amber and tar platelets below 6620 ft.

6650-6800 Ls. like at 6540 to 6610 ft, altered, with fair to excellent vuggy, interparticle, porosity; some dense, with low porosity, and more fossiliferous. Sh. and sts., gray, fine- to medium-grained, like at 6630 ft. Anhydrite and gypsum in crystals, stained, white, massive, fractured; and dense forms like between 6540 to 6610 ft. Some ss., very fine grained, calcite, clear to milky, recrystallized and megacrystalline, some tar(?) and amber.

6800-6890 Ls., gray, mottled by pellets, biosparite, oosparite, pelsparite; pink and white micrite, microcrystalline to megacrystalline; recrystallized, white calcite, gray oomicrite, biomicrosparite; and pelmicrosparite, dense, low to high vuggy and intraparticle porosity. Where altered, ls. is more porous. Sh., gray, very fine grained, soft to hard, nonmicaceous to micaceous, noncalcareous to calcareous. Greenish-gray sh., and some calcareous greenish-gray claystone. Ss., gray, very fine grained, and noncalcareous; and a very fine grained calcareously cemented sts. Most sh. and sts. are soft, have moderately low porosity, and have some brownish-gray sh. Anhydrite, like at 6750 ft intercalated with microcrystalline and sucrosic, brown, dense dol.

6890-7020 Dol., yellowish-gray, finely crystalline to sucrosic to dolomicritic, dense, with moderate porosity. Ls., increasing with depth, oolitic, gray, mottled; some biosparite, biomicrite, calcarenite, oosparite, and micrite. Sh. and sts., like at 6870 ft, very fine grained, micaceous, gray, and greenish-gray, very to slightly calcareous. Anhydrite, like at 6870 ft, and coarsely crystalline dol. Some loose quartz.

7020-7070 Ls., yellowish-gray, fossiliferous, biosparite with intragranular porosity; biomicrite, oosparite with vuggy porosity; and oomicrite, pelsparite, and much micrite, with calcite, large crystals, recrystallized, and dolomitic. Dol., calcareous, finely crystalline, sucrosic, dense to porous, interparticle porosity, dull and sparry. Sh. and sts., gray, very fine grained, little to much calcareous cement, and some green claystone and sh. Ss. (subgraywacke), gray, mottled with bronze mica, very fine grained, some noncalcareous cement, fair to good porosity, with quartz. Some white, massive anhydrite, coal and dark greenish-gray sh. Walnut hull contamination.

7070-7160 Sh. and sts., very fine grained, gray, greenish-gray, mottled, little to much calcareous cement, and hard to soft. Ls., oosparite, oomicrite, pelsparite, biosparite, biomicrite, micrite, and recrystallized calcite. Ss., very fine grained to fine grained; and sts. (subgraywacke), fair to good porosity, poor to fair sorting, angular to well-rounded grains, snd nonfossiliferous. Some white, massive, and greasy-looking anhydrite, microcrystalline to cryptocrystalline, dense partings; interbedded with gray sh. Walnut hull contamination. Lithology more immature than at 7050 ft.

7160-7200 Sh. and sts., gray, greenish-gray, and gray silty sh., with little to much calcareous cement. Ls., white to gray, some dolomitic, dense, oosparite, oomicrite, biosparite, and micrite, fossiliferous, with moderate to low porosity. Dol., gray, dense, low porosity, cryptocrystalline to coarsely-crystalline, sucrosic. Ss. (subgraywacke), gray, mottled, very fine-grained to fine-grained dolomitic, high porosity, clean to silty, moderate sorting, and nonfossiliferous. Anhydrite, white, pink, and dense, like at 7110 ft. Ls. and sh., thin beds, like at 7170 ft. Walnut hull contamination.

7200-7400 Sh., gray, some brown to greenish-gray; trace of grayish-red, partly silty, nonmicaceous to micaceous, and noncalcareous and calcareous, horizontal bedding 1-mm thick, ls., gray, mottled with pellets of biosparite, oosparite, biomicrite, oomicrite, micrite; yellow stained at 7380 ft, vuggy porosity, fossiliferous to nonfossiliferous. Fine- to medium-grained crystalline, dense, gray dol., sucrosic to cryptocrystalline, with low porosity. Ss. and sts., subgraywacke, orthoquartzite, to subarkose, white, gray, some mottled, greenish-gray, fine grained to very fine grained, well to moderately sorted, nonfossiliferous, calcareous to dolomitic, some silty and high porosity. Ss. grades to low maturity sts. Anhydrite, white, pink, dense, massive, in sh. and dol. Walnut hull contamination.

7400-7490 Lithology like at 7380 ft, with decreasing sh. to 7460 ft, and more red and brownish-gray toward the base. Increasing dol., cryptocrystalline to coarsely crystalline to 7460 ft; less ss. and sts. to 7430 ft, and then increased with depth. Some micrite, limy grainstone, and oomicritic wackestone. More coal to 7470 ft, but less at the base. Claystone, sh., and sts., with very fine grained, thin horizontal-bedded ss. intercalated. Notable amounts of anhydrite.

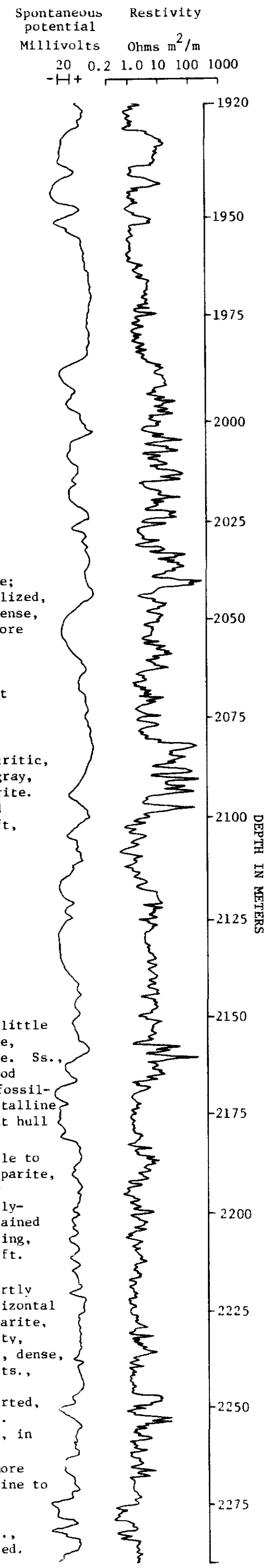
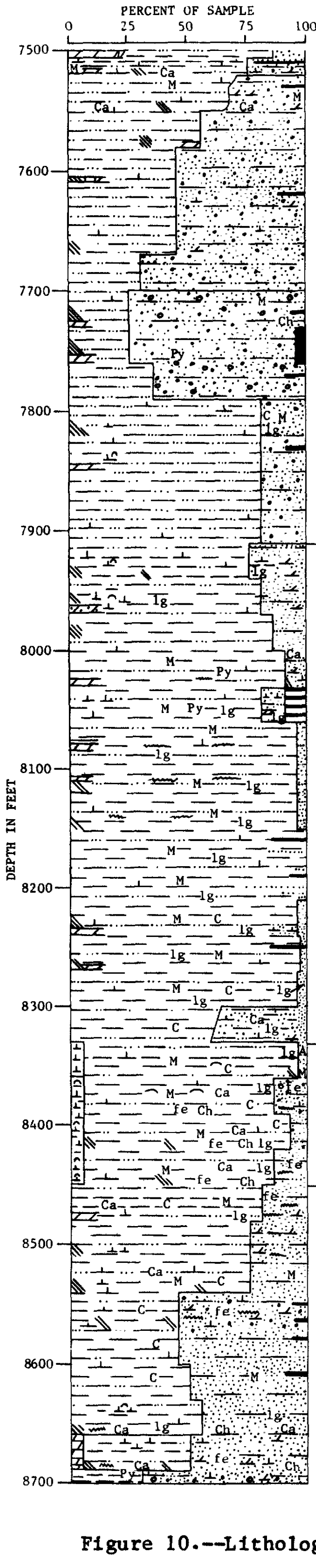


Figure 10.--Lithologic log, COST No. GE-1 well: 6,300-7,500 ft (1,920-2,286 m).



7490-7910 Sh. and very fine-grained to fine-grained sts., grayish-red, brown, and gray, faintly calcareous; and sh., gray, noncalcareous and silty. Ss. and coarse-grained sts., like at 7530 ft. A little biomicrite and dol., gray, dense, like at 7560 ft; some megacrystalline and recrystallized. Much loose, quartz sand with red clayey coatings. Walnut hull contamination.

7910-8330 Sh., and very fine grained, shaley sts., brownish-gray, greenish-gray, to grayish-red, moderately soft to moderately hard, somewhat calcareous; and sh. and sts., very fine grained, gray, partly sandy, like at 7440 ft. with some claystone. Ss., yellowish-gray to gray; and coarse-grained sts., like at 7530 ft. Ss., well-sorted, angular to subangular grains, nonfossiliferous, very fine- to medium-grained, very silty, dolomitic, calcareous to noncalcareous, dense, and with moderate to low porosity. Much loose, fine to coarse grained quartz sand. Much coal from 8040 to 8050 ft. Some coal; gray biomicrite; oomicrite, micrite, with poor porosity. Traces of pink and white anhydrite, sandy dolomicrite, and dol., gray, dense, sucrosic, and cryptocrystalline to megacrystalline. Little to much walnut hull contamination.

8330-8450 Sh., grayish-red and gray, soft to hard, slightly calcareous to noncalcareous, partly micaceous; and very fine grained sts., fossiliferous, very calcareous, grading to a shaley, sandy, and silty micrite, like at 8220 ft, fossiliferous; some soft, slightly calcareous, brownish-gray sh. Ss., gray (subarkose), clean, carbonate-cemented; micaceous ss. with less sts.; and grayish-red graywacke, fine- to coarse-grained, very silty, angular, very poorly sorted to moderately well sorted, partly indurated, with moderate to high porosity, and with iron oxide and some calcareous cement. Some calcite cement recrystallized to microcrystals to megacrystals. Loose quartz grains are angular to well rounded in finer grained sizes.

8450-8690 Sh., grayish-red, some mottled gray; with pink and gray anhydrite, silty; silty to sandy, yellowish-gray biomicrite at 8640 ft; and very fine grained to coarse-grained sts., a slightly micaceous, and calcareous, soft, and nonfossiliferous. Sh. and very fine grained sts., gray, hard, and some calcareous cement. Ss., subgraywacke, brown grayish-red to pale-red, and gray at the base, fine- to medium-grained, very angular to rounded grains, poor to well sorted, with visible moderate to high porosity, being more dense with depth, very clayey to moderately clean, poor to fair induration, and nonfossiliferous. Some megacrystalline and calcareous dol.; brown, and gray, megacrystalline and dense dol., with more at the base; and much iron oxide cement. Some dirty reddish-brown claystone; white and gray, silty, micrite and pelmicrite; and loose, iron-oxide-stained quartz grains, clear, milky, pitted, very angular to subangular, with poor to fair sorting, nonfossiliferous, and little to no auxiliary minerals. Ss., quartzose (orthoquartzite ranging to subarkose) from 8540 to 8570 ft, gray, and grayish-red, very fine grained to coarse grained, moderate to high porosity, and somewhat clayey to clean.

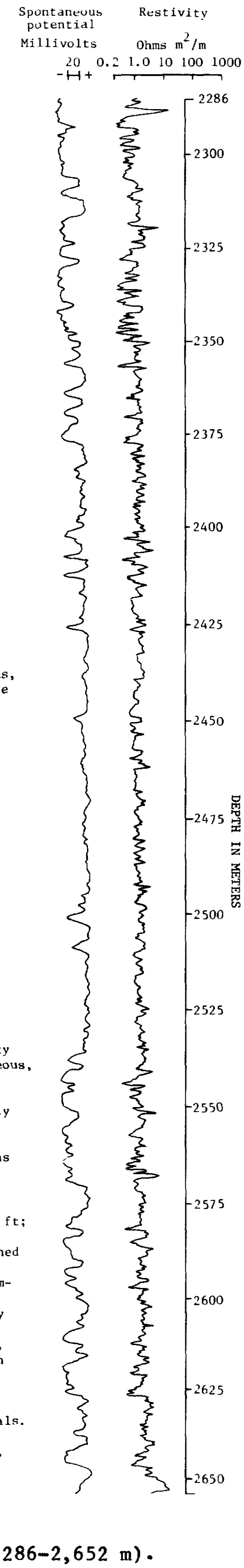
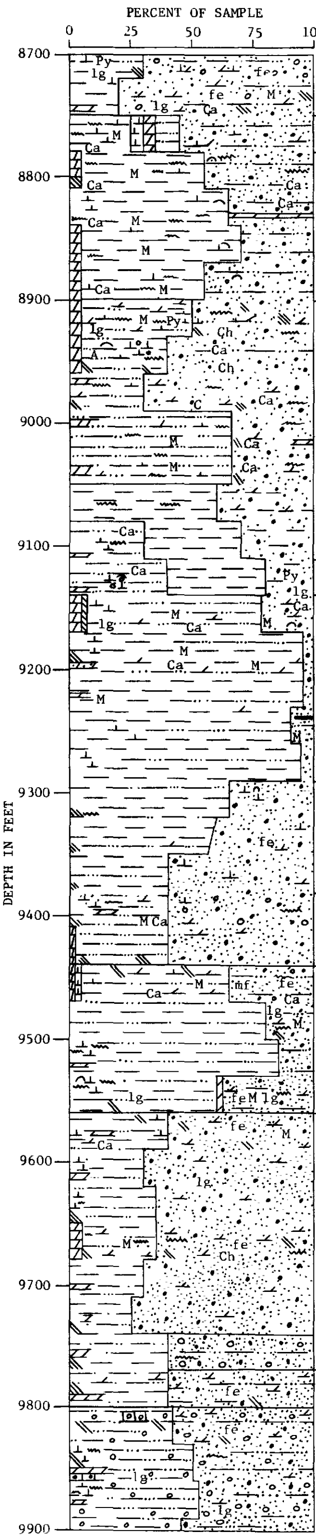


Figure 10.--Lithologic log, COST No. GE-1 well: 7,500-8,700 ft (2,286-2,652 m).



8690-8750 Ss, subarkose to subgraywacke, noncalcareous to dol.-cemented, carbonaceous, gray, mottled, coarse-grained to very fine grained subgraywacke to graywacke sts. Ss. is dense with low porosity, poorly sorted to well-sorted, very angular to well-rounded grains, and nonfossiliferous. Dol., white, gray, dense, sucrosic, microcrystalline to finely crystalline.

8750-8780 Ss., like at 8730 ft. Sh., claystone, and very fine grained sts., gray, micaceous, carbonaceous, with calcareous cement.

8780-8900 Sh. and sts., gray to brownish-gray, very fine-grained to medium-grained, denser with increased depth, micaceous, carbonaceous and some calcareous cement. Ss., gray; and grayish-red, very fine-grained to coarse-grained, carbonaceous, dol., cement, moderate to high porosity, poorly to well- sorted; some sucrosic to dolosparite rock, and few fossils.

8900-9110 Ss., gray; to grayish-red dol. and calcareous dol. cement. White, gray, brown, grayish-red ss., orthoquartzite to subgraywacke, siliceous and cement, very fine to very coarse grained, low to high porosity, poorly sorted to well-sorted, angular to well-rounded, nonfossiliferous, carbonaceous, anhydrite matrix, green mica. Sh. and sts., gray noncalcareous cement, dol. cemented, hard, micaceous. Sh., grayish-red, calcareous cement, soft to moderately hard, micaceous, and clayey. Dol., gray, white, brown, dense, coarsely crystalline (recrystallized).

9110-9140 Sh. and sts., grayish-red, dolomitic, soft to moderately hard, as above. Sh. and sts., gray; dol. cement, carbonaceous, micaceous; and sh., brownish-gray. Ss., gray to grayish-red, like at 9060 ft.

9140-9290 Sh., gray, hard, dol.-cemented, micaceous; and gray, very fine grained to medium grained, micaceous dol.-cemented sts., and carbonaceous. Sh. and sts., brownish-gray, micaceous, and dol.-cemented. Ss., gray; brown and pink, dol., calcareous dol. and calcite-cemented, to grayish-red, silica cemented, partly clayey subgraywacke, very fine grained to coarse grained, poor to good induration, low to high visible porosity, poor to moderate sorting, partly carbonaceous, micaceous, very angular. Well-rounded loose grains, and partly fossiliferous. Dol., gray to white, medio- to coarsely crystalline, dense, with quartz sand and white anhydrite. Sh. and very fine-grained to fine-grained sts., red, mottled, and gray, with squeezed, broken blebs, and contorted shale, hard to soft, micaceous, noncarbonaceous with dol. and siliceous cement. Ss., gray, calcareous.

9290-9380 Sh., brown, grayish-red, mottled gray, anhydritic; and sts., dol. to noncalcareously cemented. Ss., grayish-red, increasing with depth, fine- to coarse-grained, angular to rounded, poorly sorted. Subarkose, yellowish-gray, dense, well-indurated, faint dol. cement, and feldspar.

9380-9440 Ss., subarkose to subgraywacke, red, pink, and gray, medium-grained to very coarse grained, well to poorly indurated, moderate to very high porosity, noncalcareous to calcareous and dol. cemented, poorly sorted to well-sorted, very angular to well-rounded grains, nonfossiliferous, and feldspar. Sh. and very fine-grained sts., grayish-red and gray, mottled, dol.-cemented, gray anhydrite blebs, micaceous, and carbonaceous.

9440-9560 Sh., grayish-red, mottled gray and red with microcrystalline to massive anhydrite, moderately hard, dol.- and calcite-cemented. Very fine grained sts., gray, hard, dol. cement, carbonaceous. Ss. and sts., grayish-red, very fine to very coarse grained, friable, noncalcareous, iron oxide cement, poorly sorted, very angular to rounded grains, clear foraminifer casts; and subarkose and arkose, yellowish-gray, moderate to high porosity.

9560-9770 Ss., subarkose, subgraywacke to graywacke, red, grayish-red, pink, gray, very fine to very coarse grained, thin beds, (1.2 mm), some friable, low to high visible porosity, dol. and iron oxide cemented, poorly sorted to well-sorted, euhedral to well-rounded grains, clean to clayey, immature to submature, nonfossiliferous; containing feldspar, chlorite, mica, and green anhydrite. Less ss. but coarser at 9740 to 9770 ft. Sh., gray; and very fine grained sts., gray, green, grayish-red, soft to hard, carbonaceous, noncarbonaceous, and micaceous, with much dol. and calcareous cement. Dol., white, pink, grayish-red, dense, cryptocrystalline to coarse megacrystalline, red-stained, and sandy.

9770-10,010 Ss., yellowish-gray, subgraywacke to subarkose, pink, grayish-red, very coarse grained (1.2 mm), but generally from a medium- to coarse-grained silt to a fine- to medium-grained ss., becoming fine-grained from 9890 to 9920 ft, and granules to fine cgl. (3.7 mm) at the base. Yellowish-gray ss., poor to good visible porosity, dol.-cemented; other ss., siliceous and iron-oxide cement, poor to well sorted, euhedral, very angular to subrounded grains, nonfossiliferous, and has pink, green, and gray feldspar. Sh., gray; and sts., with dol. cement. Sh. red, noncalcareous-cemented, mottled pink, with fair to good(?) porosity. Dol., pale-brown, pink, grayish-red, gray, dense, clean to silty, sucrosic, cryptocrystalline to megacrystalline. Grayish-red sh., very fine grained sts., and purple, pebbly sts. Sh., and anhydrite mixture is soft, mottled gray, red, with clear, visible, extremely high to high porosity, and has a sintered look. Micrite, white and clayey, and pelmicrite ls. Anhydrite, gray.

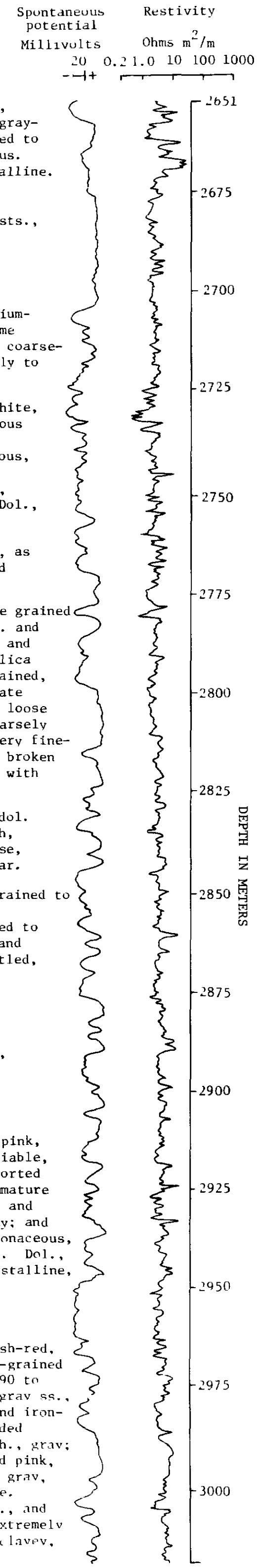


Figure 10.--Lithologic log, COST No. GE-1 well: 8,700-9,900 ft (2,652-3,018 m).

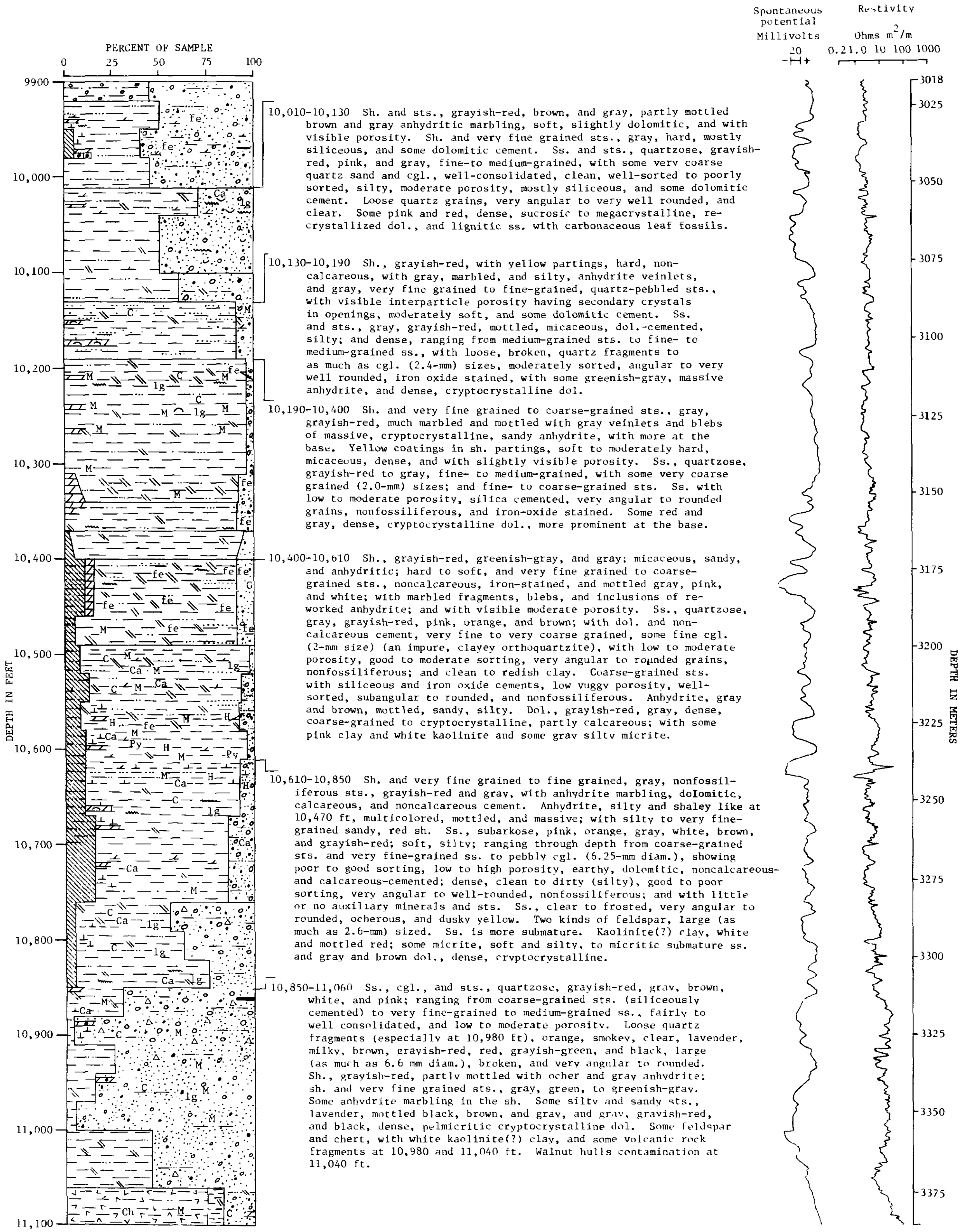
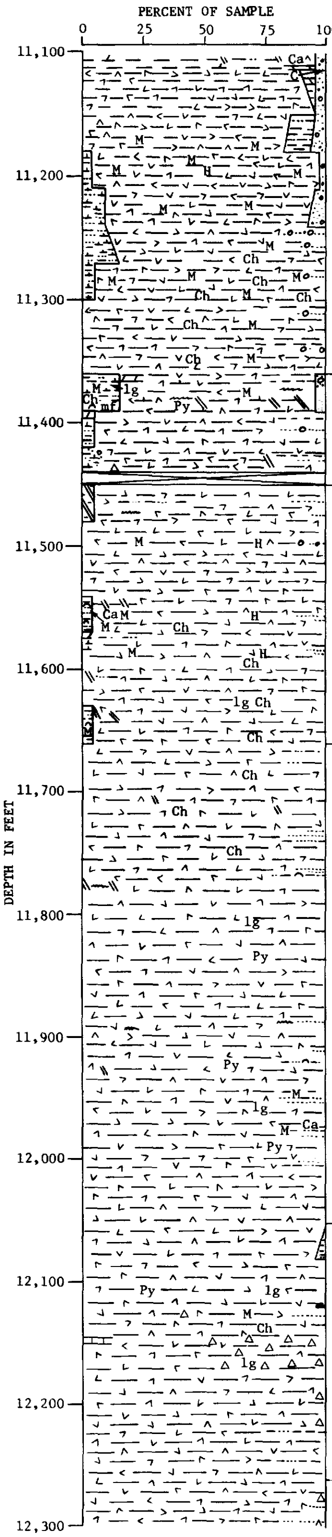


Figure 10.--Lithologic log, COST No. GE-1 well: 9,900-11,100 ft (3,018-3,383 m).



11,060-11,360 Sh., and (or) slightly metamorphosed argillite, no slaty cleavage, lavender, brownish-gray, to greenish-gray; dense, becoming more dense with depth; silica and slightly dolomite-cemented; moderately hard, more so with depth, with some conchoidal fracture; with cryptocrystalline texture and vitreous luster increasing with depth; and platey partings with quartz silt inclusions, having some grains waterworn and weathered. Sh., at 11,060-ft depth and poorly represented to absent below, grayish-red, silty; in part marbled with light-gray anhydrite blebs, fair porosity; noncalcareous, calcareous and dolomite-cemented, but with some magnesian cement at 11,100 ft. Ss., brownish-gray; and anhydritic sts., some with calcite and dol. cement, and fair porosity; and cgl., quartzose, rose-gray, brownish-gray, orange, and clear, partly mottled reddish-brown; ranging from coarse-grained sts. and fine-grained ss., to cgl. (as much as 7-mm) size, dense, hard, very poor porosity, good to fair sorting, very angular to well-rounded, and iron oxide stained, reduced to small amounts below 11,080 ft. Small amount of silty micrite beginning at 11,190 ft; with recrystallized calcite veins in the greenish gray sh. appearing at 11,250 ft.

11,360-11,450 Argillite and dense sh., mostly greenish-gray and grayish-red, both calcareous- and siliceous-cemented; and a red sts. with calcareous cement, vitreous texture, micaceous, and hard; and some soft claystone. Micrite, gray, silty, micaceous; and calcareous sts., with detrital carbon, partly fossiliferous, soft, with very porous interparticle porosity. Ss., quartzose and quartzitic, grayish-red, very fine grained to fine grained, well-sorted, silica-cemented, clean, dense, poor porosity; and a cgl. to quartzitic cgl., as much as 6-mm diam.; grains are angular to well rounded, deeply pitted, and nonfossiliferous, with opaque, hard, very fine grained, black mineral. Some gray, sucrosic dol.; white, recrystallized calcite vein in greenish-gray argillite; gray anhydrite in grayish-red sh.; and a very fine grained rock fragment.

11,450-11,670 Argillite, gray, red, purple, and greenish-gray; with brownish-black and dusky-red argillite interbedded at 11,610 ft with siliceous-cemented, calcareous dol. fillings, very hard and red, and moderately soft and pink. Some mottled-green, recrystallized, macrocrystalline calcite vein fillings, their number increasing with depth; and orange, very fine grained to fine grained, dense, low porosity, angular to rounded, poorly sorted to well-sorted quartzose ss. White kaolinite, gray and brown, micaceous, fossiliferous, with good porosity; soft sts. with calcareous cement. Some soft, porous, and earthy hematite; notable amounts of clear, quartz vein fillings, increasing rapidly with depth; noncalcareous, gray, micaceous, porous sts. with silica cement; and shaley anhydrite, some with visible, vuggy porosity; loose, broken, clear quartz is from vein fillings.

11,670-12,050 Argillite, greenish-gray, dense, siliceous, having some fragments weathered or altered to soft, light-greenish-gray, clayey fragments. Some argillite has veinlets with clear, euhedral, bipyramidal quartz. Some argillite, brownish-black and dusky-red, also present, and at 11,700 ft it has gray massive anhydrite blebs and veinlets. Some yellow, ocher and orange micaceous sts.; and white, very fine grained to fine grained, hard, dense, very porous, with visible vuggy porosity, and moderately well sorted, quartz ss. Red sh. and argillite, partly with orange and pink megacrystalline and recrystallized calcite vein fillings. Some milky to clear, very angular, quartz fragments, from quartzite veinlets in green argillite--these becoming pyritic below 11,900 ft. Some ss., quartzose, white, gray, and red, and mottled pink. Some increase with depth of a sericitic-like clayey mineral of altered argillite, composed of clay, plagioclase, and quartz; and loose, broken, vein-quartz fragments.

12,050-12,260 Argillite, more greenish-gray with little cherty (conchoidal) fracture, and with more altered clayey plagioclase and quartz. Some cherty, greenish-gray, and conchoidally fractured argillite present at 12,090 ft. Some megacrystalline, orange to grayish-green calcite crystals. Chert, dark-greenish-gray, pink, gray, and grayish-yellow, very hard, dense, and conchoidally fractured at 12,150 ft. Red and purple argillite and sh. Argillite, green, and partly chloritized; some pink to gray, very fine grained ss.; and loose, clear to milky, very angular, and broken vein quartz. Some yellowish-gray, coarsely crystalline, and sparry calcite with a greenish fine-grained mineral mottling.

12,260-12,500 Metamorphic rock with more conchoidal fracture, very dense, chertlike; and becoming more altered, greenish-gray olive and argillite-like at 12,150 ft; and also darker with increased pyrite content with depth; very fine grained, and with cryptocrystalline quartz lenses and grayish-yellow, chert fragments. Some grayish-red and grayish-purple sh. and argillite, with a heavy black mineral; loose, very angular, and milky vein quartz; and upper-hole sedimentary contaminants. Vein quartz content, increasing with depth, and includes coarsely crystalline calcite and pyrite veinlets below 12,390 ft. Some pyrite cubes altered to hematite and much goethite staining. Trace amounts of calcareous dolomitic at 12,420 to 12,460 ft.

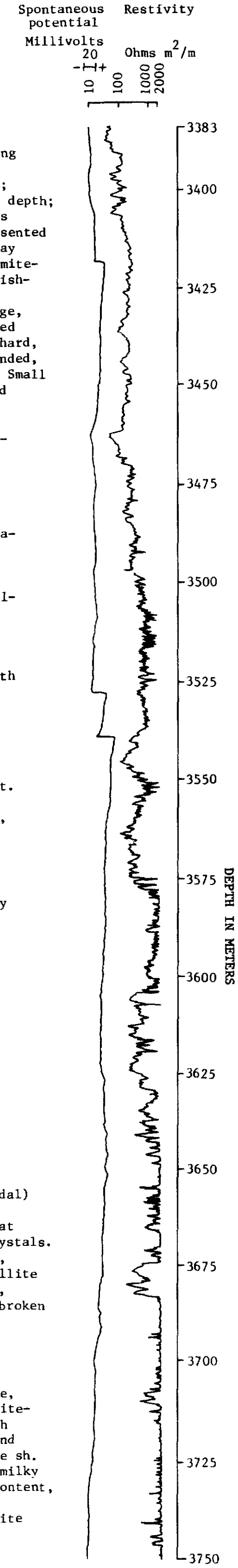
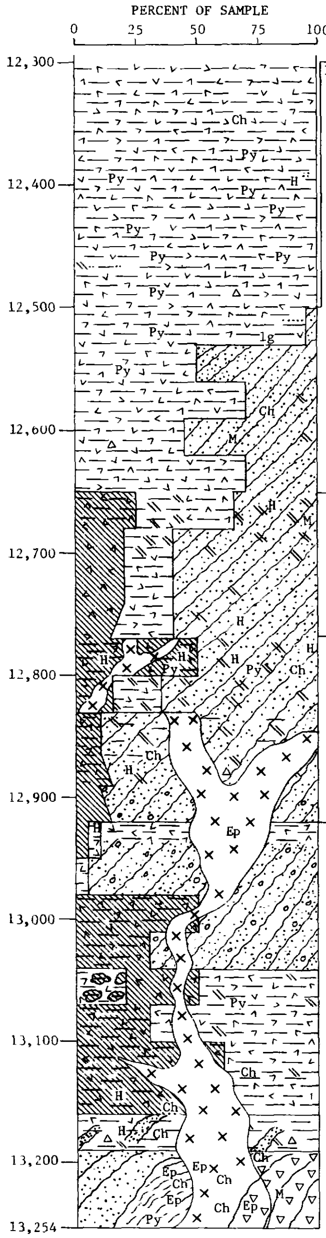


Figure 10.--Lithologic log, COST No. GE-1 well: 11,100-12,300 ft (3,383-3,749 m).



12,500-12,650 Argillite, greenish-gray and gray, pyritized like at 12,480 ft; cryptocrystalline, with increased alteration like from 12,150 to 12,490 ft above, but with increased sericitization of original sedimentary rocks; some vein quartz, with little calcareous inclusions; soft, finely crystalline, some anhydritic cement; and walnut hull and upper-hole contaminants. Pyritized siliceous argillite is harder, very fine grained, dense, quartzite-like with dark pyritic mottling of milky, clear, and translucent masses; approaches soft to hard metaquartzite. Metaquartzite is greenish-gray and gray, very fine grained to fine grained, dense, and hard to soft, with pink, red, and green soft anhydrite(?) cement, and pink and red feldspars; an unidentified black mineral in many chips.

12,650-12,770 Argillite, some anhydritic?, greenish-gray and dusky-purple, mediocrystalline to cryptocrystalline, pyrite cubes; interbedded with dusky-purple and greenish-gray anhydritic argillites and an anhydritic?-cemented, arkosic (feldspar) metaquartzite. Quartz, hard to soft, clear, very fine-grained to medium-grained, grayish-purple to brown, mottled red, green and purple (by feldspars and anhydrite?); has opaque black mineral. Quartz grains become coarser with depth, reach cgl. size at 12,750 ft, and are clear, hematite red, and milky colored. X-ray diffraction shows metaquartzite is quartz and feldspar plagioclase. Complex sample lithology.

12,770-12,920 Trachyte, becoming highly altered with quartz vein injections, very hematitic, brownish-black, with macrocrystalline recrystallized? lathes, 0.7-mm long, soft to hard, becoming harder with depth, vuggy at 12,870 ft, and mottled with earthy red and yellow specular hematite and chlorite. Some hematite blebs have dark growth rinds, and (or) pyrite nuclei suggesting moderately high-temperature alteration. Anhydritic cemented metaquartzite, some soft with red streaks, stained, and mottled dark brown with coarsely crystalline or crushed hematitic inclusions. Loose vein quartz, clear, broken, macrocrystalline; rhombic calcite; and pink, euhedral calcite showing sharp contact with siliceous, green, altered trachyte, and anhydritic argillite, and hematitic wall rock. Some anhydrite pinkish, earthy, silty, massive; grayish-red; anhydritic argillite with microcrystalline texture; and chlorite; and grayish-red chert breccia with hematitic cement. In general, major mineral type is feldspar. Major rock types are trachyte and anhydritic?-cemented metaquartzite. Large (0.6-mm) feldspar crystals, specular hematite, and vein quartz in sharp contact with anhydrite argillite and trachyte masses suggest low- to moderate-grade metamorphic activity with hydrothermal solutions. Sample represents volcanic rocks, somewhat silicified, and metamorphosed sediments.

12,920-13,040 Trachyte, altered, brownish-black, moderately hard to very hard (at injected quartz-vein contacts). A lesser amount at 13,010 to 13,040 ft. Metaquartzite, some conglomeratic, and possibly altered igneous volcanics, somewhat silicified, like at 12,780 ft. Grayish-red, microcrystalline, siliceously altered argillite, like at 12,770 to 12,920 ft, some brecciated or conglomeratic, mottled brownish-black, gray, olive, white, green, brown, red, and purple, with hematite staining and cement, silica-injected, and hardened. Much broken vein quartz, milky to clear, with sharp siliceous vein contacts. Argillite is silica-impregnated near veins, forming a cryptocrystalline metaquartzite like at 12,870 ft. Anhydrite, earthy, pink, silty, and soft. Some soft, very finely crystalline (sucrosic), grayish-green (epidote?) mineral vein calcite, and greenish-gray argillite.

13,040-13,190 Argillite, somewhat anhydritic?, metamorphosed, greenish-black, dusky-purple, to dark-red, moderately hard; pyritic, partly mottled red and green with feldspars and anhydrite? cement. Light, multicolored, and siliceously altered argillite like at 12,990 ft. Grayish-red to dusky-purple argillite, very siliceous, harder than greenish-black variety, more brecciated or conglomeratic, both with cryptocrystalline to sucrosic microcrystalline appearance and, in part, altered and hardened by siliceous injection. Trachyte, brownish-black, hematitic like from 12,780 ft downward; siliceous, metamorphic trachyte as at 12,870 ft. Earthy (clayey), light-gray to white, chalky, very soft, multicolored, mottled, and thin-bedded anhydrite masses. Vein quartz, milky white, and loose. Grayish-green, soft, unctuous, chloritic, calcitic, and anhydritic? vein with sharp contact of dusky-purple argillite. Volcanic rocks, now very silicified. Rocks have siliceous appearance. Some hematitic, red, fine-grained fragments are brecciated, and cherty to jasperite-looking (approaching hornfels) at 13,170 ft.

13,190-13,254 Metaquartzite, hornfels or jasperite-like; contact-metamorphosed argillite, greenish-black, dusky-purple, and red, completely silicified, and altered by much quartz; and chlorite and calcite vein injections. Probably very silicified, felspathic, volcanic rocks like at 12, 780 ft. Trachyte altered by quartz, calcite, and chlorite vein intrusions (Charles Milton, written commun., 1978), with more epidote and feldspars. Vein quartz, white, milky to clear, and with pink and large red feldspars near contact with host rock. Some sericitic material. Increased metamorphic activity with brecciated and (or) conglomeratic rock, as in the last several hundred feet.

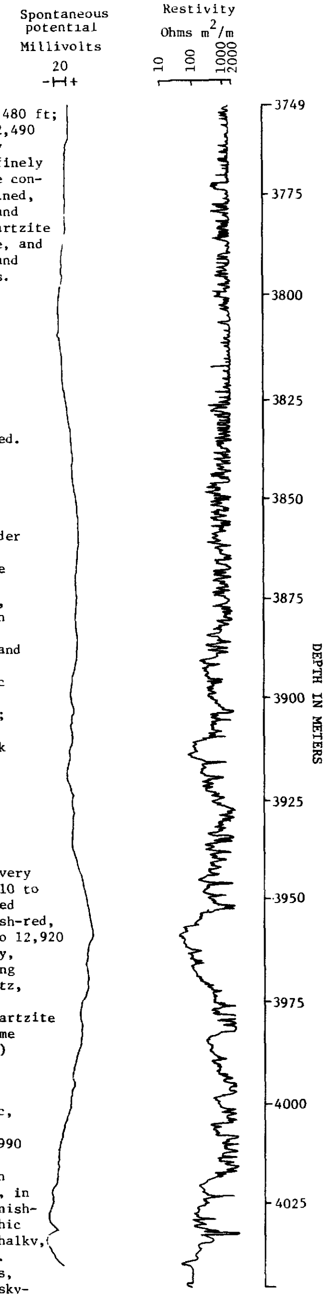


Figure 10.--Lithologic log, COST No. GE-1 well: 12,300-13,254 ft (3,749-4,040 m).

PETROPHYSICAL SUMMARY [1/]

E. K. Simonis

Ten conventional cores and 68 sidewall cores recvered from the COST No. GE-1 well were analyzed by Core Laboratories, Inc. (1977). Results of the analyses are summarized in tables 2 and 3, and in figures 11, 12, and 13. For the conventional cores, the analyses were performed on 1-in. (2.5-cm)- diameter plugs taken at approximately 1-ft (0.3-m) intervals, resulting in a wide range of porosity and permeability values (table 2, figs. 11, 12). On the basis of the results of the core analyses, rocks with the best reservoir characteristics appear to be concentrated between 5,700 and 10,000 ft (1,750-3,050 m) (figs. 11, 12); however, intervals in which core analyses are not available may contain additional favorable reservoir rocks.

Above 5,700 ft (1,700 m), no sandstones were recovered in either the conventional or sidewall cores. Many of the limestones in this section are highly porous chalks, but their permeabilities are very low; they plot outside the general trend on the porosity versus permeability plot in figure 13. The chalks may prove to be potential reservoir rocks, however. For example, chalks with low permeability values are highly productive in the North Sea. Between 5,700 and 10,000 ft (1,750-3,050 m), sandstone is the lithology that has the best reservoir characteristics. Porosities from 25 to 30 percent are common and permeabilities are as much as 4,000 md.

[1/] This section is reprinted, with minor changes, from Amato and Bebout (1978).

Table 2. Record of conventional cores, their range of porosity and permeability, and their dominant lithology

[Footage designations can be converted to meters by multiplying the number of feet by 3.3. Leaders (--) indicate no data available]

Core No.	Cored interval (feet) Top	Bottom	Feet cut	Core recovery (feet)	Porosity (percent) High	Low	Mean	Permeability (md) High	Low	Mean	Dominant lithology
1	3,024	3,054	30	30.0	30.5	7.5	19.8	0.68	0.01	0.1	Limestone.
2	6,607	6,657	50	48.4	23.3	4.8	12.8	8.1	0.05	0.8	Do.
3	7,040	7,100	60	58.9	29.3	3.5	11.4	284.0	0.07	22.8	Do.
4	8,331	8,391	60	59.8	29.1	3.3	18.3	4,110.0	0.01	600.0	Sandstone.
5	9,453	9,513	60	53.1	20.9	2.3	10.5	203.0	0.01	29.0	Do.
6	10,518	10,520	2	0.33	10.8	10.8	10.8	4.2	4.2	4.2	Do.
7	10,520	10,580	60	46.1	18.5	2.8	9.3	14.0	0.01	1.5	Do.
8	10,931	10,933	2	0.0	--	--	--	--	--	--	--
9	10,933	10,935	2	0.0	--	--	--	--	--	--	--
10	11,000	11,002	2	0.0	--	--	--	--	--	--	--
11	11,357	11,387	30	29.0	1.4	0.1	0.42	0.01	0.01	0.01	Argillite.
12	11,635	11,643	8	7.4	0.2	0.2	0.2	0.01	0.01	0.01	Do.
13	12,624	18,627	3	1.0	0.6	0.6	0.6	0.01	0.01	0.01	Do.
14	13,247	13,251	4	0.1	--	--	--	--	--	--	Meta-basalt (?).
15	13,252	13,254	2	0.66	--	--	--	--	--	--	Do.

Table 3.--Porosities, permeabilities, grain densities, and dominant lithologies of sidewall cores from COST No. GE-1 well

[Data from Core Laboratories, Inc., 1977
Permeability values marked by asterisk were determined empirically]

Depth (feet)	Depth (meters)	Porosity (percent)	Permeability (millidarcies)	Calculated grain density (g/cm^3)	Lithology
1,867	569	36.2	0.5	2.56	Chalk.
2,244	684	39.5	2.3	2.72	Do.
2,288	697	33.9	2.0	2.55	Do.
2,433	742	21.9	0.1*	2.71	Do.
2,754	839	44.1	2.2	2.73	Do.
2,790	850	36.9	2.7*	2.53	Do.
2,924	891	22.8	1.9	2.64	Do.
2,985	910	43.7	6.1	2.37	Do.
2,988	911	41.6	2.1*	2.61	Do.
2,998	914	44.2	2.7	2.52	Do.
3,010	917	33.2	1.7	2.56	Do.
4,360	1,329	23.2	0.1	2.57	Do.
5,755	1,754	19.1	3.5*	2.64	Sandstone.
5,804	1,769	25.6	447.0	2.63	Do.
5,850	1,783	23.8	10.0	2.63	Do.
6,028	1,837	30.1	3.8	2.67	Do.
6,110	1,862	31.2	46.0	2.60	Do.
6,162	1,878	25.9	15.0	2.61	Do.
6,374	1,943	27.2	19.0	2.57	Do.
6,398	1,950	27.3	14.0	2.60	Do.
6,546	1,995	23.0	0.1*	2.71	Limestone.
6,900	2,103	24.2	0.1*	2.77	Do.
6,940	2,115	20.2	0.1	2.59	Do.
7,040	2,146	18.3	3.6	2.72	Do.
7,114	2,168	25.0	67.0	2.63	Sandstone.
7,210	2,198	27.7	0.4*	2.61	Siltstone.
7,306	2,227	19.4	0.1*	2.56	Limestone.
7,373	2,247	27.7	33.0	2.66	Sandstone.
7,456	2,273	28.3	55.0	2.65	Do.
7,501	2,286	25.8	29.0*	2.66	Do.
7,546	2,300	25.5	19.0*	2.63	Do.
7,608	2,319	25.5	54.0	2.63	Do.
7,648	2,331	28.2	7.0*	2.65	Do.
7,660	2,335	32.7	255.0	2.68	Do.
7,753	2,363	25.8	6.3*	2.64	Do.
7,791	2,375	26.8	54.0	2.63	Do.
7,849	2,392	22.3	3.0*	2.63	Do.
7,910	2,411	28.9	530.0*	2.63	Sandstone
7,954	2,424	27.0	56.0	2.66	Do.
8,032	2,448	27.1	5.7*	2.68	Do.
8,280	2,524	21.8	0.1*	2.67	Do.
8,343	2,543	24.3	7.0*	2.60	Do.
8,388	2,557	22.8	3.2*	2.59	Do.
8,414	2,565	33.4	700.0*	2.66	Do.
8,484	2,586	26.6	7.2*	2.62	Do.
8,566	2,611	29.4	28.0	2.62	Do.
8,594	2,619	31.1	181.0	2.65	Do.
8,612	2,625	28.8	49.0*	2.64	Do.
8,673	2,644	29.2	135.0*	2.67	Do.
8,875	2,705	29.0	150.0*	2.64	Do.
9,053	2,759	26.4	26.0*	2.63	Do.
9,117	2,779	26.3	19.0	2.65	Do.
9,172	2,796	28.1	23.0*	2.63	Do.
9,294	2,833	24.0	20.0*	2.64	Do.
9,560	2,914	23.9	5.1	2.61	Do.
9,676	2,949	26.6	27.0	2.65	Do.
9,770	2,998	26.7	49.0	2.67	Do.
9,782	2,982	26.8	25.0*	2.65	Do.
9,850	3,002	28.7	280.0	2.63	Do.
9,864	3,007	30.5	220.0*	2.66	Do.
9,970	3,039	25.3	18.0	2.63	Do.
9,990	3,045	27.2	50.0	2.64	Do.
10,114	3,083	18.9	0.9	2.60	Do.
10,357	3,157	16.5	0.5	2.61	Do.
10,363	3,159	15.1	0.7	2.61	Do.
10,406	3,172	13.0	0.2	2.60	Do.
10,706	3,263	16.3	1.1	2.61	Do.
10,726	3,269	15.5	1.7	2.62	Do.

Most of the permeable sandstones are very fine to medium grained, moderately to poorly sorted, and incompletely cemented by quartz overgrowths and hematite. Porosities and permeabilities of carbonate rocks are generally lower, but a sandy dolomite recovered in conventional core No. 3, between 7,093 and 7,099 ft (2,161-2,163 m), has a porosity of 29 percent and a permeability of 280 md.

The core analyses indicate a sharp reduction of porosity and permeability below 10,000 ft (3,050 m). Between 10,000 and 11,050 ft (3,050-3,368 m), the porosities of analyzed sandstones drop below 20 percent and most of the permeability values are less than 10 md. Intensified cementation by quartz overgrowth and compaction by pressure solution appear to be important factors in the reduction of porosity and permeability.

Below 11,050 ft (3,368 m), to the total depth of the well at 13,254 ft (4,039 m), the section consists of essentially impermeable, metamorphosed or highly indurated sedimentary and igneous rocks of Paleozoic age.

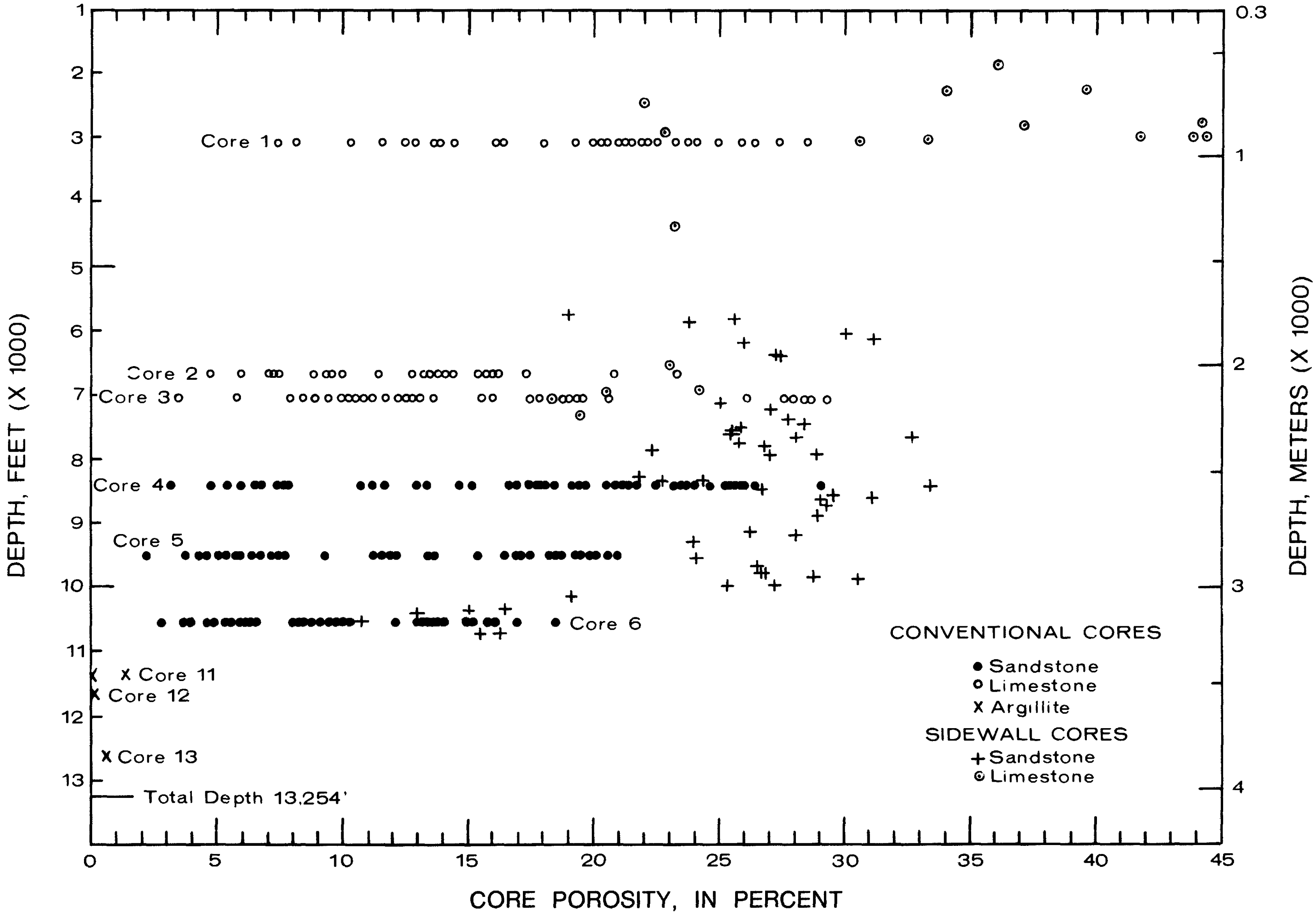


Figure 11.-- Porosities of conventional cores and sidewall cores, COST No. GE-1 well.

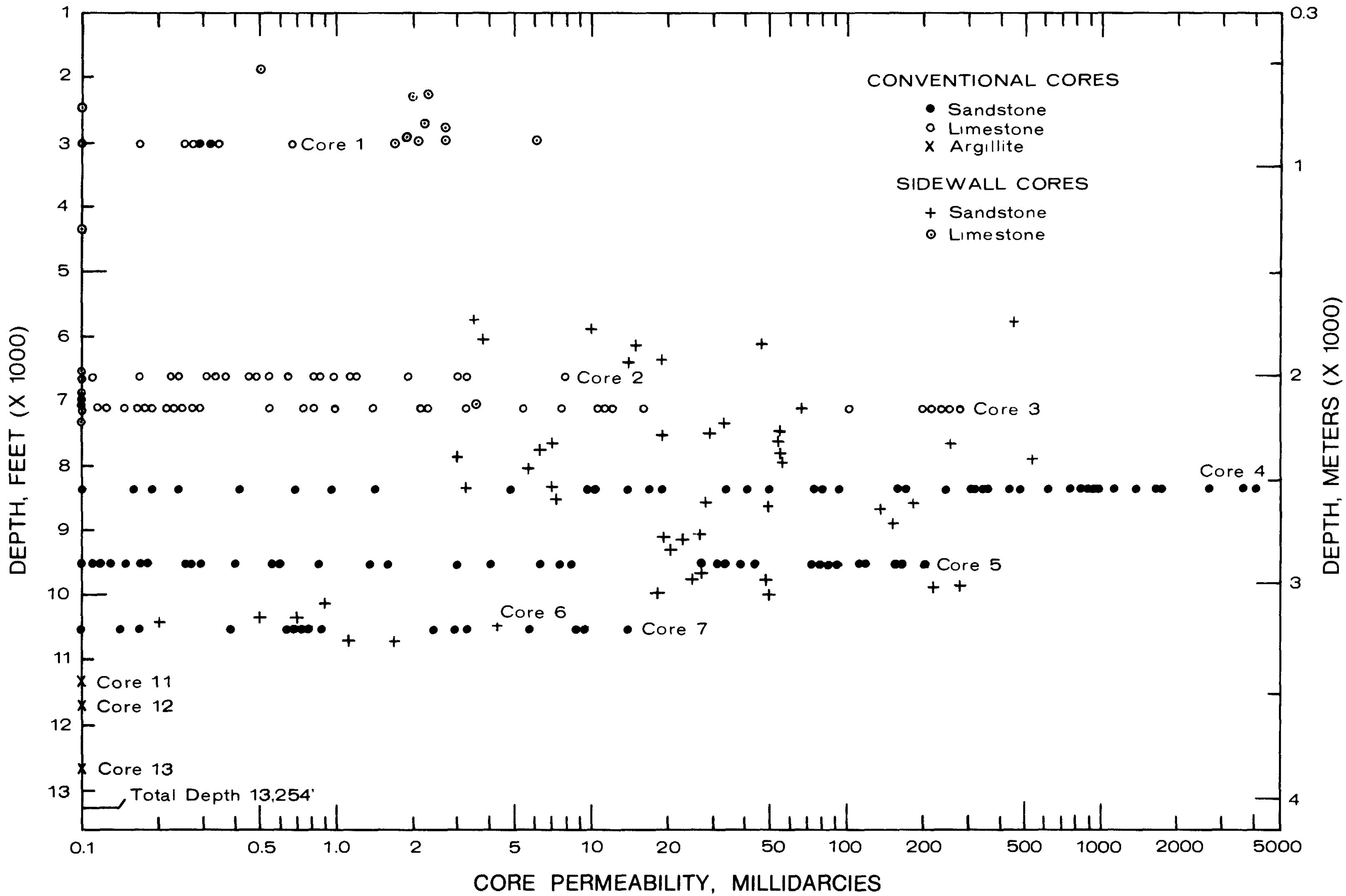


Figure 12.--Permeabilities of conventional cores and sidewall cores, COST No. GE-1 well.

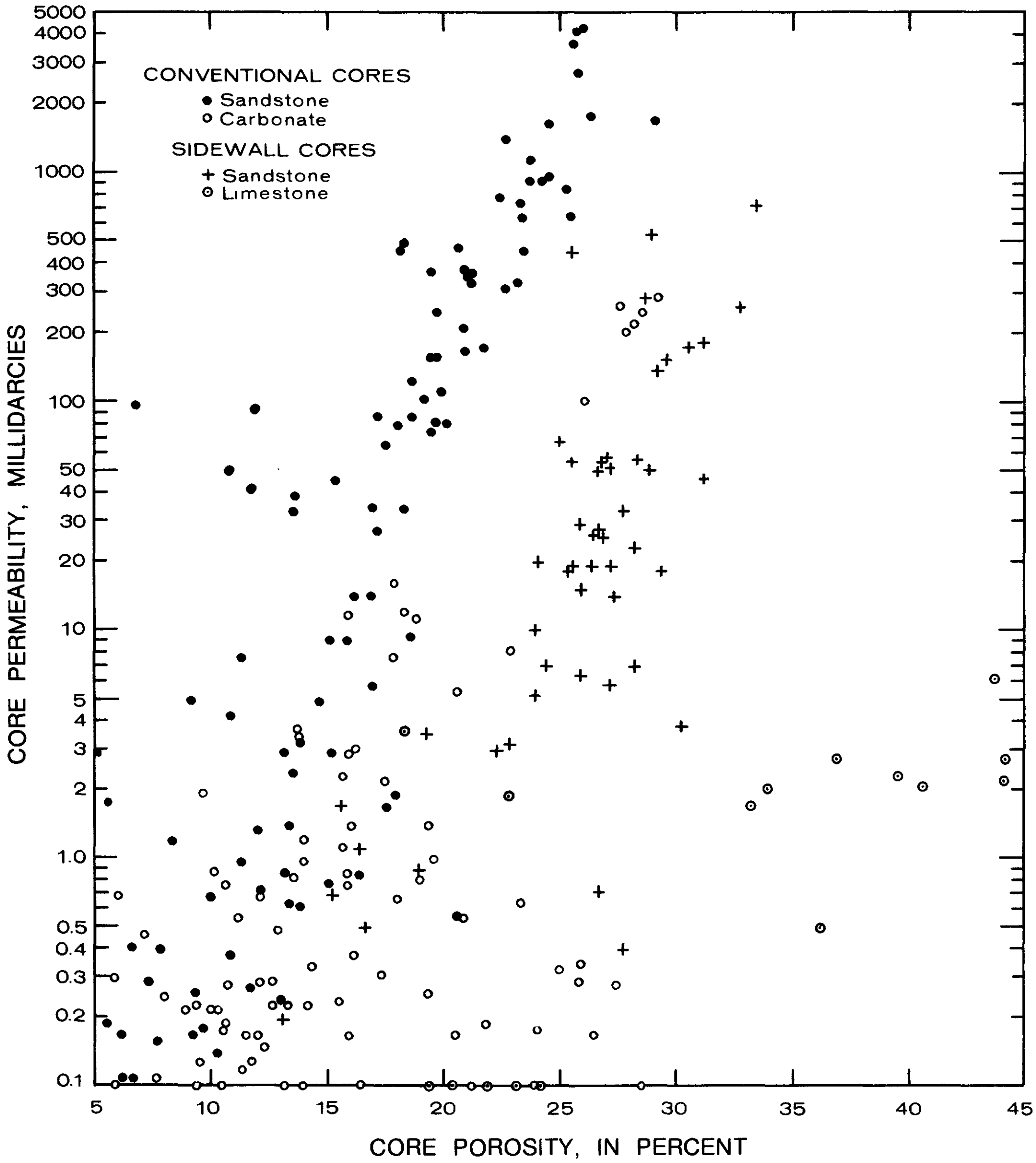


Figure 13.--Core porosities plotted against core permeabilities, COST No. GE-1 well.

PETROGRAPHIC SUMMARY

Robert B. Halley

INTRODUCTION

Rock chips from drill cuttings at 56 intervals were selected by hand and thin sections were made to provide material for a brief petrographic overview of the lithologies encountered in the COST No. GE-1 well. Each thin section contained between 10 and 30 rock chips and was stained for potassium feldspar, calcite, ferroan calcite, and ferroan dolomite. Observations and classification of these rocks, based on visual estimates, are tabulated in tables 4 and 5. The classification procedure follows that of Folk (1968). Working with cuttings tends to diffuse lithologic boundaries by contaminating those cuttings from the indicated sample depth with material from above. Nevertheless, cuttings provide valuable information not only on composition, texture, and depositional environment, but also on postdepositional alteration of the sediments. Depositional environments are discussed elsewhere in this volume (Poag and Hall, this volume; Valentine, this volume). Composition and diagenesis of the rocks are reviewed here with particular reference to preservation, creation, or destruction of porosity.

The stratigraphic section at GE-1 consists predominantly of carbonate rocks above about 7,150 ft (2,180 m) and of terrigenous clastic rocks below this depth. Data from carbonate and terrigenous clastic units in the well are listed separately in table 4 and are discussed separately below.

CARBONATE ROCKS

Beneath a blanket of shelf terrigenous clastics and carbonates less than 800 ft (250 m) thick, the GE-1 well encountered open-shelf and slope carbonate rocks to a depth of about 5,800 ft (1,800 m). These rocks are primarily fine-grained, cherty and argillaceous limestones with some calcareous shales. Most have a clayey carbonate-mud matrix with Foraminifera as the most abundant allochem. Even the samples from 1,230 ft (375 m), 1,620 ft (494 m), and 2,130 ft (649 m), which contain sand-sized fragments of red and green algae, bryozoans, echinoderms, and mollusks, are fine-grained, indicating a shallow-water, yet relatively low energy, environment. Most of these limestones have a chalky texture, and samples from 3,570 to 5,700 ft (1,090-1,750 m) are true argillaceous chalks and calcareous shales with globigerinid Foraminifera set in a matrix of clay and calcite mud containing coccoliths (figs. 14-16).

Porosity in these fine-grained carbonate rocks is rarely visible in thin section because pore size is small, on the order of 5 to 10 m or less (Halley, 1978). Occasionally, pore space is visible, as in the interior of Foraminifera, and in these cases the porosity is almost always primary. Most of the fine-grained porosity is inferred to be primary as well. Scholle (1977a, c) has recently discussed chalk diagenesis and the importance of burial diagenesis in these fine-grained carbonate rocks. In particular, the role of pressure solution of original fine-grained calcite with reprecipitation as cement appears to be a first-order control on porosity in chalks during burial.

Porosity determined from well logs shows an irregular but discernible decrease with depth to about 5,700 ft (1,750 m) in the COST No. GE-1 well. A generalized plot of porosity versus depth for the upper portion of the GE-1 well (fig. 17) shows that the fine-grained carbonates, some of which are not strictly true chalks because of their argillaceous matrix, appear to behave similarly to chalks with respect to porosity modification. The porosity decrease with depth is very similar to that in chalks of the Gulf Coast and is perhaps intermediate between that of the Gulf Coast and Scotian Shelf when plotted with data from Scholle (1977a).

From about 5,700 to 7,200 ft (1,750-2,200 m), the GE-1 well contains a varied sequence of generally medium grained calcarenites, dolomite, and anhydrite, with minor but significant amounts of quartz sandstone, pyrite, and glauconite. Common rock types include oolites, fossiliferous calcarenites, dolomite, micrite, and anhydrite. These rocks indicate a shallow-marine, often restricted, carbonate-bank or shelf setting. At about 5,800 ft (1,800 m), a conspicuous, carbonate-cemented, feldspathic, glauconitic sandstone suggests a major regression, if not a hiatus, between the shallow-water restricted-shelf carbonates and overlying fine-grained open-marine limestones. This observation is supported by biostratigraphic data (Poag and Hall, this volume).

Table 4.--Petrography of carbonate rocks from the COST No. GE-1 well

[Depths, given in feet and meters, represent 30-ft (9-m) sampling intervals from stated depth downward: X = common; XX = very common; t= trace; ? = possible]

Explanation of abbreviations used in table:

MM = micrite or clay matrix

Grain size:
- F = fine
- M = medium
- C = coarse

Constituent:
- Ar = arthropod skeletal fragments
- Al = algal
- Br = bryozoan
- Mo = Mollusk
- Ec = echinoderm
- Fo = foraminifer
- Sp = sponge spicules
- Pe = peloids
- Oo = ooids
- Q = quartz

Cement/Matrix:
- BC = blocky calcite
- FC = fibrous or bladed calcite
- Si = chert or chalcedony
- D = dolomite
- A = anhydrite

Porosity:
- P = primary
- S = secondary

Rock Name:
- FCL = fossiliferous calcilutite
- FCC = fossiliferous calcarenite
- CSS = calcite-cemented sandstone
- FCS = fossiliferous calcareous sandstone
- FOCC = fossiliferous oolitic calcareous
- OCC = oolitic calcarenite

Miscellaneous:
- CH = chert
- Dol = dolomite
- GL = glauconite
- PY = pyrite
- F = feldspar
- A = anhydrite
- FEC = ferroan calcite
- VC = calcite-filled fractures

Depth	Depth		Grains			Constituents										Cements					Porosity			
(ft)	(m)	MM	F	M	C	Ar	Al	Br	Mo	Ec	Fo	Sp	Pe	Oo	Q	BC	FC	Si	D	A	P	S	Rock name	Miscellaneous
600	183			x	x				x		x			x	x	x					x		Uncons. sand	
1,050	320	x	x				x				x					x					x		FCL	CH, GL.
1,230	375		x					x	x		x	x				x		x			x	x	FCC	CH.
1,680	512		x			x			x	x	x	x	x			x		x					FCC	CH.
2,130	649	x	x						x		x	x			x	x		x					FCL, FCC	CH.
2,490	759	x	x							x	x	x	x			x		x					FCL, FCC	CH, Dol.
2,850	869		x						x		x		x			x		x	x		x		FCC	CH, Dol.
3,120	951	x	x								x	x			x								FCL	
3,570	1,088	x	x								x	x						x			x		FCL	CH, GL.
3,660	1,116	x	x								x	x				x		x			x		FCL	CH.
4,020	1,225	x	x								x	x			x								FCL	
4,140	1,262	x	x								x							x					FCL	CH.
4,350	1,326	x	x						x		x	x											FCL	
4,440	1,353			x							x	x				x		x					FCL	CH.
4,500	1,372	x	x								x												FCL	
4,830	1,472	x	x								x												FCL	
5,100	1,554	x	x								x												FCL	
5,370	1,332	x	x	x							x					x							FCL-FCC	PY, FEC, VC
5,700	1,737	x	x								x					x							FCL	
5,760	1,756		x							x					x	x							FCC	F, GL, FEC
5,790	1,765			x											x	x							CSS	F, GL
5,880	1,792			x	x				x		x		x	x	x								FCSS	GL, PY, FEC
6,030	1,838			x					x						x	x							FCSS	GL, PY, FEC
6,090	1,856			x					x						x	x						x	FCSS	GL, PY
6,210	1,893			x			x		x	x	x			x	x	x							FOCC	
6,540	1,993			x					x					x	x	x	x	x		x	x	x	FOCC	PY, FEC
6,570	2,003			x					x		x			x	x	x				x		x	FOCC	
6,600	2,012	x																					Dolomicrite	A
6,720	2,048			x									x	x		x			x			x	OCC	A
6,870	2,094	x																					Dolomicrite	A
7,170	2,185	x		x					x	x				x	x				x			x	OCC	Dol

Porosity varies widely and unsystematically with depth in the zone between 5,700 and 7,200 ft (1,750-2,200 m). Here, diagenesis has played a much more complex role in determinining porosity distribution than in the overlying fine-grained carbonate rocks. In addition to some primary porosity in these rocks (figs. 18, 19), considerable secondary porosity is produced by dissolution of ooid grains and nuclei (figs. 20, 21). Secondary porosity is particularly prominent in the 6,540- and 6,720-ft (1,993- and 2,048-m) samples, but is also visible at scattered intervals between 5,800 and 7,200 ft (1,750-2,200 m). Dolomite, while common, is not abundant and is usually dense and nonporous. Significant intercrystalline dolomite porosity was not observed, except where dolomite had partially occluded secondary porosity in limestones. Three generations of calcite cement are distinguishable in the 5,700- to 7,200-ft (1,750- to 2,200-m) interval. The earliest is a bladed to fibrous, isopachous, nonferroan cement

Table 5.--Petrography of terrigenous clastic, metasedimentary, metamorphic and metamorphosed volcanic rocks from the COST No. GE-1 well

[Depths, given in feet and meters, represent 30-ft (9-m) sampling intervals from stated depth downward; X = common; XX = very common; t = trace: ? = possible]

Explanation of abbreviations used in table:

Grain size:
- F = fine
- M = medium
- C = coarse

Constituent:
- Q = quartz
- K = potassium feldspar
- P = plagioclase
- R = rock fragments
- Mi = mica

Cement/Matrix:
- Q = quartz
- Cl = clay
- C = calcite
- D = dolomite
- A = anhydrite

Porosity:
- P = primary
- S = secondary

Rock Name:
- A = arkose
- SA = subarkose
- FQA = feldspathic quartzarenite
- OA = quartzarenite
- OT = quartzite
- AR = argillite

Miscellaneous:
- Dol = dolomite
- VRF = volcanic rock fragments
- MRF = metamorphic rock fragments
- SLST = siltstone
- SH = shale
- P = primary porosity
- HC = hematite coatings
- VQ = vein quartz

Depth (ft)	Depth (m)	Grain size F	M	C	Constituents Q	K	P	R	Mi	Cements O	Cl	C	D	A	Rock name	Miscellaneous
								Terrigenous clastic rocks								
7,500	2,286	x	x		x	x	x	x	x	x		x			A-SA	VRF, MRF, HC
7,740	2,359	x			x	x	x	x			x	x	x	x	A-SA	VRF, HC
8,340	2,542	x	x		x	x	x						x		A-SA	HC, SLST
8,640	2,633	x	x		x	x		x	x		x		x		A	HC, SLST
8,930	2,722		x		x	x				x	x				OA-SA	HC, P
9,330	2,844	x			x										A	HC, SLST
9,480	2,890	x	x		x	x				x			x		FOA-SA	HC, SLST, SH
9,570	2,917		x		x	x							x	x	FOA-SA	HS, Dol, P
9,690	2,954		x		x	x							x		SA	HC, P
9,830	2,996	x			x	x		x					x		FQA-SA	HC, Dol, SH
10,170	3,100															Dol, SLST, SH
10,380	3,164		x		x					x			x		FOA-SA	Dol, SLST, SH
10,800	3,292		x		x	x							x		OA-FQA	
								Metasedimentary rocks								
10,860	3,310		x		x				x	x					QT	
10,920	3,328		x		x				x	x					QT	
11,100	3,383	x			x				x	x		x			AR	
11,250	3,429	x			x				x	x		x			AR	
11,460	3,493	x			x				x	x		x			AR	HC
11,610	3,539	x			x				x	x		x			AR	HC
11,700	3,566	x			x	x			x	x	x				AR	
12,150	3,703	x			x				x						AR	VO
12,600	3,840	x	x		x	x			x	x					AR,OT	
12,720	3,877	x	x		x	x			x	x					AR,OT	
								Metamorphic and metamorphosed volcanic rocks								
12,990	3,959														Hornfels, metamorphosed lavas.	
13,230	4,032														Hornfels, acidic lavas (trachyte).	

around ooids, possibly an early submarine cement. This is followed by a blocky calcite cement. Both generations are found in rocks containing considerable primary pore space. The final cement generation is ferroan blocky calcite and occludes most remaining primary and some secondary pore space. Anhydrite cement fills primary and secondary pore space in several samples, and extremely fine grained pyrite is a final pore coating in samples from 6,030 ft (1,838 m). The fine-grained pyrite is easily mistaken for a solid hydrocarbon until viewed in reflected light.

TERRIGENOUS CLASTIC ROCKS

Below 7,200 ft (2,200 m) lies a thick red-bed sequence consisting of red arkose, siltstone, and shale with minor amounts of dark shale and quartzarenite. The angularity, poor

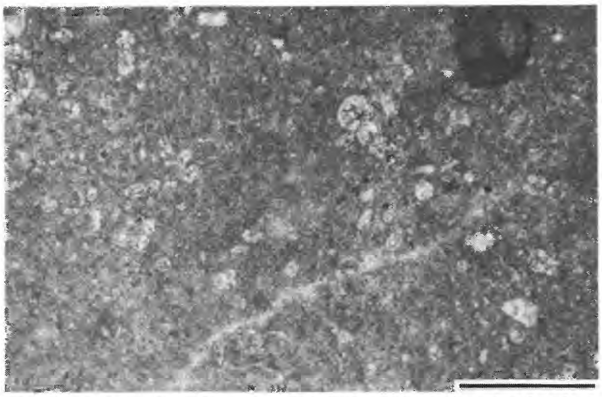


Figure 14.--Chalk: partially silicified planktonic Foraminifera and tabular mollusk(?) fragments in a fine-grained calcitic and siliceous matrix. Sample No. 3120; bar scale is 150 µm.

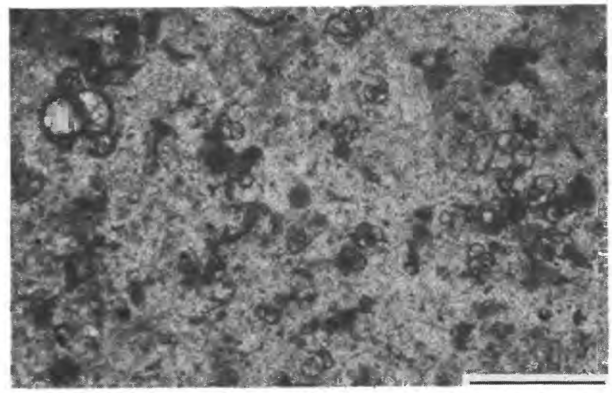


Figure 16.--Calcareous shale: planktonic Foraminifera (stained dark with calcite stain) in fine-grained argillaceous matrix. Sample No. 4830; bar scale is 300 µm.

sorting, and, in some samples, clay matrix of these sandstones suggest that only a moderate amount of depositional porosity originally was present. The primary porosity of these rocks has been diminished by compaction, pressure solution of quartz grains, quartz overgrowths, and cementation by carbonates and anhydrite. Diagenesis, together with the presumed moderate initial porosity of these sands, has left little visible porosity. Nevertheless, some primary porosity is preserved in samples from 8,130, 9,570, and 9,690 ft (2,478, 2,917, and 2,954 m, respectively), as shown in figures 22 and 23. The general lack of feldspar alteration through the 7,200- to 10,850-ft (2,194- to 3,307-m) interval suggests that moderate amounts of primary porosity will occur where cementation by quartz, carbonate, or anhydrite is not extensive. The base of this sequence at about 10,850 ft (3,307 m) marks another major break in the stratigraphic section of the COST No. GE-1 well.

A sequence of slightly metamorphosed sedimentary rocks, now quartzites and argillites, occurs below about 10,850 ft (3,307 m). Complete cementation in the quartzites and pressure solution, chlorite cementation, and compaction in the argillites have obliterated porosity in these rocks (fig. 24).

The last two samples examined, 12,990 and 13,230 ft (3,959 and 4,033 m) (fig. 25), contain cuttings of true metamorphic and metamorphosed igneous rocks, signifying another major break in the sequence; these may represent the basement(?) underlying the sedimentary sequence.

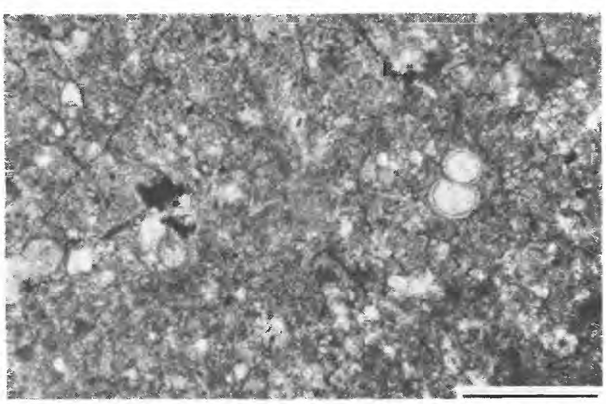


Figure 15.--Chalk: planktonic and benthonic Foraminifera in a fine-grained calcitic matrix. Note primary pore space in foraminiferal chambers. Sample No. 4020; bar scale is 300 µm.

Summary

The probability of reservoir rocks occurring below about 10,850 ft (3,300 m) is negligible owing to metamorphism evident in samples from below that level. Between about 10,850 and 7,200 ft (3,300-2,200 m), scattered intervals of significant porosity and permeability may be found in a red-bed sequence, where cementation and pressure solution/compaction have not obliterated primary pore space. Significant secondary-porosity development due to feldspar removal was not observed and does not seem likely in light of the fresh appearance of most feldspars in this interval. The best reservoir rocks are within restricted shelf carbonates occurring between 5,700 and 7,200 ft (1,750-2,200 m), where high primary and secondary porosity account for much of the best permeability encountered below 1,000 ft (304 m) in the GE-1 well. Although possessing good porosity, the fine-grained limestones above about 5,700 ft (1,750 m) probably are so impermeable as to make them unlikely candidates for reservoir rocks unless they are extensively fractured or contain undetected permeable horizons. Data presented by Scholle (1977a, c) suggest that permeabilities of 3 md or less should be expected throughout the interval from 1,000 to 5,700 ft (300-1,750 m).

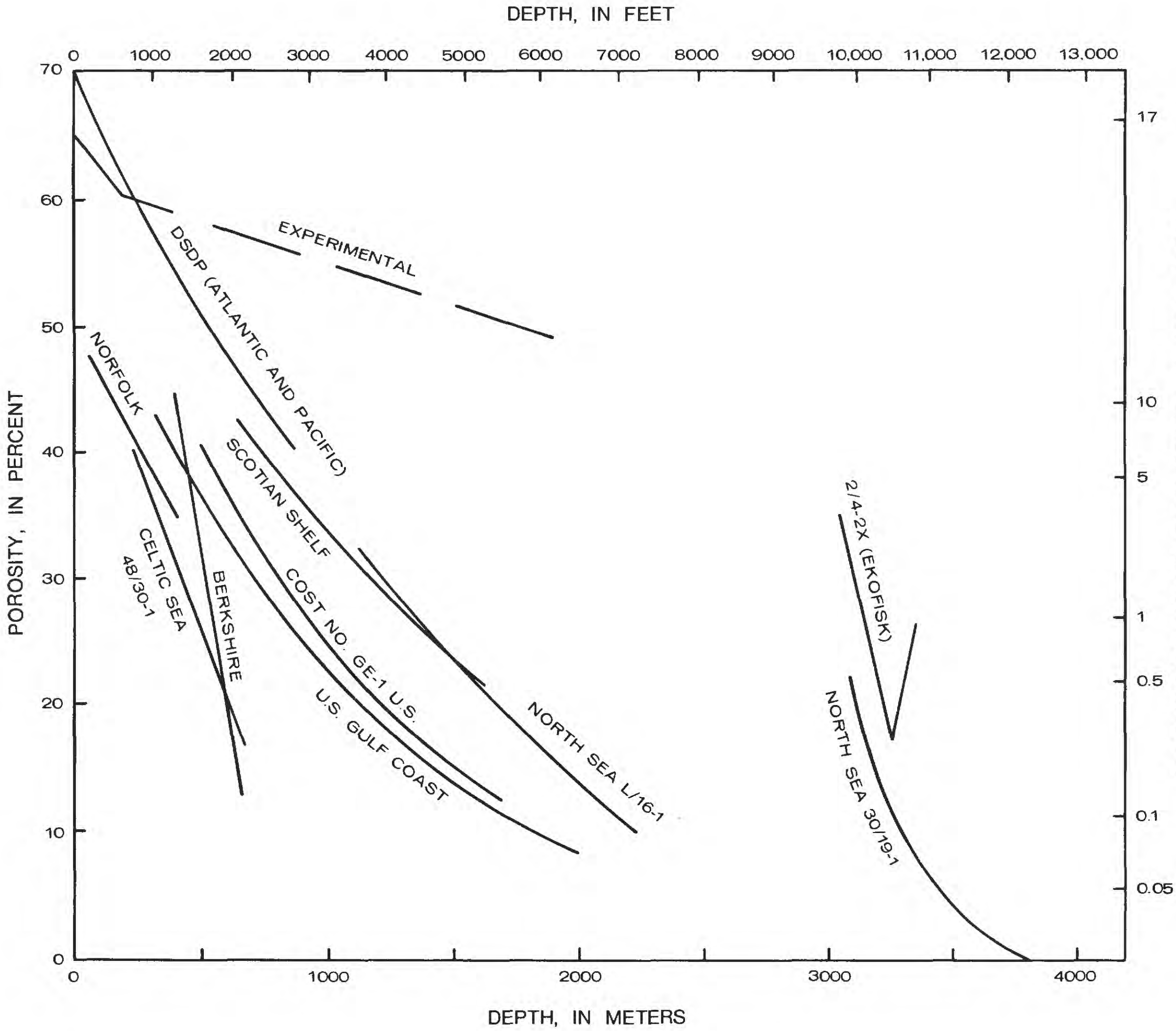


Figure 17.--Generalized porosity-depth relation for upper 5,700 ft (1,730 m) of COST No. GE-1 well, compared to some typical chalks (modified from Scholle, 1977a, c).

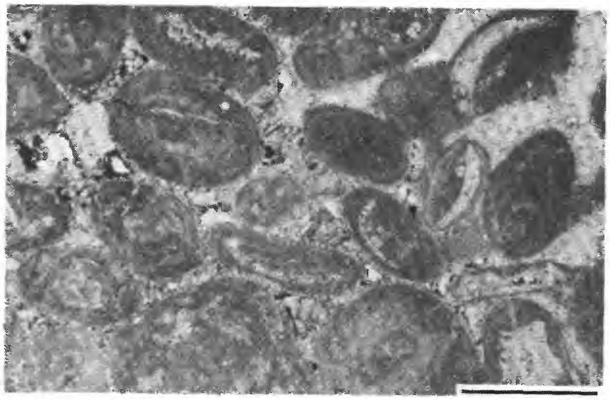


Figure 18.--Oolite: individual ooids with first-stage fringe of small, iron-poor calcite crystals and second stage of large, scattered, iron-rich blocky calcite crystals. Dark material lining pores is pyrite. Sample No. 6540; bar scale is 300 µm.

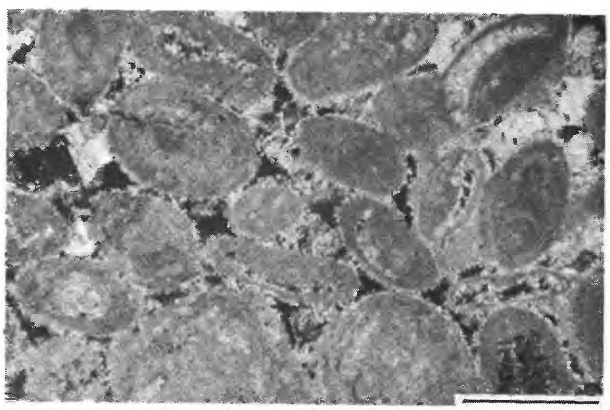


Figure 19.--Same view as figure 18, but with crossed polarizers to emphasize extensive primary and secondary porosity (black).

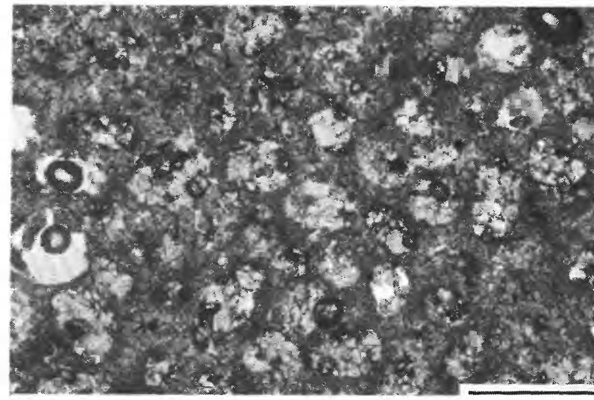


Figure 20.--Moldic porosity (after ooids?) in blocky calcite cement. Calcite is stained dark; lighter dolomite partially fills molds. Sample No. 6720; bar scale is 300 µm.

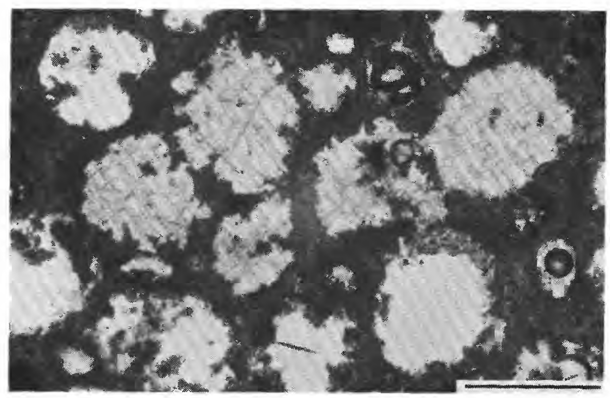


Figure 21.--Oomoldic porosity in blocky calcite cement, stanined dark. Some porosity loss has resulted from molds being secondarily filled with anhydrite. Sample No. 6720; bar scale is 300 µm.

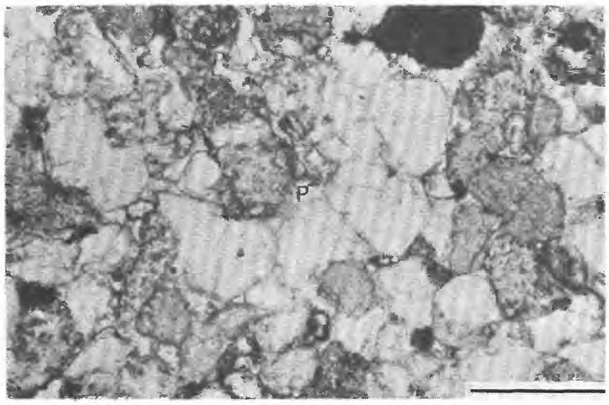


Figure 22.--Arkose: fine-grained; feldspars stained dark; minor amounts of rock fragments and dolomite cement. Small amount of visible primary porosity labeled (P). Sample No. 8640; bar scale is 300 µm.

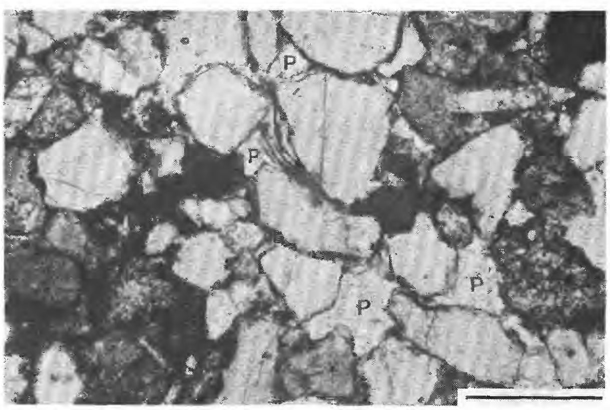


Figure 23.--Arkose: medium-grained; feldspars stained dark; minor rock fragments and opaque iron minerals (hematite?). Considerable primary pore space (P). Sample No. 9570; bar scale is 300 µm.

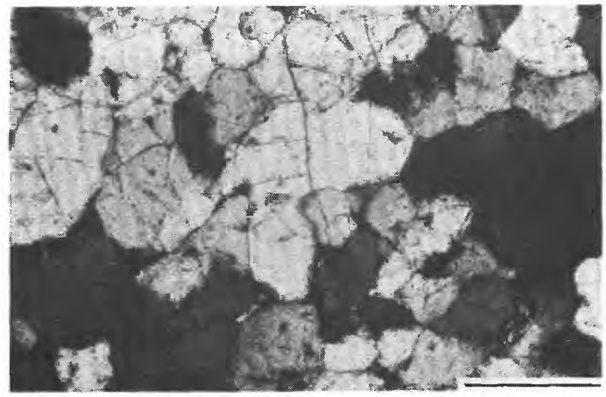


Figure 24.--Quartzite: pressure solution-modified grain contacts; no visible porosity. Sample No. 10,860; bar scale is 300 m.

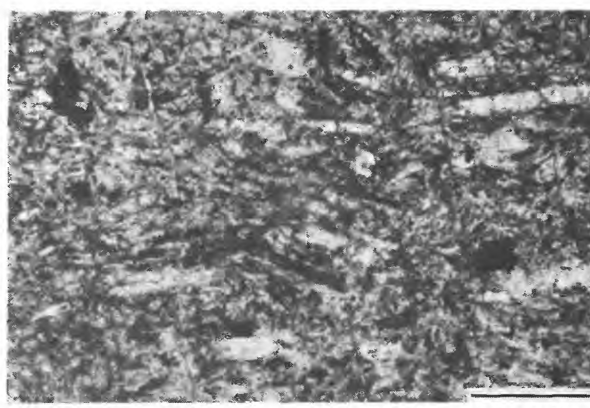


Figure 25.--Volcanic rock: oriented feldspar laths in trachyte. Sample No. 13,230; bar scale is 300 µm.

FORAMINIFERAL BIOSTRATIGRAPHY, PALEOECOLOGY, AND SEDIMENT ACCUMULATION RATES

C. Wylie Poag and Raymond E. Hall

INTRODUCTION

Very little geologic information has been published concerning the middle and outer parts of the Florida-Georgia Continental Shelf. The only previous stratigraphic studies based (in part) on foraminifers are those of Bunce and others (1965) and Schlee (1977), who studied cores from holes drilled by the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES); and of Hathaway and others (1976), who briefly described the data from core hole 6002 of the USGS Atlantic Margin Coring Project (AMCOR). In addition to the analysis of the COST No. GE-1 well samples presented here, we reinterpreted the data from JOIDES core holes J-1 and J-2 and more thoroughly discuss the data from AMCOR 6002. The biostratigraphic analysis of the Neogene strata is a joint effort by Poag and Hall. The other analyses and interpretations presented herein are those of Poag.

Rotary-ditch samples from the GE-1 well were collected at 30 ft (9.1 m) intervals, beginning at about 364 ft (111 m) below the KB. Each sample is a composite of approximately 30 ft (9.1 m) of drilled sedimentary rocks. We examined each sample in the Miocene through Pliocene interval and in the lower Eocene through middle Coniacian interval; otherwise, we examined samples at 90-ft (27.3-m) intervals. Samples below 8,840 ft (2,695 m) have been reported to contain no foraminiferal assemblages (Amato and Bebout, 1978), and we have not examined that part of the section. We did, however, examine foraminiferal assemblages from 77 sidewall cores taken in the GE-1 well. (See Amato and Bebout, 1978.) We sampled the JOIDES J-1 and J-2 core holes at 1 ft (30-cm) intervals and the AMCOR 6002 core hole at 30-ft (9-m) intervals. Depths cited for the JOIDES and AMCOR core holes are given as distance penetrated below the sea floor (bsf), but depths for the GE-1 well are in distance below the KB. For consistency, biostratigraphic changes that occur between samples are placed halfway between sample tops.

In this analysis, the age of the rocks is based primarily on planktic foraminifers, but these determinations are supplemented by benthic species when applicable. Paleoenvironments are interpreted from the generic composition of the benthic assemblages, from the relative abundance of planktic specimens, and from the general diversity of species in each sample. The time scales and biostratigraphic zones used here are those of Berggren and van Couvering (1974) for the Cenozoic, and van Hinte (1976) for the Cretaceous. Interpretation of the data presented here is preliminary, and modifications can be expected as new data arise and further analyses take place.

STRATIGRAPHY AND CORRELATION OF STRATA IN THE GE-1 WELL

Upper Pliocene Rocks (~364 to ~544 ft; (~111 to ~166 m).--The youngest sample available from the GE-1 well is of late Pliocene age (fig. 25). We assume that the upper 131 ft (40 m) of sediment (down to 364 ft (111 m)) is Pleistocene, based on comparison with samples from the other core holes (J-1, J-2, AMCOR 6002). At 386 ft (118 m), *Globorotaloides planispira* and *Globigerina incisa* are present along with *Neogloboquadrina dutertrei* and *Sphaeroidinella dehiscens*. *Globigerinoides obliquus* appears at 420 ft (128 m), and *Globorotalia miocenica* appears at 447 ft (136 m), along with *Globigerina apertura* and *Globigerinoides conglobatus*. Lower in this interval, other typical Pliocene species appear, such as *Globigerina decoraperta*, *Globorotalia exilis*, and *Globorotaloides planispira*. The entire interval is assigned to Zone N. 21 of the late Pliocene. Zone N. 21 is also present, but thinner, in J-1 and J-2 (on the southern rim of the embayment), but the entire Pliocene is missing in AMCOR 6002 (on the northern rim of the embayment) (fig. 27).

Middle Miocene Rocks (~364 to ~544 ft (~166 to ~219 m)).--We observed no evidence of lower Pliocene Zones N. 19 to N. 20 or of upper Miocene Zones N. 13 to N. 18 in the GE-1 well. A hiatus of 10 m.y. separates the upper Pliocene and middle Miocene rocks (fig. 25). At 561 ft (171 m), *Globorotalia praefohsi*, *Orbulina suturalis*, *Turborotalia siakensis*, and a host of additional planktic species mark middle Miocene Zone N. 11/12. At 589 ft (179 m), *Globorotalia peripheroronda* and *G. peripheroacuta* appear.

Zone N. 10 is represented at 610 ft (186 m) by Clavatorella bermudezi and Globigerinoides sicanus indicate Zone N. 9. Strata of early Miocene age are absent in the GE-1 well.

The Miocene record is not as uniform across the embayment as that of the Pliocene (fig. 27). Part of the upper Miocene (Zones N. 17 and N. 18) is present at AMCOR 6002, the middle Miocene section is represented at J-1 and 6002, and part of the lower Miocene (Zones N. 4-N. 8) is present at each peripheral site. The lower Miocene is particularly thick at J-2.

Middle and Lower Oligocene Rocks (~719 to ~1,217 ft (~219 to ~371 m)).--Zones N. 4 to N. 8 of the early Miocene and Zone P. 22 of the late Oligocene are missing from the GE-1 well (hiatus

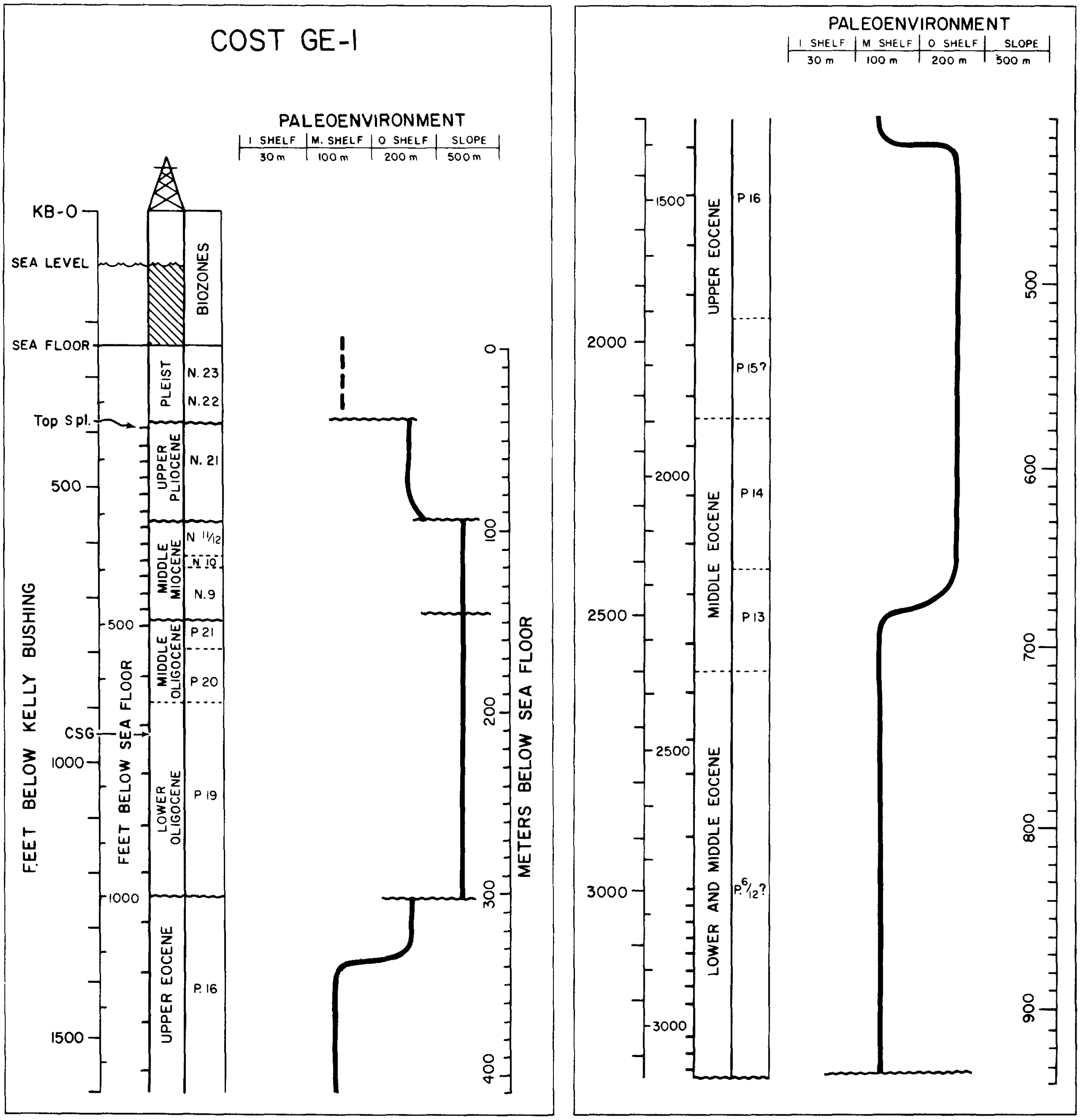
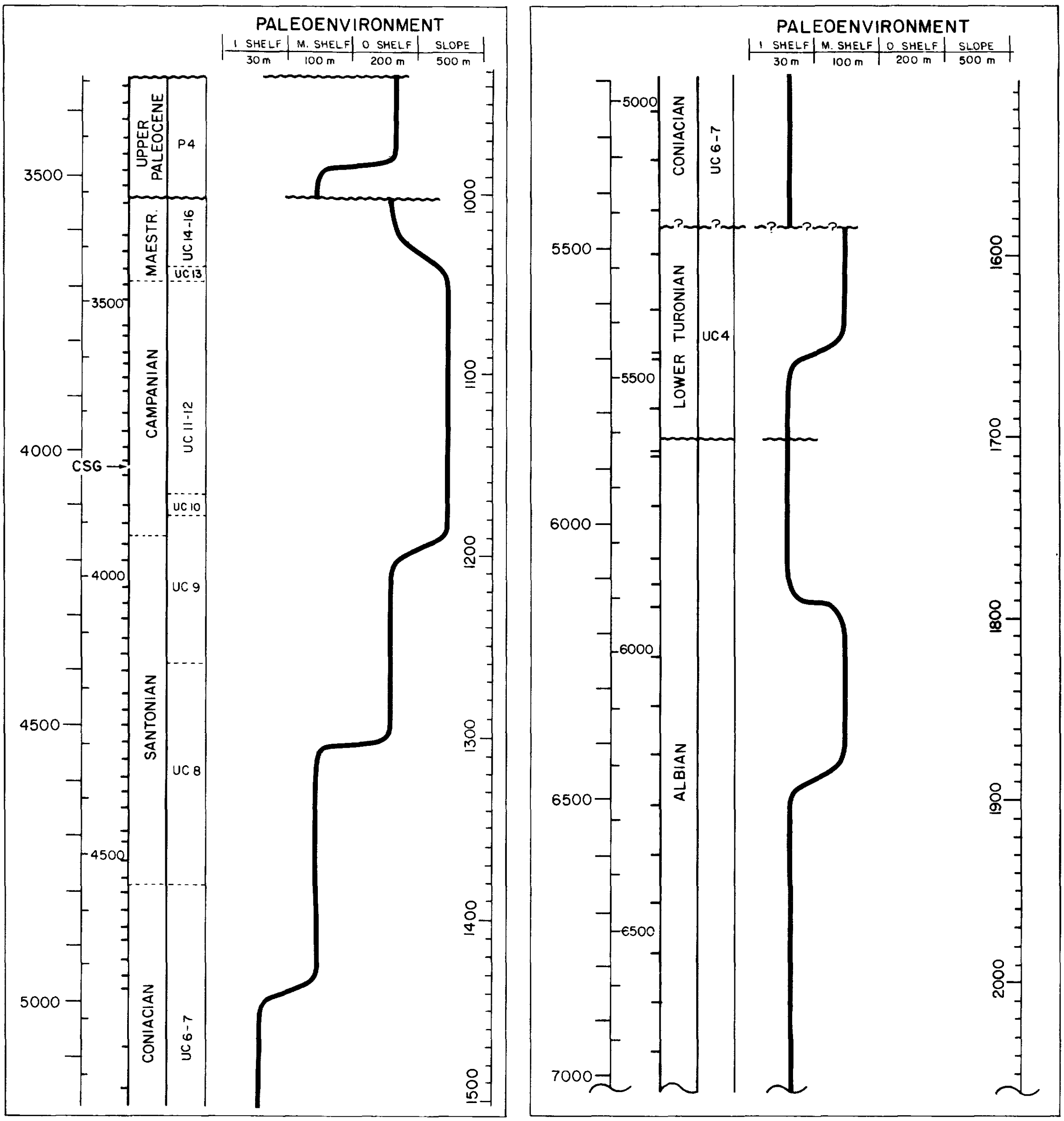


Figure 26.--Biostratigraphic column for Albian through Pleistocene rocks penetrated by the COST Cretaceous from van Hite (1976). KB, Kelly Bushing on rig floor; CSG, casing point; tick inner shelf; M. Shelf, middle shelf; and O. Shelf, outer shelf.

of 14 m.y.; fig. 25). Chiloguembelina cubensis, Globigerina officinalis, and members of the Globigerina ciperoensis group occur at 725 ft (221 m) and appear to represent Zone P. 21 of the middle Oligocene, because Turborotalia kugleri, which is typical of Zone P. 22, is absent. Turborotalia ampliapertura, Globoquadrina gortanii, Globigerina ouachitaensis, and Globigerinita unicava primitiva appear at 824 ft (251 m), marking Zone P. 20. At 915 ft (279 m), Turborotalia increbescens, Globoquadrina tapuriensis, and Pseudohastigerina barbadoensis mark Zone P. 19 of the lower Oligocene; Turborotalia euapertura also was first observed in this sample. Zone P. 19 continues in the sample at 1,184 ft (361 m),



No. GE-1 well. Biozone designations for Cenozoic from Berggren and van Couvering (1974); for marks at left column under derrick symbol, location of top of examined cuttings samples: I. Shelf,

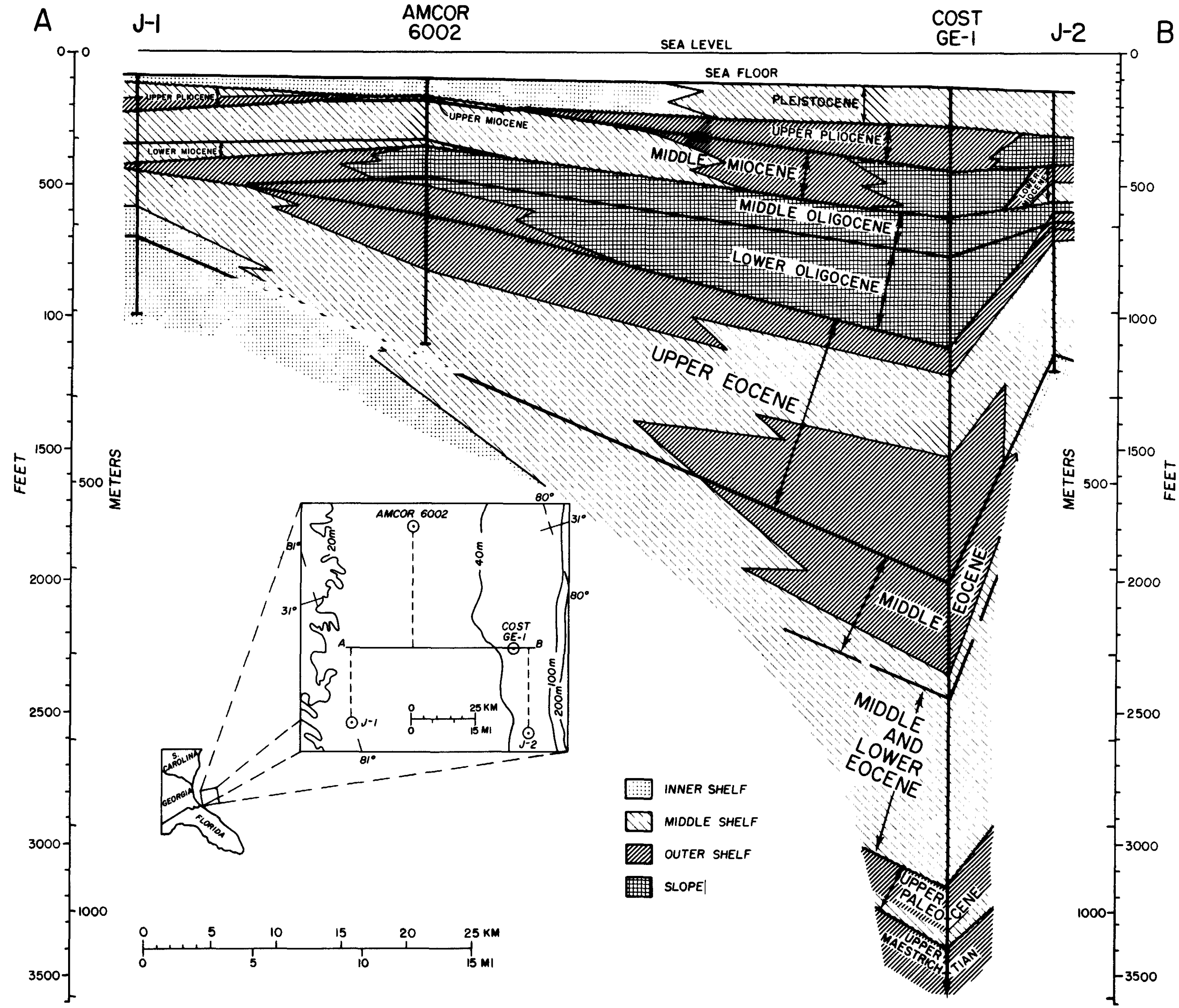


Figure 27.--Approximate dip section of Cenozoic rocks near axis of Southeast Georgia Embayment showing foraminiferal biostratigraphy and paleoecology. Line of section is drawn through the COST No. GE-1 well. J-1 and J-2 wells near southern rim and AMCOR 6002 well near northern rim of embayment are projected onto line of section. This projection causes the reversed dip from GE-1 to J-2. Vertical exaggeration X 63.

where Globoguadrina sellii accompanies an assemblage of small globigerinids. The middle and lower Oligocene units of GE-1 are also present at AMCOR 6002 and J-2, but only the middle Oligocene is represented at J-1 (fig. 27).

Eocene Rocks (~1,217 to 3,300 ft (~371 to ~1,006 m)).--A hiatus of 5 m.y. separates the lower Oligocene Zone P. 19 from the upper Eocene Zone P. 16 in the GE-1 well (fig. 25). The presence of Hantkenina primitiva and Globigerinatheka index tropicalis, along with numerous Lepidocyclina and nummulitids at 1,266 ft (386 m), marks the highest occurrence of upper Eocene Zone P. 16. Globigerinatheka mexicana mexicana, Turborotalia cerroazulensis cerroazulensis, and T. cerroazulensis cocoaensis, also typical of Zone P. 16, occur in various samples down to 1,873 ft (571 m). At 1,972 ft (601 m), Zone P. 15 is indicated by Globigerinatheka index rubriformis, G. subconglobata luterbacheri, and Acarinina primitiva. A similar sequence of upper Eocene zones is present at J-1 and J-2 on the southern rim of the embayment. But AMCOR 6002 did not penetrate deeply enough to reach the lowest part of the upper Eocene (fig. 27).

Middle Eocene Zone P. 14 is represented at 2,162 ft (659 m) in the GE-1 well by Truncorotaloides topilensis, Acarinina senni, and A. broedermanni. Zone P. 13 is indicated at 2,431 ft (741 m) by Orbulinoides beckmani and Globigerinatheka kugleri. Similar assemblages occur in the lowest parts of J-1 and J-2 (fig. 27).

The interval from 2,568 to 3,300 ft (783-1,006 m) in the GE-1 well contains poorly preserved, sparse foraminiferal assemblages which are difficult to interpret. Scattered occurrences of species such as Acarinina quetra, A. nitida, Morozovella wilcoxensis, M. aequa, and M. subbotinae indicate that lower Eocene rocks are probably present, but that the specimens are too scarce to permit more refined zonation (fig. 25).

Paleocene Rocks (~3,300 to ~3,513 ft (~1,006 to ~1,071 m)).--The precise position of the youngest Paleocene rocks in GE-1 is also difficult to distinguish. Scattered specimens of Planorotalites pseudomenardii, Subbotina triloculinoides, and Acarinina pusilla pusilla, which are lower upper Paleocene species, occur as high as 3,055 ft (931 m), but sidewall cores at 3,211 ft (979 m) still contain lower Eocene species. The highest occurrence of apparently in situ Paleocene foraminifers is at 3,317 ft (1,011 m), where Planorotalites pseudomenardii, Morozovella kolchidica, M. velascoensis, Acarinia angulata, A. pusilla pusilla, Subbotina velascoensis, and S. triloculinoides occur together and indicate Zone P. 4 of the lower upper Paleocene. Thus, a hiatus of 2-3 m.y. may separate the lower Eocene from the upper Paleocene (fig. 25).

Maestrichtian Rocks (~3,514 to ~3,671 ft (~1,071 to ~1,119 m)).--The lowest Paleocene zones (P. 1-P. 3) and uppermost Maestrichtian zone (UC 17) seem to be missing in the GE-1 well (fig. 25). The hiatus represents a gap of 8 m.y. Zone UC 16 is represented at 3,530 ft (1,076 m) by a diverse assemblage of planktic species including Globotruncana gansseri, G. patelliformis, G. arca, G. stuartiformis, G. stuarti, G. elevata, Rugotruncana rugosa, Globotruncanella petalloidea, Pseudotextularia deformis, P. elegans, and Pseudoguembelina costulata. At 3,619 ft (1,103 m), a similar planktic assemblage is accompanied by the highest occurrence of Bolivinoides miliaris, which signifies the lower part of Zone UC 14

Campanian Rocks (~3,671 to ~4,130 ft (~1,119 to ~1,259 m)).--At 3,684 ft (1,123 m) Neoflabellina rugosa and Globotruncana ventricosa mark the middle part of Zone UC 12 (fig. 25); these species are accompanied by Rugoglobigerina milamensis, Archaeoglobigerina cretacea, A. blowi, Globotruncana linneiana, and G. contusa. Zone UC 13 (youngest Maestrichtian), if present, is less than 30 ft (10 m) thick. At 4,072 ft (1,241 m), the highest occurrence of Bolivinoides decoratus and Kyphpyxa christneri indicate Zone UC 10.

Santonian Rocks (~4,130 to ~4,760 ft (~1,259 to ~1,451 m)).--The first indication of species of Zone UC 9 occurs at 4,120 ft (1,256 m), where Marginotruncana angusticarenata and Globorotalites multiseptus first occur (fig. 26). Bolivinoides strigillatus occurs at 4,285 ft (1,306 m). At 4,383 ft (1,336 m) the first occurrence of Globotruncana concavata indicates Zone UC 8; Sigalia appears 90 ft (30 m) lower; Whiteinella archaeocretacea and W. aprica(?) occur at 4,668 ft (1,423 m).

Coniacian Rocks (~4,760 to ~5,433 ft (~1,451 to ~1,656 m)).--The first evidence for Zone UC 7 occurs at 4,776 ft (1,456 m), where Marginotruncana sigali and M. marginata appear. Clavihedbergella simplex occurs at 4,950 ft (1,509 m); Marginotruncana schneegansi occurs at 5,138 ft (1,566 m). Reworked specimens of the Cenomanian markers Rotalipora cushmani and R. greenhornensis occur at 5,062 and 5,219 ft (1,543 and 1,591 m), respectively (fig. 26).

Lower Turonian Rocks (~5,433 to ~5,810 ft (~1,656 to ~1,771 m)).--Globotruncana helvetica the marker for Zone UC 5 of the middle Turonian, appears at 5,482 ft (1,671 m), but it is accompanied by the Zone UC 4 markers Praeglobotruncana stephani and P. turbinata. This faunal association and the evidence of shoaling water depth at 5,433 ft (1,656 m) (fig. 26) suggest that upper and middle Turonian rocks have been eroded away.

Albian Rocks (~5,810 ft to ~7,405 ft (~1,771 m to ~2,257 m)).--Below 5,810 ft (1,771 m), the foraminiferal faunas of the GE-1 well are largely sparse benthic assemblages that contain no distinct age-diagnostic species. No evidence of Cenomanian assemblages exists. The Albian interval was identified on the basis of palynomorphs. Based on the lithology, paleoenvironment, and comparative depositional rates, discussed more fully below, we conclude that Cenomanian rocks are missing from this well (fig. 26).

Aptian to Valanginian(?) Rocks (~7,405 to ~10,990 ft (~2,257 to ~3,350 m)).--Palynomorphs examined by R. Christopher and J. Bebout (USGS, written commun., 1978) suggest that Aptian rocks are present at 7,411 ft (2,259 m). At 9,525 ft (2,903 m), an Early Cretaceous flora is still present, but the species are long ranging, indicating an age of Barremian to Aptian (but no older than Barremian). The remaining 1,467-ft (447-m) interval above basement in the GE-1 well (9,525-10,758 ft (2,903-3,279 m)) is not fossiliferous, but one can estimate the age of the oldest sedimentary rocks as approximately Valanginian (Early Cretaceous) on the basis of an extrapolation of sediment accumulation rates. (See further discussion below.)

STRATIGRAPHIC DISCUSSION

As shown above, much of Cenozoic and Late Cretaceous time is well represented in the Southeast Georgia Embayment by fossiliferous marine sedimentary rocks that show evidence of thickening from surrounding core holes into the GE-1 well. In contrast, rocks of Early Cretaceous age are largely sparsely fossiliferous or barren. Seven regional hiatuses interrupt the depositional record. They occur between the Albian and Turonian, upper Maestrichtian and upper Paleocene, upper Eocene and lower Oligocene, middle Oligocene and middle Miocene, middle Miocene and upper Pliocene, and upper Pliocene and lower Pleistocene (figs. 26, 27). A comparison of the Cenozoic rock record in nearby core holes (J-1, J-2, and AMCOR 6002; fig. 27) reveals that the biostratigraphic zones present there are nearly identical to those in GE-1. The hiatuses at the top of the Eocene, top of the Oligocene, and top of the Miocene are present in each core hole and can be traced elsewhere throughout the embayment using high-resolution seismic-reflection profiles (C. Paull, USGS, oral commun., 1978). They correspond to periods of low global sea level, as described by Vail and others (1977b; fig. 28). The hiatuses at the tops of the Paleocene, Maestrichtian, and the Albian are also regionally recognizable on Common Depth Point (CDP) seismic-reflection profiles (Dillon, oral commun., 1978) but are not yet corroborated by additional deep wells. They too correspond to times of low global sea level (Vail and others, 1977b).

By comparing the paleobathymetric trends that are discussed in the following section with estimates of sea-level drops given by Vail and others (1977b), we conclude that the surfaces marking the following hiatuses in the GE-1 well are unconformities caused by subaerial erosion: late Albian to early Turonian, late Maestrichtian to late Paleocene, late Paleocene to early Eocene, and late Pliocene to early Pleistocene. The late Oligocene to middle Miocene and the middle Miocene to late Pliocene hiatuses were caused by nondeposition in a marine environment, and the late Eocene to early Oligocene hiatus is the result of submarine erosion.

PALEOECOLOGY

The depositional environments of sediments penetrated by the GE-1 well vary from terrestrial (nonfossiliferous) biotopes to ocean depths equivalent to those of the modern upper continental slope (650-1,650 ft (200-500 m)). Most of the Cenozoic and Upper Cretaceous rocks accumulated in marine continental-shelf biotopes, but the Lower Cretaceous rocks are largely nonmarine and marginal-marine deposits. The following paleoecologic discussion proceeds from the oldest to youngest rocks in order to preserve the proper geochronologic perspective.

Valanginian(?) to Aptian Rocks.--The Valanginian(?) to Aptian rocks are largely red shales and sandstones of terrestrial origin, as indicated by the sparsity of marine fossils and the presence of terrestrial palynomorphs in some samples. To date, the only marine fossils observed in this interval are an assemblage of dinoflagellates at 8,690-8,891 ft (2,649-2,710 m). Additional shallow-marine intervals are indicated by the presence of anhydrite and dolomite, but no marine fossils have yet been observed in them.

Albian Rocks.--Albian sediments (cuttings samples) below 7,713 ft (2,351 m) contain scattered, sparse assemblages of shallow-water, inner shelf, benthic foraminifers, such as miliolids, along with bioclastic limestones, aggregates of anhydrite or gypsum crystals, limy casts of microgastropods and bivalves, and numerous ostracodes. These assemblages indicate restricted, high-salinity, carbonate environments.

A distinctly different assemblage is present between 6,105 and 6,466 ft (1,861-1,971 m). It is characterized by large, coarse-grained, agglutinant foraminifers of the genus Ammobaculites(?). Small specimens of Cyclammina sp. and fragile-walled Trochammina sp. are less abundant. The ammobaculitid tests are composed of quartz grains held together by calcareous cement, but nonagglutinated calcareous species were not recovered in this interval. The presence of oolitic limestone and free ooids attests to vigorous water agitation within this carbonate province. The water depthsd of quartz grains held together by calcareous cement, but nonagglutinated calcareous species were not recovered in this interval. The presence of oolitic limestone and free ooids attests to vigorous water agitation within this carbonate province. The water depths were probably equivalent to those of today's middle shelf (fig. 26).

The upper part of the Albian section, 6,105-6,466 ft (1,861-1,971 m), contains a sparse assemblage of benthic species (Gavelinella, Lingulogavelinella), some of which are characteristically pyritized. This assemblage indicates an inner-shelf environment (fig. 26).

Turonian Rocks.--The lowest Turonian rocks in the GE-1 well contain sparse faunas similar to those of the upper Albian rocks; and they represent, likewise, inner-shelf conditions. Between 5,482 ft and 5,515 ft (1,671 m-1,651 m), however, the increased abundance of Lingulogavelinella turonica, accompanied by a moderately well developed planktic assemblage, suggests a deepening to middle-shelf water depths (fig. 26).

Coniacian Rocks.--The lower two-thirds of the Coniacian section, 5,416-4,990 ft (1,651-1,521 m), contains a sparse assemblage of small benthic specimens belonging to Neobulimina canadensis, Gavelinella sp., and Lenticulina sp. This assemblage and the accompanying ostracode fauna suggest an inner-shelf environment. The upper Coniacian beds, 4,951-4,760 ft (1,511-1,451 m), contain a better developed planktic assemblage, plus a moderately large assemblage of several species of Gavelinella (cf. berthelini, cf. thalmanni, cf. sculptilis, cf. clementiana) that suggests middle-shelf environments (fig. 26).

Santonian Rocks.--The lower part of the Santonian interval, 4,760-4,530 ft (1,451-1,381 m), contains assemblages of small benthic species (Lingulogavelinella sp., Gavelinella cf. berthelini, Bolivinita costata, and Eouvigerina aculeata) and a moderately rich planktic assemblage, which suggest continued middle-shelf conditions. Between 4,530 and 4,169 ft (1,381-1,271 m), the benthic fauna is much richer and more diverse than any of the older assemblages. Large specimens of Gavelinella clementiana are abundant, but the most prominent forms are large agglutinants such as Lituola taylorensis, Plectina watersi, Gaudryina ellisorae, Martinottiella sp., and Liebusella(?) sp. Planktic specimens are abundant and Globorotalites multiseptus has its highest occurrence here. This assemblage indicates that the embayment had deepened to outer-shelf depths (fig. 26).

Campanian Rocks.--The Campanian assemblages represent the deepest water conditions that prevailed in this area during the Cretaceous. Both planktic and benthic assemblages are rich in specimens and species. Benthic forms include Neoflabellina rugosa, Osangularia sp., Clavulinoides trilatera forma concava, Pleurostomella sp., Heterostomella sp., Kyphopyxa christneri, Bolivinoides decoratus, and many others, which suggest conditions equivalent to those of the modern upper continental slope (fig. 26).

Maestrichtian Rocks.--Upper-slope faunas persist into the lower half of the Maestrichtian beds (3,710-3,595 ft (1,131-1,096 m)). Benthic species include Bulimina kickapooensis, Brizalina incrassata, Globorotalites michelinianus, Bulimina trihedra, Bolivinita eleyi, Planulina taylorensis, and others. A shallowing of water to outer-shelf depths is indicated in the upper Maestrichtian interval from 3,595 to 3,513 ft (1,096-1,071 m). The faunas there remain rich in specimens and species, but the deeper-water species disappear. Typical benthic forms are Arenobulimina americana, Gavelinella danica, Marssonella sp., Stensioina pommerana, Bolivinoides draco, Reophax texanus, Ammodiscus glabratus, Gaudryina austinana, Clavulinoides aspera, C. trilatera, several dentalinids (fig. 26).

Paleocene Rocks.--The oldest Paleocene sediments, 3,513-3,448 ft (1,071-1,051 m), contain sparse faunas of both benthic and planktic species. Gavelinella danica is one of the few identifiable forms. Several reworked Cretaceous forms also are present. This assemblage suggests middle-shelf conditions (figs. 26, 27). A richer and deeper-water assemblage occurs above this between 3,448 and 3,284 ft (1,051-1,001 m). Here, prominent benthic species include Gavelinella danica, Eponides bollii, Spiroplectammina trinitatensis, Dorothia bulleta, Marssonella dentata, Textularia sp., Lenticulina spp., Globobulimina sp., Cibicides spp., and Bulimina sp. This assemblage, accompanied by an increase in planktic species, indicates outer-shelf conditions (figs. 26, 27).

Eocene Rocks.--The interval assigned to the lower and lower middle Eocene, 3,284-2,463 ft, (1,001-751 m)) contains very few benthic specimens. A few scattered tiny specimens of unidentified calcareous species appear to indicate middle-shelf conditions (figs. 26, 27). This assemblage contrasts significantly with the contents of two sidewall cores at 3,750 and 3,643 ft (1,129.4 and 1,110.5 m), which contain abundant segments of large Bathysiphon, rare Melonis cf. pompilioides, and abundant large spherical radiolarians. This association suggests that depths may have reached the equivalent of today's upper to middle continental slope. Extensive silicification of all the calcareous elements in this interval, and perhaps dissolution as well, complicates the interpretation even further. Obviously, the nature of the paleoenvironment and the precise age of this interval must be determined by further analysis; but, for the present, we accept a middle-shelf interpretation, which is supported by the nannofossil analysis (Valentine, Calcareous nannofossil biostratigraphy, this volume).

The upper part of the middle Eocene, 2,463-2,103 ft (751-641 m), and the lower part of the upper Eocene, 2,103-1,627 ft (641-496 m), contain a rich benthic assemblage including frequent Uvigerina and Bulimina that indicate outer-shelf deposition (figs. 26, 27). Nummulitids and operculinids, which are normally associated with shallow carbonate banks and reefs (for example, Frost, 1977), are also present here, but appear to have been displaced from shallower water along the rims of the embayment. These larger foraminifers are present in greater abundance nearby in the J-1, J-2, and AMCOR 6002 core holes, where they and lepidocyclinids are the predominant benthic foraminifers in shallower-water carbonate-bank assemblages (fig. 27). The shallow-carbonate-bank environment, typified by abundant lepidocyclinids, nummulitids, and a hash of cheilostome bryozoans, extended to the GE-1 well site during the late Eocene, as seen in the interval from 1,627 to 1,332 ft (496-406 m) (figs. 26, 27). The assemblages at this location and in the surrounding core holes suggest that a broad carbonate platform developed at this time in waters of inner- and middle-shelf depths.

Near the end of the Eocene, outer-shelf conditions returned to the site of the GE-1 well (1,332-1,217 ft (406-371 m)), and they prevailed at J-2 and AMCOR 6002 as well (figs. 26, 27). Characteristic benthic species include Textularia adalta, T. recta, T. dibollensis, large Lenticulina spp., Sigmoidella plummerae, Brizalina caelata, B. huneri, B. jacksonensis, Siphonina advena, Nodosaria spp., Gyroidina octocamerata, Eponides jacksonensis, Cibicides pippeni, Dentalina cocoaensis group, Uvigerina cocoaensis, Anomalina bilateralis, and Cibicidina blanpeidi. Lepidocyclinids and nummulitids are still present, but appear to have originated from shallower biotopes such as that concurrently present at J-1 (fig. 27).

Oligocene Rocks.--The sediments bounding the hiatus separating Oligocene from Eocene rocks in the GE-1 well bear evidence of weathering. Polished, abraded, and oxidized specimens of foraminifers are common and are associated with polished glauconitic grains and abraded mollusk fragments. This characteristic mineral and fossil assemblage is also present at the same stratigraphic position in the J-2 and AMCOR 6002 core holes.

The indigenous faunas of the Oligocene in the GE-1 well originated in deeper water than any of the older Cenozoic assemblages, except perhaps those of the early Eocene (figs. 26, 27). Forms such as Planulina cooperensis, Bulimina sculptilis, Globobulimina sp., Chilostomella sp., Cancris sp., large Saracenaria sp., Sigmomorphina sp., polymorphinids, and abundant diverse planktic faunas indicate deposition in depths equivalent to today's upper continental slope. On the other hand, the lower Oligocene sediments at J-2 and AMCOR 6002 accumulated in outer-shelf conditions, as indicated by the predominance of uvigerinids and reduced planktic assemblages; but slope faunas are present in the middle Oligocene at these sites, as indicated by the abundance of Bulimina sculptilis and B. alazanensis (fig. 27). At J-1, lower Oligocene rocks are missing, and the thin middle Oligocene section accumulated in an outer-shelf environment; Brizalina, Florilus, Pararotalia, and small planktic specimens are predominant.

Miocene Rocks.--Following a period of erosion or nondeposition in the late Oligocene and early Miocene (fig. 27), deposition of upper continental slope sediments continued at the GE-1 well site during the middle Miocene. Rich and diverse planktic assemblages accompany diverse benthis assemblages typified by Bolivina floridana, Siphogenerina lamellata, Uvigerina rustica, U. peregrina, Laticarinina pauperata, Stilostomella sp., and large Vaginulinopsis.

At AMCOR 6002 and J-1, the middle Miocene environments were somewhat shallower, and foraminifers and other calcareous fossils are rare (fig. 27). Instead, the predominant microfossils are diatoms, which are accompanied by silicoflagellates and radiolarians. Glauconite and quartz sand are abundant; and fish vertebrae, teeth, and scales, and polished phosphoritic grains are common. The diatom assemblages contain shallow-water benthic forms and also species indicative of cool-water masses (W. H. Abbott, South Carolina Geological Survey, written commun., 1978). Abbott suggests that water depths within the photic zone of about 300 ft (100 m) or less were necessary to allow the benthic diatoms to photosynthesize. The few calcareous benthic foraminifers within these siliceous assemblages are mainly Bulimina elongata, Florilus mediocostatus, F. pizzarensis, and Epistominella sp., forms whose modern counterparts are characteristic of shallow waters having a high nutrient content (Seiglie, 1968). A similar assemblage has also been reported beneath the delta-front water mass of the Mississippi River (Lankford, 1959).

Lower Miocene sediments are missing or are very thin in the GE-1 well, but are present in J-2 and AMCOR 6002 and perhaps at J-1 (fig. 27). The Bulimina/Florilus/Epistominella assemblage is present in the lower Miocene section at AMCOR 6002, indicating middle-shelf deposition. At J-2 the lower half of the lower Miocene section also contains this high-nutrient, middle-shelf assemblage, but the upper half of this unit is characterized by abundant planktic species and predominantly Brizalina among the benthic assemblage. This is an outer-shelf assemblage.

The only upper Miocene strata recognized in the area were penetrated in the AMCOR 6002 core hole (fig. 27). Diatomaceous strata are still common there; but, in addition, the strata contain a foraminiferal fauna of low diversity including primarily Bulimina elongata, Florilus grateloupi, and Lenticulina spinosa, a middle-shelf assemblage.

Pliocene Rocks.--Upper Pliocene sediments of outer-shelf origin lie above the early

Pliocene-late Miocene hiatus in the GE-1 well (fig. 27). Characteristic benthic species include Lenticulina americana, L. spinosa, Bulimina marginata, B. elongata, Uvigerina sp., Fursenkoina sp., Plectofrondicularia sp., Brizalina spp., Nodosaria sp., and Siphogenerina lamellata. Planktic species are also abundant and diverse. Slightly deeper water (upper-continental-slope depths) prevailed during the late Pliocene at J-2 (fig. 27), where a rich planktic assemblage is accompanied by a diverse benthic assemblage of predominantly Uvigerina spp., Bulimina sp., and Cassidulina spp. At J-1, the lower part of the upper Pliocene beds contains abundant specimens of Florilus grateloupi, small Uvigerina sp., and Cassidulina carinata, accompanied by a lesser number of Lenticulina spinosa, Bulimina elongata, and Brizalina spp. These indicate outer-shelf deposition. The upper part of the upper Pliocene at J-1 was deposited in middle-shelf environments, as indicated by the predominance among the benthic foraminifers of Trifarina sp., Cibicidoides sp., and Hanzawaia sp. The Pliocene is missing at AMCOR 6002 (fig. 27).

Pleistocene Rocks.--Pleistocene paleoenvironments are estimated to have ranged from inner- to middle-shelf depths based on the sandy nature of the sediments and a general knowledge of Pleistocene glacioeustatic events. We have no good sample evidence from the boreholes, however (fig. 27).

PALEOECOLOGIC DISCUSSION

The sequence of paleoenvironments represented in the GE-1 well and surrounding core holes can be correlated with the second-order cycles (supercycles) of global sea level change outlined by Vail and others (1977a, b; figs. 28A, B). In the GE-1 well, supercycle Ka of Vail and others, began with nonmarine and marginal-marine deposition in the Early Cretaceous (Valanginian? to Aptian) and culminated with middle-continental-shelf conditions in the late Albian. Supercycle Kb began with erosion and nondeposition during the Cenomanian and early Turonian and culminated with upper-continental-slope conditions during the Campanian and early Maestrichtian.

In the Tertiary, supercycle Ta began with erosion and nondeposition during the early Paleocene (and latest Maestrichtian) and culminated with perhaps middle-continental-slope deposition in the early Eocene. Supercycle Tb began with erosion and nondeposition during the early Eocene and culminated with upper-continental-slope conditions in the middle Oligocene. Supercycle Tc began with erosion and nondeposition in the late Oligocene and early Miocene and culminated with upper-continental-slope conditions in the middle Miocene. Supercycle Td began with erosion and nondeposition in the late Miocene and early Pliocene and culminated in outer-shelf conditions in the late Pliocene.

The Quaternary supercycle Q began with erosion and nondeposition during the early Pleistocene and culminated with middle-shelf conditions that currently prevail at the GE-1 and J-2 sites.

Corroboration of the third-order sea level cycles of Vail and others (1977a, b) requires further analysis; but evidence for some of them, such as TO1 (early to middle Oligocene) and TM2.2 (middle Miocene), is readily apparent (figs. 28A, B).

SEDIMENT ACCUMULATION RATES

By plotting the thickness of sedimentary units against a geochronologic time scale for the Cretaceous (van Hinte, 1976) and the Cenozoic (Berggren and van Couvering, 1974), we have estimated the rate of sediment accumulation at the site of the GE-1 well (fig. 29). Using van Hinte's (1978) notation, the formula for this calculation is $uR = \frac{T_p}{10A}$, where uR = uncorrected accumulation rate in cm/1,000 years (not corrected for compaction and thus a minimum rate; see van Hinte, 1978), Tp = present thickness of a given unit in meters, and A = duration of deposition in millions of years. These rates must be taken only as estimates, especially for the Cretaceous, when absolute dates are less reliable and less abundant, and for which two different time scales have recently been published (Obradovich and Cobban, 1975; van Hinte, 1976). In spite of the generalized nature of the results, the relative changes are useful in interpreting the geologic history of the region, and the rate curves can be used for extrapolating the age of unfossiliferous sections, detecting hiatuses, and estimating the age, thickness, or stratigraphic depth of units lying below the bottom of a given core hole.

The accumulation-rate curves for the GE-1 well (fig. 29) show that the highest rates of accumulation (2.0-2.5 in./1,000 yrs (5.0-6.4 cm/1,000 yrs)) took place during the Albian through Santonian interval ("middle Cretaceous"), middle and late Eocene, and middle Miocene. Lowest rates (0.51-0.71 in./1,000 yrs (1.3-1.8 cm/1,000 yrs)) prevailed during the Late Cretaceous (Campanian and Maestrichtian), in early through middle Oligocene time (1.0 in./1,000 yrs (2.5 cm/1,000 yrs)), and during the Pleistocene (1.0 in./1,000 yrs 2.5 cm/1,000 yrs)).

Comparison of the Cenozoic rates at GE-1 with those at nearby core holes (fig. 30) reveals that accumulation at GE-1 was generally more rapid than at the other sites. The central part of the embayment appears to have remained low and thus to have accumulated a thicker section of sediments throughout each Cenozoic epoch, except during part of the middle Eocene when the rate at J-1 was similar to that at GE-1, and during the Pleistocene when the rates at J-2 and GE-1 were equivalent. The stratigraphic

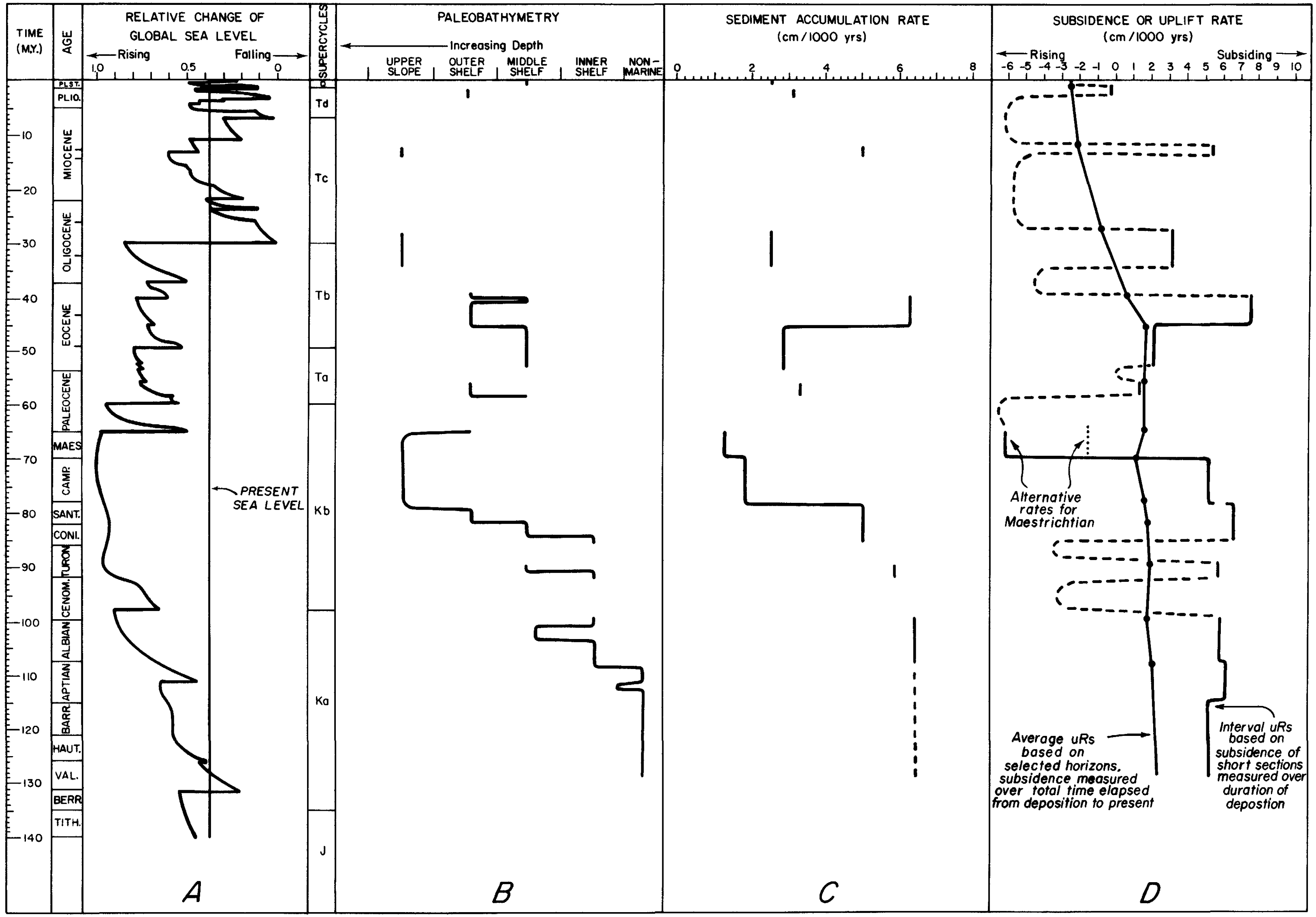


Figure 28.--Comparison of paleobathymetry, sediment-accumulation rate, and subsidence rate of rocks penetrated in the COST No. GE-1 well with relative changes in global sea level postulated by Vail, Mitchum, and Thompson (1977a, b). uRs is the subsidence rate (uncorrected for compaction). Dashed lines in interval uRs curves represent inferred rates during hiatal gaps.

changes in accumulation rate at these nearby boreholes also generally coincide with the changes at GE-1. The early and middle Oligocene rates were lowest (0.08–0.35 in./1,000 yrs (0.2–0.9 cm/1,000 yrs)) at J-1 and J-2, but on the northern margin of the embayment (AMCOR 6002), the lowest rates occurred during the early Miocene. Highest rates were obtained during the

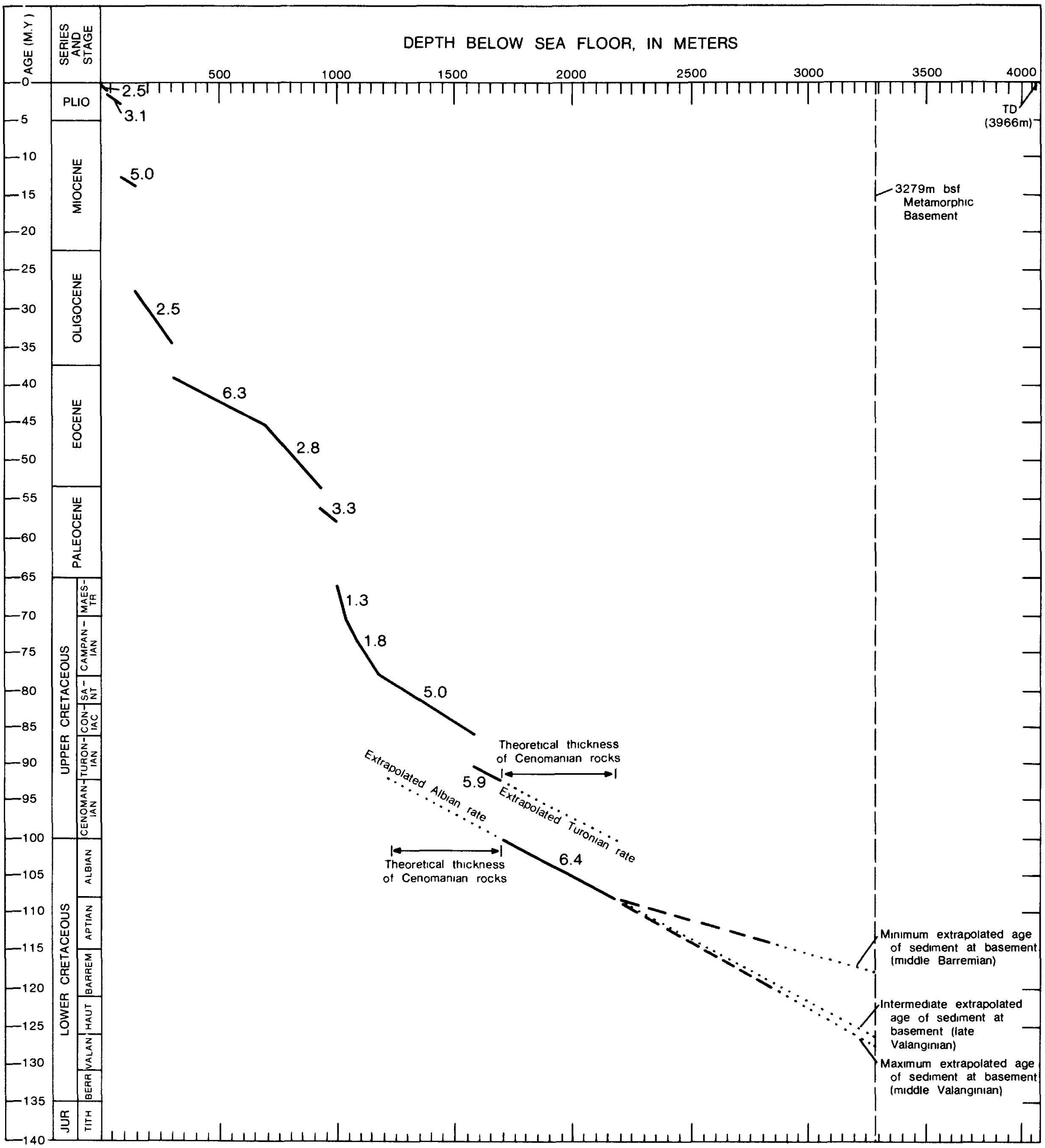


Figure 29.--Curve of sediment-accumulation rate for the COST No. GE-1 well. Gaps in the curve are hiatuses, whose time span can be measured on the time scale at the left. Number above segments of curve are sediment-accumulation rates measured in cm/1,000 yrs.

middle and late Eocene and Pleistocene (0.59-0.67 in./1,000 yrs (1.5-1.7 cm/1,000 yrs)) at J-2, and during the middle Eocene and early and middle Miocene at J-1 and AMCOR 6002.

Whitten (1976a, b; 1977) calculated sediment-accumulation rates in a similar manner (based on present thickness of units) for selected coastal wells located between Long Island and Florida. He found that when using either the time scale of Obradovich and Cobban (1975) or of van Hinte (1976), the most rapid rates (>2.0 to >6.0 in./1,000 yrs (>5 to >15 cm/1,000 yrs)) were established in the Aptian-Albian interval and in the Campanian. He speculated that the high Campanian rates might have extended through Florida, but he had no data for that region. Our calculations for the GE-1 well show that here, too, Aptian and Albian rates were higher than those of later Cretaceous time (3.0 in./1000 yrs (6.4 cm/1000 yrs), comparable to Whitten's data), although apparently they were not significantly greater than those of earlier Cretaceous time (fig. 29). In contrast to Whitten's findings, however, the rates for the Campanian are next to lowest in the entire drilled section in GE-1 (0.71 in./1000 yrs (1.8 cm/1000 yrs)). Thus, the rapid Campanian rates noted by Whitten (1977) seem to have been the result of localized phenomena.

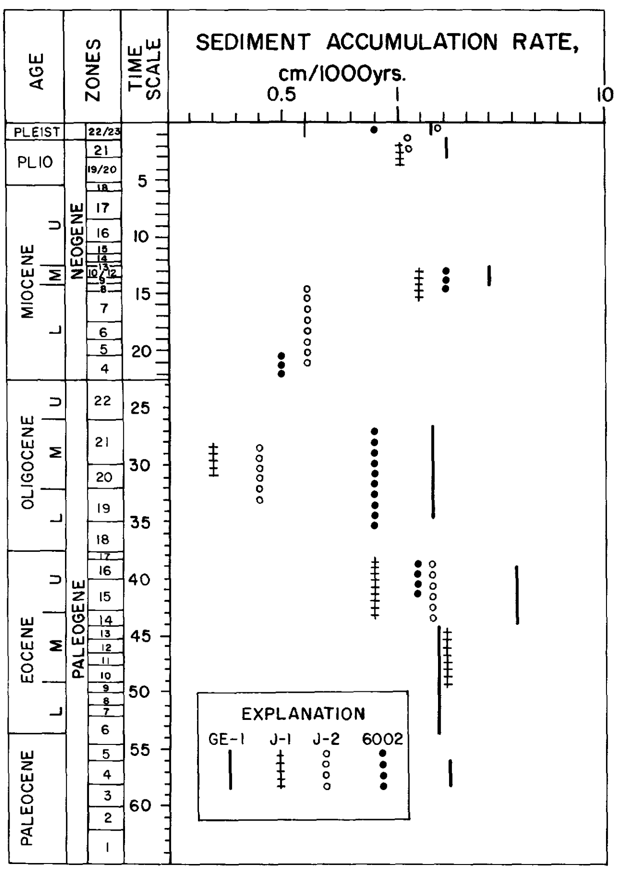


Figure 30.--Comparison of sediment accumulation rates for Cenozoic rocks at the COST No. GE-1 well and nearby core holes J-1, J-2, and AMCOR 6002.

As noted above, the sediment-accumulation rates can be extrapolated in order to detect the presence of hiatuses and to estimate the age of unfossiliferous strata. We have used it, for example (fig. 29), to support the paleontologic and paleoenvironmental evidence that Cenomanian rocks are missing in the GE-1 well. By extrapolating the Turonian rate downward to the top of the Albian (fig. 29), we can determine that Cenomanian rocks should theoretically be 1,541 ft (470 m) thick. Extrapolation of Albian rates upward to the Turonian would yield a slightly thicker theoretical Cenomanian unit--1,679 ft (512 m). On the other hand, if we assume that the entire Cenomanian is represented by the 82-ft (25-m) interval between the lowest observed Turonian and highest Albian samples, the calculated rate of deposition would be 0.12 in./1,000 yrs (0.3 cm/1,000 yrs). This is 4 times lower than the lowest rate calculated for rocks actually penetrated at GE-1 (0.51 in./1,000 yrs (1.3 cm/1,000 yrs) in the Maestrichtian) and nearly 20 times lower than the Turonian rate. In view of these results, it seems reasonable to postulate that Cenomanian rocks were eroded from, or not deposited at, the GE-1 well during the long (4 to 6 m.y.) Cenomanian low sea level stand described by Vail and others (1977b).

We have also extrapolated the Albian accumulation rate downward in order to estimate the age of the unfossiliferous sedimentary rocks resting on Devonian metamorphic basement (fig. 29). A straight-line extrapolation dates the oldest post-Devonian rocks as approximately late Valanginian. Two alternative estimates can be made by using the maximum (Barremian) and minimum (Aptian) possible ages of the deepest fossiliferous sample in the GE-1 well, at 9,524 ft (2,903 m). If this sample is assumed to be of early Aptian age, the downwardly extrapolated rate would yield an age of middle Barremian at basement. If the sample at 9,524 ft (2,903 m) is assumed to be of early Barremian age (which is also suggested by extrapolating the Albian rate downward), then the extrapolated rate yields a middle Valanginian age at basement. Thus we have estimated the age of the sediments at basement to be Valanginian(?).

SUBSIDENCE AND UPLIFT OF THE EMBAYMENT

Approximate subsidence and uplift rates for given horizons in the GE-1 well have been calculated and plotted against a time scale to yield a subsidence curve (fig. 28D). We have used two different approaches to calculate subsidence rates. The first method determines the subsidence of a given horizon as an average rate measured over the total time elapsed since deposition. The basis for the calculation is illustrated in the following example, using a modified version of van Hinte's (1978) notation. Let us calculate the uncorrected rate of subsidence, uRs, for the top of the Maestrichtian section in the GE-1 well (rate uncorrected for compaction). The present depth (D_p) of this horizon is 1,000 m below the present sea floor (SF_p, fig. 31A) and 1,040 m below present sea level (SL_p). (Present water depth (W_p) is 40 m.) But Vail and others (1977b, fig. 6) estimated that sea level was about 325 m higher than at present during the late Maestrichtian (SL_m). We have estimated that the late Maestrichtian sea floor (SF_m) was 200 m below the late Maestrichtian sea level (Maestrichtian water depth W_m = 200 m), or 125 m above the present sea level. Thus, the Maestrichtian sea floor (SF_m) was 165 m higher than the present sea floor, and the uncorrected subsidence for the Maestrichtian top is 1,000 + 165 or 1,165 m. This is divided by the time elapsed for this subsidence (66 m.y.) yielding an uncorrected subsidence rate of 1.8 cm/1,000 yrs. Thus, the equation for the calculation may be expressed as:

$$uRs = \frac{Dp + (SLm - Wm) + Wp}{10A} \quad \text{or}$$

$$uRs = \frac{1{,}000 + (325 - 200) + 40}{660} =$$

1.8 cm/1,000 yrs (0.71 in./1,000 yrs). Negative answers indicate uplift rather than subsidence.

The averaged subsidence rates in figure 28D show that Lower Cretaceous rocks (Valanginian? to Albian) have subsided at an average rate of 0.79-1.0 in./1,000 yrs (2-2.6 cm/1,000 yrs) since their deposition. Because the well reached basement just below Valaginian(?) rocks, the average subsidence rate of the oldest Valanginian(?) rocks (1.0 in./1,000 yrs (2.6 cm/1,000 yrs)) is also the average subsidence of the basement during the past 128 m.y. Similar subsidence rates continued into the early Eocene, although significant changes occurred in paleobathymetry and sediment-accumulation rates. Thus, according to this curve, the significant deepening of the embayment during the Campanian seems to have been largely a result of rising global sea level and reduction of accumulation rate to 0.51 in./1,000 yrs (1.3 cm/1,000 yrs), perhaps due to increased distance to clastic sources on a uniformly subsiding shelf.

Rocks deposited during the middle and late Eocene have subsided more slowly. This was a period of thick carbonate buildup when accumulation rates rose to more than 2.36 in./1,000 yrs (6 cm/1,000 yrs), the highest rate of the Cenozoic. Subsidence stopped during the middle Oligocene, but a major global rise in sea level increased the water depths and the accumulation rates were lowered.

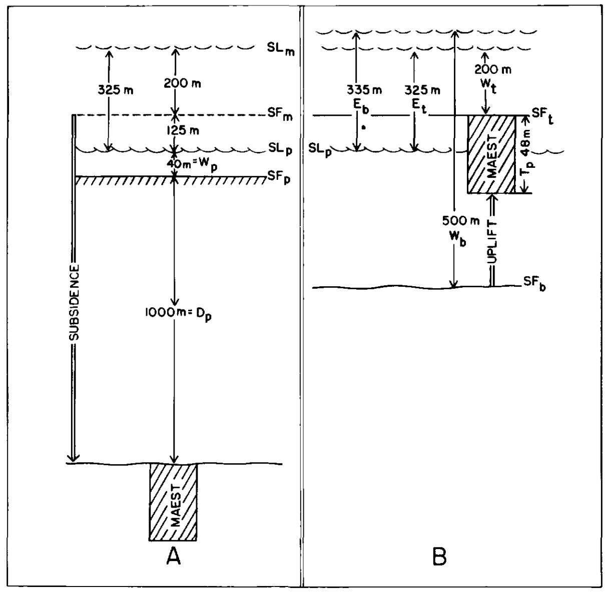


Figure 31.--A, Diagrammatic examples (not to scale) of calculations used to derive averaged and interval subsidence rates. Averaged subsidence rate.

$$\text{Formula:} \quad uRs = \frac{D_p + (SL_m - W_m) + W_p}{10A},$$

where uRs = uncorrected subsidence rate (uncorrected for compaction), D_p = present depth to Maestrichtian top, SL_m = sea level at end of Maestrichtian relative to today, W_m = water depth at end of Maestrichtian (note this refers to the top of Maestrichtian deposits as seen in this well, not the true end of Maestrichtian time), W_p = water depth at present over COST No. GE-1 well site, SF_p = sea floor at present at COST No. GE-1 well site, and SL = sea level at present at GE-1 well site. B, Interval subsidence rate.

$$\text{Formula:} \quad uRs = \frac{T_p - (W + E)}{10A}; \quad W = W_b - W_t; \quad E = E_b - E_t:$$

where uRs = uncorrected subsidence rate (uncorrected for compaction), T_p = present thickness of unit (for example Maestrichtian beds), W = change in water depth during deposition of unit, W_b = water depth during deposition of base of unit, W_t = water depth during deposition of top of unit, E = change in eustatic sea level during deposition of unit, E_b = eustatic sea level (relative to present) during deposition of base of unit, E_t = eustatic sea level (relative to present) during deposition of top of unit, SF_b = sea floor during deposition of base of unit, SF_t = sea floor during deposition of top of unit, and SL_p = present sea level.

Middle Miocene and upper Pliocene rocks have been uplifted at a rate of 0.79-1.2 in./1,000 yrs (2-3 cm/1,000 yrs), although high sea level stands maintained outer-shelf and upper-slope environments during their deposition.

The second method of calculating the uncorrected subsidence rate is taken directly from van Hinte (1978). The equation is

$$uRs = \frac{T_p - (W + E)}{10A}$$

(fig. 31B), where T_p is present thickness of a given unit (for example, the Maestrichtian interval), W is the change in water depth during deposition of the unit (taken from our paleobathymetric interpretation), and E is the eustatic sea level change during deposition of the unit (taken from Vail and others, 1977b, fig. 6). Deepening from 0 to 164 ft (0-50 m) would yield W = 50; a eustatic rise of 164 ft (50 m) would yield E = +50. A is the duration of deposition in millions of years. This method yields a short-term or "interval" rate of subsidence by measuring average subsidence of the base of a given unit only during the time of deposition of the unit.

Figure 28D shows that the curve constructed by this method produces significant departures from the averaged curve at several points. The Lower Cretaceous rates are rather uniform (2.2-2.6 in./1,000 yrs (5.5-6.5 cm/1,000 yrs)), but higher than those shown by averaging, and are approximately equivalent to the Lower Cretaceous accumulation rates. The interval curve corroborates the previous interpretation from the averaged curve that the Campanian deepening was due mainly to rising global sea level. A major discrepancy is present in the Maestrichtian, where the slight decrease shown on the averaged curve is a pronounced uplift on the interval curve. The interval method produces this departure through the necessity to account for the 1,000-ft (300-m) shoaling of waters that occurred near the end of the Maestrichtian. The 33-ft (10-m) sea-level drop proposed for this time interval by Vail and others (1977b, fig. 6) would account for only an insignificant amount of the shoaling. However, if we assume that the 660-ft (200-m) drop in sea level, estimated by Vail and others (1977b) to have occurred at the end of the Maestrichtian, actually occurred somewhat earlier in the late Maestrichtian, the required uplift would be reduced to 0.5 in./1,000 yrs (1.2 cm/1,000 yrs). Furthermore, if the estimated paleo-bathymetric change were 660 ft rather than 1,000 ft (200 m rather than 300 m), and it could well have been, then the calculation would yield a uRs of 0 (equilibrium). This demonstrates the dependence of the interval method on the accuracy of the estimated parameters, which unfortunately are only gross estimates.

The next major departure of the interval curve is an acceleration of subsidence in the middle and late Eocene that is necessary to account for the significant thickness of shallow-water carbonates; it probably was triggered by accelerated sediment accumulation. The interval subsidence rates for the Oligocene and Pliocene slowly decreased, converging toward the averaged curve, and the Pleistocene rates became nearly identical with the long-term average. During the Miocene, however, subsidence increased substantially, in unison with rising global sea level, probably because sediment accumulation accelerated significantly. Following this, near equilibrium was reached in the late Pliocene, and the embayment was uplifted during the Pleistocene. This resulted in the filling of the embayment to its present topographic level, even though sediment accumulation decreased. The paleoecologic analysis supports this interpretation of Pliocene-Pleistocene uplift and filling by showing a significant change in the late Pliocene paleobathymetry. During most of the earlier Cenozoic, water depths were deeper at GE-1 than at the other borehole sites (implying that GE-1 occupied a topographic depression). However, during the late Pliocene, site GE-1 became shallower than site J-2; the two sites occupied similar depths during the Pleistocene.

It is clear that the averaged subsidence curve yields only generalized results that illustrate long-term relative changes. The calculations that produce the averaged curve encompass the time span (A) represented by several major hiatuses, whereas the interval-curve calculations deal only with time spans (A) during which the existing rocks were deposited. Therefore, the averaged curve displays rates that are generally lower than those of the interval curve. As a result, the interval subsidence curve allows more detailed comparisons with the sediment-accumulation curve, because they are calculated over identical time spans. The interval curve is more accurate in relative terms than the averaged curve, but its accuracy in absolute terms has a wide margin of error, because calculations are made from parameters that are gross estimates.

Because of the smoothing effect inherent in the averaged curve, it yields information concerning subsidence during the hiatal gaps in the interval curve. For example, from the averaged curve (fig. 28D), we see that the top of the middle Oligocene section has been uplifted at the rate of 0.16 in./1,000 yrs (0.4 cm/1,000 yrs) over the past 30 m.y. But the interval curve shows that the embayment actually subsided during deposition of the Miocene and Pliocene rocks penetrated in the well. Therefore, we conclude that during the hiatuses, significant uplift must have occurred. Accordingly, we have schematically inserted dashed lines in the hiatal parts of the interval curve to show uplift during the hiatuses. This hiatal uplift apparently was a response to sediment unloading (erosion) or the cessation of loading (nondeposition). It seems sufficient to conclude from these curves that (1) Cretaceous subsidence was more rapid than that of most of the Cenozoic in the Southeast Georgia Embayment; (2) Cenozoic rates have steadily decreased since the middle or late Eocene, and uplift has been dominant since the middle Oligocene; (3) most of the major paleobathymetric changes were caused by eustatic sea level fluctuations; and (4) isostatic balance of the embayment was sensitive to sediment loading; subsidence correspondingly increased during periods of rapid sediment accumulation and decreased or reversed during periods of prolonged erosion or nondeposition.

CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY AND PALEOENVIRONMENTAL INTERPRETATION

Page C. Valentine

INTRODUCTION

The COST No. GE-1 well, located on the outer part of the Continental Shelf off Georgia, was drilled into a deep part of the Southeast Georgia Embayment. The well penetrated sedimentary strata of Early Cretaceous through Quaternary age that overlie metamorphic rocks believed to be of Devonian age. Paleoenvironments include both nonmarine and marine in the Lower Cretaceous, whereas the Upper Cretaceous and Cenozoic are marine throughout. Calcareous nannofossils are rare in the Lower Cretaceous but are common and usually well preserved in younger strata.

NANNOFOSSIL BIOSTRATIGRAPHY

Calcareous nannofossil biostratigraphy of the COST No. GE-1 well is based on the study of samples of rotary drill cuttings collected over 10- to 30-ft (3- to 9-m) intervals (table 6). With few exceptions, cutting samples were analyzed at intervals of 90 ft (27 m) or less from 390 to 8,860 ft (119-2,702 m) in the well. A complete sequence of samples was studied from 570 to 780 ft (174-238 m) and from 3,360 to 4,020 ft (1,025-1,226 m). Discrete rock fragments representing each of the major lithologic units present in a single cuttings sample were processed for calcareous nannofossils. The oldest nannofossil assemblage identified in a sample was considered to indicate the age of the strata of that level. Species listed as representative of a stratigraphic interval do not necessarily occur in every sample studied from that interval. In all, 260 subsamples from 110 levels in the well were studied. Sample depths are relative to the KB. The stratigraphic ranges for the Mesozoic calcareous nannofossils treated here are based, for the most part, on determinations made by Thierstein (1971, 1973, 1976) and Smith (in press). The reports on COST No. GE-1 well biostratigraphy and paleoenvironments by International Biostratigraphers, Inc. (1977) and Amato and Bebout (1978) were consulted; and selected information, as cited, has been incorporated from these reports into the present study.

NEOGENE (390-720 ft (119-220 m))

The first sample was collected from the COST No. GE-1 well at 390 ft (119 m). The highly calcareous strata from this level down to the top of the Oligocene at 720 ft (220 m) are almost barren of nannofossils, no doubt a result of postdepositional dissolution. Although other groups of calcareous marine fossils are present in this interval, nannofossils were found in only one sample (600-630 ft (183-192 m)), a moderately well preserved assemblage indicative of a late early to early middle Miocene age. The following species are present: Coccolithus eopelagicus, C. pelagicus, Cyclicargolithus abisectus, C. floridanus, Discoaster deflandrei, D. exilis, Discolithina sp., Helicosphaera carteri, H. recta?, Reticulofenestra sp., and Sphenolithus heteromorphus. The presence of Sphenolithus heteromorphus places this flora in the Helicosphaera ampliaperta and Sphenolithus heteromorphus Zones of Bukry (1973, 1975).

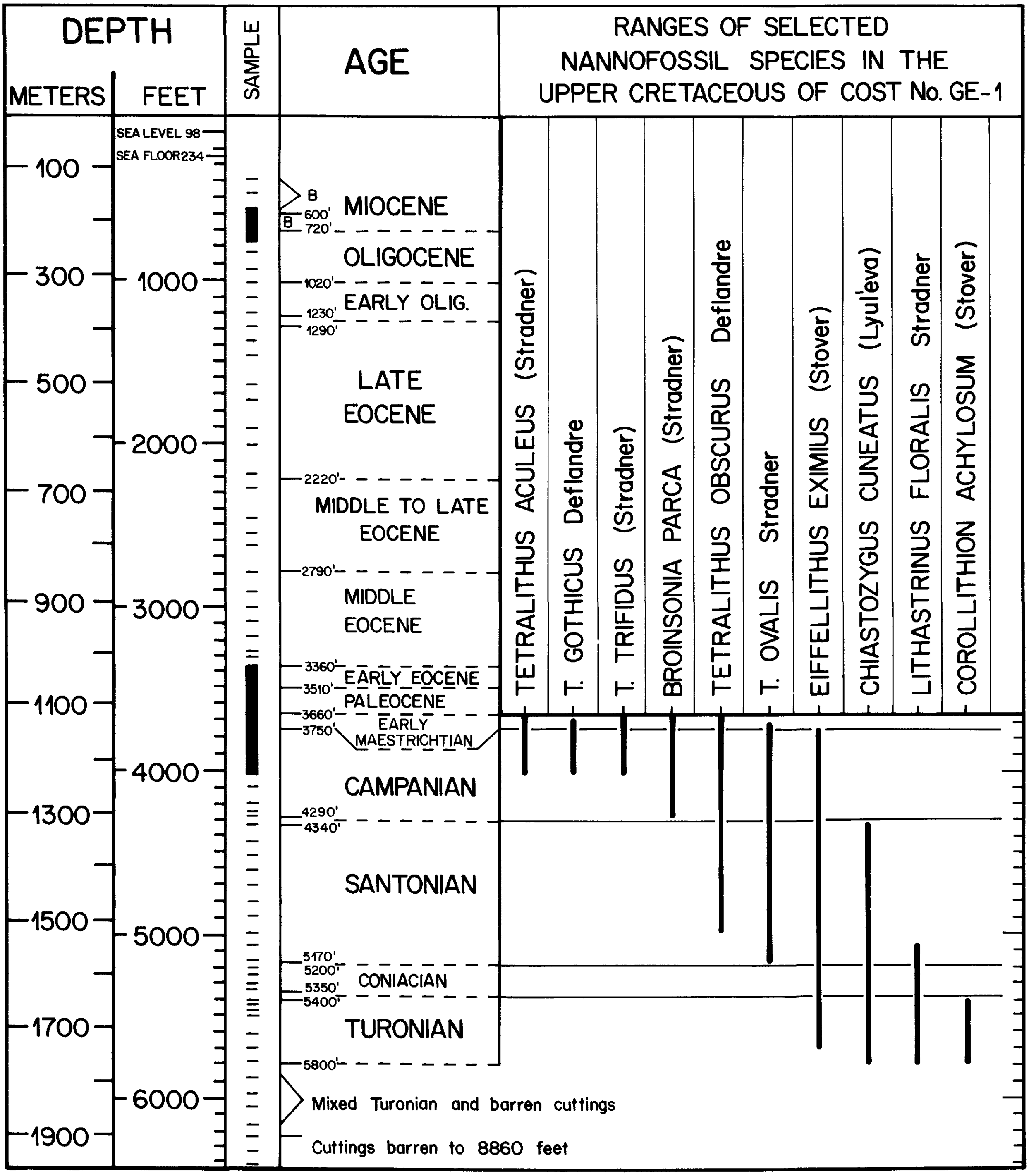
OLIGOCENE (722-1,230 ft (220-375 m))

Oligocene calcareous sedimentary beds are present in a 510-ft (155-m) interval from 720 to 1,230 ft (220-375 m). The occurrence of calcareous nannofossil species varies from rare to abundant, and preservation is poor to moderate. On the basis of assemblages of rather low diversity, the sequence down to 1,020 ft (311 m) represents undifferentiated Oligocene strata, and characteristic species include Coccolithus pelagicus, Cyclicargolithus abisectus, C. floridanus, Dictyococcites bisectus, D. scrippsae, Discolithina spp., Helicosphaera bramlettei, H. compacta, H. euphratis, Reticulofenestra hillae, Reticulofenestra cf. scissurus of Bramlette and Wilcoxon, R. sp., and Transversopontis sp.

Nannofossil assemblages are more diverse from 1,020 to 1,230 ft (311-375 m). The highest (youngest) occurrence of Cyclococcolithina formosa and Reticulofenestra umbilica is at the top of this interval, which is dated as early Oligocene and contains the following assemblage: Blackites sp., Braarudosphaera bigelowii, B. discula, Chiasmolithus sp.,

Table 6.--Calcareous nannofossil biostratigraphy of the COST No. GE-1 well

[Depths are relative to the KB, 98 ft (30 m) above sea level. In sample column, blacked-in areas indicate a complete sequence of samples studied; B indicates cuttings barren of nannofossils. Ages are based on findings of this study but incorporate some biostratigraphic information from International Biostratigraphers, Inc. (1977). Ranges of selected Late Cretaceous calcareous nannofossil species are based on cuttings samples of this study]



Coccolithus eopelagicus, C. pelagicus, C. sarsiae of Bybell, Cyclicargolithus floridanus, Cyclococcolithina formosa, C. kingii, Dictyococcites bisectus, D. scrippsae, Discolithina spp., Helicosphaera compacta, H. intermedia, H. wilcoxonii, Lanternithus minutus, Reticulofenestra hillae, R. cf. scissurus of Bramlette and Wilcoxon, R. umbilica, Transversopontis duocavus?, T. obliquipons, T. zigzag, and Zygrhablithus bijugatus.

EOCENE (1,290-3,510 ft (393-1,071 m))

Below the Oligocene lies a sequence of Eocene limestones that is 2,220 ft (678 m) thick. Nannofossils vary in occurrence from rare to abundant, and preservation is poor to moderate, reflecting differential solution within the beds of this interval. The top of the Eocene is correlated with the highest occurrence of Reticulofenestra reticulata at 1,290 ft (393 m). Upper Eocene beds are believed to be about 930 ft (284 m) thick based on the occurrence of the following species: Braarudosphaera bigelowii, B. discula, Chiasmolithus titus, Coccolithus eopelagicus, C. sarsiae of Bybell, Cyclicargolithus floridanus, Cyclococcolithina formosa, C. kingii, Dictyococcites bisectus, D. scrippsae, Discoaster saipanensis, Discolithina spp., Helicosphaera compacta, H. euphratis, H. intermedia, Lanternithus minutus, Reticulofenestra reticulata, R. umbilica, Sphenolithus predistentus, Transversopontis obliquipons, T. zigzag, and Zygrhablithus bijugatus.

Between 2,220 and 2,790 ft (677-851 m) the cuttings are characterized by rare, poorly preserved nannofossil species constituting assemblages of low diversity. Reticulofenestra reticulata occurs in several samples, whereas R. umbilica is absent. This interval is tentatively dated as late middle Eocene to early late Eocene based on the occurrence of Braarudosphaera bigelowii, B. discula, Coccolithus eopelagicus, C. sarsiae of Bybell, Cyclicargolithus floridanus, Cyclococcolithina formosa, C. kingii, Dictyococcites scrippsae, Discoaster saipanesis, Reticulofenestra reticulata, and Sphenolithus predistentus.

Middle Eocene strata that are 570 ft (174 m) thick occur from 2,790 ft to 3,360 ft (851-1,025 m). The samples from this interval contain common, moderately well preserved nannofossils in diverse assemblages. The highest occurrences of Cyclococcolithina gammation and Sphenolithus radians are at 2,790 ft (851 m); and Campylosphaera dela, Helicosphaera lophota, H. seminulum, and Neococcolithes dubius are not found higher than 3,000 ft (915 m). Chiasmolithus gigas occurs at 3,000 ft (915 m) and 3,090 ft (942 m); and Discoaster lodoensis, at 3,270 ft (997 m). The nannofossil assemblage from this interval includes Blackites creber, B. sp., Braarudosphaera bigelowii, B. discula, Campylosphaera dela, Cepekiella lumina, Chiasmolithus bidens/solitus, C. gigas, C. eopelagicus, C. jugatus, C. pelagicus, C. sarsiae of Bybell, Cyclicargolithus floridanus, Cyclococcolithina formosa, C. gammation, Daktylethra punctulata, Dictyococcites scrippsae, Discoaster barbadiensis, D. deflandrei, D. delicatus, D. lodoensis, D. nodifer?, D. spp., Discolithina bicaveata, D. spp., Helicosphaera compacta, H. lophota, H. seminulum, Lophodolithus nascens, Neococcolithes dubius, Reticulofenestra coenura, R. sp., Sphenolithus radians, S. spiniger, Transversopontis obliquipons, T. pulcher, and Zygrhablithus bijugatus.

The early Eocene is represented by a relatively thin limestone interval, 150 ft (46 m) thick, from 3,360 to 3,510 ft (1,025-1,071 m). These strata are darker gray than the overlying units. Nannofossil occurrences are rare to common, and preservation is poor to moderate. Several samples at the top of this interval contain diverse assemblages. The highest occurrences of typical early Eocene species, such as Discoaster binodosus, D. diastypus, Discoasteroides kuepperi, and Tribrachiatus orthostylus, were observed at 3,360 ft (1,025 m). The following were identified: Braarudosphaera bigelowii, Campylosphaera dela, Chiasmolithus californicus, C. consuetus, Coccolithus eopelagicus, C. pelagicus, Cyclicargolithus floridanus, Cyclococcolithina formosa, C. gammation, Dictyococcites scrippsae, Discoaster barbadiensis, D. binodosus, D. diastypus, D. lodoensis, D. salisburgensis, Discoasteroides kuepperi, Ellipsolithus distichus, E. macellus, Helicosphaera lophota, H. seminulum, Lophodolithus nascens, Micrantholithus flos, Neochiastozygus distentus, Neococcolithes dubius, Prinsius bisulcus, Sphenolithus anarrhopus, S. radians, S. spiniger, Transversopontis duocavus, T. obliquipons, T. pulcher, Tribrachiatus orthostylus, and Zygrhablithus bijugatus.

PALEOCENE (3,510-3,660 ft (1,071-1,116 m))

The Paleocene, like the early Eocene, is represented by a thin interval of dark-gray limestones not more than 150 ft (45 m) thick. Although, in this study, Maestrichtian nannofossil assemblages first occur at 3,660 ft (1,116 m), the Cretaceous-Tertiary boundary is placed somewhat higher by International Biostratigraphers, Inc. (1977). The uppermost sample believed to be in the Paleocene interval, at 3,510-3,540 ft (1,071-1080 m), contains a small assemblage of poorly preserved nannofossil species of Paleocene-Eocene aspect and includes Discoaster multiradiatus, Fasciculithus involutus, Prinsius bisulcus, and Toweius eminens. The other samples studied exhibit richer, more diverse, and better preserved assemblages. The following species indicative of the middle and late Paleocene were identified in this interval: Braarudosphaera bigelowii, B. discula, Chiasmolithus bidens, C. californicus, C. consuetus, Coccolithus eopelagicus, C. pelagicus, Cyclococcolithina robusta, Discoaster multiradiatus, Discolithina sp., Fasciculithus involutus, F. tympaniformis, Micrantholithus crenulatus, M. flos, M. sp, Neochiastozygus distentus, Neococcolithes concinnus, N. protenus, Prinsius bisulcus, Toweius eminens, Zygolithus aff. plectopons, and Z. sigmoides.

MAESTRICHTIAN (3,660-3,750 ft (1,116-1,144 m))

The top of the Maestrichtian is placed at 3,570 ft (1,078 m) in the COST No. GE-1 well by International Biostratigraphers, Inc. (1977) based on foraminifers in cuttings samples; and a study of calcareous nannofossils in the same report indicates the presence of the late Maestrichtian Micula mura Zone in a sidewall core from 3,604 ft (1,099 m).

In the present study, the top of the Maestrichtian, based on observed nannofossil occurrences, is placed at 3,660 ft (1,116 m) (table 6). This depth coincides with a color change apparent in the cuttings samples. The highest occurrence of Cretaceous ostracodes in cuttings is at 3,630 ft (1,107 m). Late Cretaceous (Maestrichtian and older) beds in this well are chiefly fine-grained, dark-gray calcilutites that contain terrigenous components such as quartz and organic matter in somewhat greater amounts than are found in the overlying Tertiary limestones. In contrast to the Tertiary, the nannofossil assemblages of the Upper Cretaceous are more consistently diverse, contain species that are common to abundant, and exhibit moderate to good preservation. The Upper Cretaceous nannoflora is characterized by many species that range throughout most of the interval: Ahmuellerella octoradiata, Arkhangelskiella cymbiformis, Biscutum blackii, Braarudosphaera bigelowii, Chiastozygus amphipons, C. plicatus, Corollithion signum, Cretarhabdus conicus, C. coronadventis, C. crenulatus, Cribrosphaera ehrenbergii, Cylindralithus coronatus, Eiffellithus turriseiffeli, Gartnerago costatum, G. segmentatum, Kamptnerius magnificus, K. punctatus, Lithraphidites carniolensis, Lucianorhabdus cayeuxii, Manivitella pemmatoidea, Microrhabdulus belgicus, M. decoratus, M. stradneri, Micula staurophora, Parhabdolithus angustus, P. embergeri, P. regularis, P. splendens, Prediscosphaera cretacea, Tranolithus orionatus, Vagalapilla elliptica, V. matalosa, Watznaueria barnesae, W. biporta, Zygodiscus acanthus, Z. diplogrammus, and Z. fibuliformis. The ranges of stratigraphic marker species are discussed below and are illustrated in table 6.

While no nannofossils of late Maestrichtian age occur in the cuttings, early Maestrichtian assemblages are found in a 90-ft (28-m) interval from 3,660 to 3,750 ft (1,116-1,144 m). Broinsonia parca, Tetralithus aculeus, T. gothicus, and T. trifidus are present here; but Eiffellithus eximius, a species observed in the next lower sample whose extinction marks the top of the Campanian (table 6), is not.

CAMPANIAN (3,750-4,290 ft (1,144-1,308 m))

Based on the highest occurrence of Eiffellithus eximius at 3,750 ft (1,144 m) and the lowest occurrence of Broinsonia parca at 4,290 ft (1,308 m), the Campanian sequence is about 540 ft (164 m) thick.

SANTONIAN (4,340-5,170 ft (1,324-1,577 m))

Santonian strata occur in an 830-ft (253-m)-thick interval from 4,340 to 5,170 ft (1,324-1,577 m). The Santonian extends from just below the lowest occurrence of Broinsonia parca down to the lowest occurrence of Tetralithus obscurus/ovalis (table 6). These beds also exhibit the highest occurrences of Chiastozygus cuneatus at 4,340 ft (1,324 m) and of Lithastrinus floralis at 5,070 ft (1,546 m).

CONIACIAN (5,200-5,350 ft (1,586-1,632 m))

The Coniacian interval is rather difficult to delineate in this section. It is represented by several samples in a 150-ft (46-m) sequence occurring between the base of the Santonian recognized at the lowest occurrence of Tetralithus obscurus/ovalis (5,170 ft (1,577 m)) and as the top of the Turonian, at the highest occurrence of Corollithion achylosum (5,400 ft (1,647 m)).

TURONIAN (5,400-5,800 ft (1,647-1,769 m))

Turonian strata at least 400 ft (122 m) thick occur from approximately 5,400 to 5,800 ft (1,647-1,769 m). The top of the Turonian is recognized at the highest occurrence of Corollithion achylosum (table 6). International Biostratigraphers, Inc. (1977) reported this species to be present in a sidewall core at 5,342 ft (1,629 m), and although it was not observed in the cuttings sample from 5,340-5,350 ft (1,629-1,632 m) of the present study, the species does occur in the next lower sample studied (5,400-5,410 ft (1,647-1,650 m)). The lowest occurrences of both Eiffellithus eximius (5,710 ft (1,742 m)) and Corollithion exiguum (5,800 ft (1,769 m)) are within this interval.

The base of the Turonian is placed at 5,800 ft (1,769 m), a level at which a significant lithologic break occurs in the cuttings. The sample from 5,790-5,800 ft (1,766-1,769 m) contains Turonian dark-gray argillaceous chalk of marine origin, but the chalk is associated with fragments of wood and mollusk shells and with nonfossiliferous calcareous sandstone containing abundant quartz, pyrite, and organic matter, all of which are indicative of a shallow-nearshore environment of deposition. The age of this lithologic change at 5,800 ft (1,769 m) is in doubt. International Biostratigraphers, Inc. (1977) placed the base of the Turonian at 5,830 ft (1,778 m) and reported the highest occurrence of Albian spores and pollen at 5,950 ft (1,815 m); however, no definitively Cenomanian nannofossils, foraminifers, or palynomorphs were identified in sidewall cores or cuttings from the intervening beds (5,830-5,950 ft (1,778 m-1,815 m)). Moreover, no nannofossil assemblages of Cenomanian Age are present in cuttings samples of the present study. Thus, the contact at approximately 5,800 ft (1,769 m), where Turonian marine limestone overlies shallow-marine calcareous sandstone, may mark the top of a short sequence of Cenomanian beds or could represent a hiatus separating Albian and Turonian rocks.

Calcareous nannofossils older than Turonian were not observed in samples from 5,800 to 8,860 ft (1,769-2,702 m), the deepest sample studied here. International Biostratigraphers, Inc. (1977) reported the occurrence of late Albian nannofossils in a sidewall core from 6,495 ft (1,981 m), but all other samples studied by them (13,196 ft (4,025 m)) are barren of nannofossils.

PALEOENVIRONMENT

The paleoenvironmental interpretaton of the COST No. GE-1 well presented here is based on the composition and diversity of calcareous nannofossil and ostracode assemblages, general lithology, and occurrences of glauconite, wood, and molluskan shell fragments. In addition, paleoenvironmental interpretations based on the occurrences of benthic and planktic foraminifers, sporomorphs, and dinoflagellates are considered (International Biostratigraphers, Inc., 1977).

The lower part of the sedimentary sequence at GE-1, from about 11,000 ft to total depth at 13,254 ft (3,355-4,042 m), is radiometrically dated as Paleozoic (Devonian). The sequence includes nonfossiliferous quartzite, shale, and slate, underlain by schist and metavolcanic rocks. Overlying these strata are approximately 3,500 ft (1,067 m) of red sandstones, siltstones, and shales, including some gray shales, anhydrite, and fragments of lignite or wood. The lower 2,300 ft (702 m) of this nonmarine red-bed sequence is almost barren of fossils. However, a dark-gray siltstone from 9,670 ft (2,934 m) yielded a sporomorph assemblage of Barremian to Aptian Age (R. Christopher, USGS, oral commun., 1978) A 180-ft (55-m) interval of dark siltstones and shales from 8,720 to 8,900 ft (2,660-2,715 m) contains spores, pollen, and Aptian dinoflagellates, marking the occurrence of a shallow-marine interval within the nonmarine red-beds (International Biostratigraphers, Inc., 1977). From approximately 8,700 ft upward to 7,500 ft (2,654-2,288 m), red sandstones, siltstones, and shales and minor gray shales contain a discontinuous sequence of sporomorph and dinoflagellate assemblages (International Biostratigraphers, Inc., 1977) that are indicative of fluctuating nonmarine and shallow-marine conditions.

Overlying the red beds, from 7,500 to 5,950 ft (2,288-1,815 m) is a varied sequence of sedimentary strata 1,550 ft (473 m) thick that includes limestones, calcareous sands, and minor amounts of dolomite, oolite, and anhydrite. These beds represent a sedimentary regime and regional paleoclimate that differed markedly from that of the underlying red-bed facies. Marine depositional environments prevailed, and shallow-marine calcareous sands, limestones, and even some evaporites were deposited. Sporomorphs and dinoflagellates are present, and several samples near the top of the interval exhibit poor assemblages of calcareous nannofossils and predominantly arenaceous foraminifers (International Biostratigraphers, Inc., 1977; Poag and Hall, this volume). Sporomorphs studied by Ray Christopher (oral commun., 1978) from three levels in this interval suggest a probable Aptian Age for a sample from 7,520 ft (2,294 m), an Albian Age for a sample from 7,370 ft (2,248 m); and an Albian-Cenomanian Age for an assemblage at 6,110 ft (1,864 m). Palynomorph species that are not known to range above the Albian occur at the top of this sequence (5,850 ft (1,815 m)); however, the base of the Albian has not been identified, and most of the section from about 8,700 to 6,500 ft (2,654-1,982 m) represents undifferentiated Aptian-Albian strata (International Biostratigraphers, Inc., 1977).

A very short interval containing argillaceous limestones and calcareous sandstones of equivocal age extends from 5,850 to 5,800 ft (1,769-1,815 m). Sporomorphs, dinoflagellates, and poor assemblages of arenaceus foraminifers are present and, although they are not age-diagnostic, they are collectively indicative of a shallow-marine environment (International Biostratigraphers, Inc., 1977). These poorly dated beds may mark an unconformity at the base of the Turonian, dark marine transgressive chalks.

The Upper Cretaceous in the COST No. GE-1 well consists of approximately 2,200 ft (671 m) of predominantly dark calcilutites and calcarenites from 5,800 to 3,600 ft (1,769-1,098 m). Turonian through Maestrichtian strata contain rich assemblages of calcareous nannofossils, foraminifers, and palynomorphs, especially dinoflagellates. Ostracodes are also present, but not in abundance, and assemblages are not diverse. The entire Upper Cretaceous sequence has been interpreted, on the basis of foraminifers, to indicate a marine environment of deposition at shelf and upper-slope water depths (International Biostratigraphers, Inc., 1977; Poag and Hall, this volume).

The environmental preferences of calcareous nannofossils are not as well known as those of foraminifers, but among nannofossil species that are typically found in continental-margin environments (Thierstein, 1976; Gartner, 1977), Braarudosphaera bigelowii, Lithastrinus floralis, Lucianorhabdus cayeuxii, and Tetralithus obscurus/ovalis are well represented within their appropriate ranges in the Upper Cretaceous of GE-1.

Ostracodes, on the other hand, are good environmental indicators, and the modest Upper Cretaceous assemblages display an association of genera indicative of shelf and upper-slope paleoenvironments that include the following: Krithe, a reliable outer shelf and slope genus; Phacorhabdotus, an indicator of open-ocean conditions, most commonly associated with chalks (J. E. Hazel, USGS, written commun., 1978); Bairdia and Cytherella, two genera that occur at all depths; Haplocytheridea, a genus that generally occurs on the inner and middle shelf; and other species whose environmental preferences are not well known (Alatacythere, Brachycythere, Cythereis, and Veenia).

Paleocene gray limestones contain nannofossil assemblages that include several species of Braarudosphaera and Micrantholithus, two genera that characteristically occur in continental shelf deposits. The presence of these nannofossils thereby corroborates the interpretation based on foraminifers that these strata were deposited in an outer-shelf environment (International Biostratigraphers, Inc., 1977; Poag and Hall, this volume). The environmental preferences attributed to Tertiary nannofossil species are based on reports by Bukry and others (1971), Bybell (1975), Bybell and Gartner (1972), Gartner (1977), Martini (1965, 1970), and Sullivan (1964, 1965).

Lower Eocene limestones exhibit a diverse nannofossil assemblage that contains many species and genera indicative of a marine-shelf environment of deposition (Braarudosphaera, Discoaster binodosus, Helicosphaera lophota, H. seminulum, Micrantholithus, three species of Transversopontis, and Zygrhablithus bijugatus). Other species that occur in shelf deposits as well as in sediments from deeper environments are Cyclococcolithina gammation, Ellipsolithus macellus, and Tribrachiatus orthostylus. This interpretation that the lower Eocene strata were deposited in a marine-shelf environment agrees with the preliminary conclusions of Poag and Hall (this volume). However, it disagrees with the International Biostratigraphers, Inc. (1977) report that suggests a paleoenvironment of middle- to lower-slope depths based on the presence of radiolarians and a species of arenaceous foraminifer.

The very thick sequence (2,070 ft (631 m)) of middle and upper Eocene strata is interpreted by International Biostratigraphers, Inc. (1977) to be a marine-middle-shelf deposit based on the occurrence of larger benthic foraminifers in the upper part of the Eocene (above 1,750 ft (534 m)) and lithologic uniformity throughout the interval. Poag and Hall (this volume), on the other hand, interpret most of this interval to be indicative of an outer-shelf paleoenvironment. Calcareous nannofossil assemblages from the middle and upper Eocene vary in diversity and preservation, but numerous species and genera are present that occur predominantly in continental shelf sediments (Braarudsphaera, Discolithina, Daktylethra, Helicosphaera lophota, H. seminulum, Lanternithus, Reticulofenestra reticulata, and Transversopontis). Other forms that occur in both shelf and deeper-water deposits include Cyclococcolithina gammation, Helicosphaera compacta, and Sphenolithus predistentus. Ostracodes, though never common, are also present in the middle and upper Eocene part of this section. In the upper Eocene, ostracodes are associated with larger foraminifers, bryozoans, and bivalves; they are very rare and poorly preserved below the base of the upper Eocene (2,220 ft (677 m)). The Upper Eocene assemblage is characteristic of the middle shelf and contains several genera that are chiefly found in inner- and middle-shelf deposits (Actinocythereis, Cytheretta, and Hermanites); one genus that is most commonly found in outer-shelf and slope environments (Echinocythereis); and genera that inhabit a wider range of depths (Bairdia, Cytherella, and Cytherelloidea). Several genera are also represented whose depth preference is not known (Digmocythere, Jugosocythereis, and Oertliella).

Above the Eocene, a thin sequence (210 ft (64 m)) of fine-grained limestone and dolomite of early Oligocene age contains a relatively diverse assemblage of nannofossils. Many of the constituent species belong to genera that exhibit preference for a neritic environment (Braarudosphaera, Discolithina, Transversopontis, and Zygrhablithus). Ostracodes are very rare, and only two species are present: a species of Cytherella (shelf and slope environments), and a single occurrence of a species of Cytheretta (usually found on the inner shelf). Although the ostracode occurrences are equivocal, the nannofossils indicate the presence of a marine-shelf environment in the early Oligocene rather than the upper-slope environment based on foraminifers from cuttings samples (International Biostratigraphers, Inc., 1977; Poag and Hall, this volume).

The upper 300 ft (92 m) of the Oligocene is composed of limestone and shelly carbonate sands. The nannofossil assemblage is not very diverse, and most of the neritic species found in the lower Oligocene are absent. An ostracode assemblage indicative of outer-shelf and upper-slope deposits is consistently present though, and contains Buntonia, Cytherella, Echinocythereis, Henryhowella, Krithe, and Paracypris. Other ostracode genera present are Acanthocythereis, Actinocythereis, Cytherelloidea, Digmocythere, and Pterygocythereis. Ostracode and calcareous nannofossil assemblages therefore indicate that these beds were deposited at upper-slope depths and support the interpretation based on forami-nifers (International Biostratigraphers, Inc., 1977; Poag and Hall, this volume).

The overlying lower to middle Miocene carbonates are similar lithologically to those of the upper part of the Oligocene. Only one nannofossil sample is fossiliferous, and the assemblage has a pelagic aspect, as almost all the commonly occurring neritic species are absent. Ostracodes in two samples from the Miocene include species of Cytheropteron, Echinocythereis, Henryhowella, Marocypris, and Muellerina, an association indicative of outer-shelf and upper-slope environments. Several other ostracode genera that are generally found at outer-shelf and shallower depths are also present (Actinocythereis, Acanthocythereis, "Cytheretta," and Pterygocythereis). Benthic foraminifers occurring in the Miocene section point to deposition in upper- to middle-slope water depths (International Biostratigraphers, Inc., 1977; Poag and Hall, this volume), whereas the ostracodes and calcareous nannofossils imply upper-slope depths.

In summary, the post-Paleozoic rocks in the COST No. GE-1 well represent, in a broad sense, a transgressive sequence of Lower Cretaceous nonmarine sandstone and shale red beds, interrupted at least once by a shallow-marine transgression in the Aptian and overlain by alternating nonmarine to shallow-marine sandstones and shales of Aptian-Albian Age. These clastic rocks are succeeded by shallow-marine carbonate strata associated with evaporites. A relatively thin, poorly dated interval composed of shallow-marine limestone and calcareous sandstone, which occurs above Albian carbonate rocks and below Turonian chalks, may mark an unconformity of probable Cenomanian Age. The Upper Cretaceous argillaceous chalks represent a marine carbonate environment indicative of shelf and upper-slope depths that prevailed through the Maestrichtian. A marine carbonate-shelf environment persisted throughout the Paleocene, Eocene, and lower part of the Oligocene interval. The limestones and shelly carbonate sands of the upper part of the Oligocene sequence and the lower to middle Miocene were, however, deposited at upper-slope depths and represent a deepening that probably resulted from a eustatic rise in sea level. Previous investigations of cores from this area have also documented a deepening of the marine environment during the Miocene (Charm and others, 1969). Post-Miocene bioclastic calcareous sands are characteristic of deposition in a marine-shelf environment.

RADIOMETRIC AGE DETERMINATIONS [1/]

E. K. Simonis

Radiometric dating of selected samples between 11,250 and 13,254 ft (4,329-4,040 m) appears to indicate a Late Devonian (approximately 355 m.y.) age for the sampled section. The radiometric ages may, however, reflect the effects of a Late Devonian thermal event and at least some of the rocks may be older.

The dominant lithology from an unconformity at 11,050 ft to 12,750 ft (3,368-3,886 m) consists of green and green-gray, very fine grained, highly indurated or weakly metamorphosed, pelitic, possibly bentonitic sedimentary rocks. Meta-igneous rocks containing albite, epidote, chlorite, and numerous quartz veins increase in abundance below 12,750 ft (3,886 m). A brief examination of a thin section from core No. 15 (13,252-13,254 ft (4039 to 4040 m)) reveals a relict igneous texture consisting of fine-grained felted plagioclase and epidote with phenocrysts and (or) xenocrysts of altered feldspar and less abundant olivine and (or) pyroxene. It is not clear if the igneous rocks represent flows or shallow intrusives. Presence of epidote, albite, and chlorite, and the absence of minerals associated with higher grades of metamorphism indicate a relatively low grade of metamorphism.

Whole-rock K-Ar ages of three samples were determined by Geochron Laboratories (written commun., 1977) with the following results:

11,250 ft (3,429 m) meta-bentonite(?)
374 ± 14 m.y.
13,128 ft (4,001 m) quartz sericite schist(?)
346 ± 12 m.y.
13,247 ft (4,038 m) felsic rock
159 ± 6 m.y.

The Mesozoic (159 ± 6 m.y.) K-Ar age of the felsic rock from 13,247 ft (4,038 m) is made questionable by Rb-Sr age determinations. Paul D. Fullagar of the University of North Carolina (written commun., 1977) obtained Rb-Sr model ages on seven whole-rock samples (table 7).The isochron age of all seven samples is 363 ± 7 m.y. However, Fullagar pointed out that, with the exception of the sample from 13,128 ft (4,038 m) (table 7), the remaining six points are highly colinear on the isochron plot and give an age of 355 ± 3 m.y. He considered this to be the most reliable age for the sampled section.

Table 7.--Rb-Sr whole-rock analyses from the COST No. GE-1 well

Sample No.	Depth Feet	Depth Meters	Radiometric age (m.y.)
1	12,900-13,025	3,932-3,970	353 ± 4
2	12,900-13,025	3,932-3,970	360 ± 4
3	13,128	4,001	383 ± 4
4	13,128	4,001	350 ± 10
5	13,207	4,025	353 ± 10
6	13,247	4,038	331 ± 85
7	13,252-13,254	4,039-4,040	372 ± 30

[1/] This section reprinted, with minor changes, from Amato and Bebout (1978).

GEOTHERMAL GRADIENTS

E. I. Robbins

Present-day subsurface temperatures can be used to approximate 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. GE-1 well, 58 geothermal values have been plotted (fig. 32) using approximate equilibrium temperatures calculated from the three available temperature logs. Data points were chosen at approximately 500-ft (150-m) intervals. The eight other points, represented by crosses in figure 32, are temperature values taken from headers of other geophysical logs run in the well. Although these latter points are considered less reliable than the temperature log values, they do provide some check on the overall accuracy of the temperature-logs. A linear regression was computed using data points from the two deepest temperature logs; it shows a very systematic increase in temperature with depth (correlation coefficient = 0.99). The geothermal gradient is calculated to be 0.89°F/100 ft (16.2°C/km), with a surface intercept of 108°F (42°C). This gradient is somewhat lower than typical values for basins around the North Atlantic Ocean (table 8).

The liquid-petroleum window is based largely on empirical observations and generally is considered to have a lower limit of about 150°F (66°C) and an upper limit of 270°-300°F (132°-149°C) (Pusey, 1973; Harrison, 1976). The upper and lower temperature limits may be significantly higher if heating times are short. Using the present geothermal gradient in the GE-1 well, the liquid-petroleum window would be expected to occur between 4,700 and 20,000 ft (1,425-6,100 m), provided these temperatures have been maintained over a significant period of time. Organic geochemical analyses, coupled with vitrinite reflectance and visual analysis of color alteration of organic matter (summarized by Miller and others, this volume) suggest that similar geothermal gradients have prevailed over the past 120 m.y. However, most reconstructions of the geologic history of the Atlantic Continental Margin (Bott, 1971; Falvey, 1974; Sleep, 1971) would predict considerably higher geothermal gradients in the past, particularly during Triassic and Jurassic rifting. Thus, the older sedimentary rocks within the Southeast Georgia Embayment may have been subjected to higher temperatures than those calculated from present-day geothermal gradients.

Table 8.--Circum-Atlantic offshore geothermal gradients

Basin	Gradients (°F/100 ft)	(°C/km)	References
Scotian Shelf basin	1.2	21.9	Robbins and Rhodehamel, 1976.
Southern North Sea	1.7	29.7	Harper, 1971.
Baltimore Canyon basin	1.3	23.7	Scholle, 1977a.
Niger Delta shelf	1.4	25.5	Nwachukwu, 1976.
South Pass, La.	1.2	21.9	Pusey, 1973.
Offshore Louisiana	1.3	23.7	Jam and others, 1969.
Southeast Georgia Embayment	0.9	16.2	This paper.

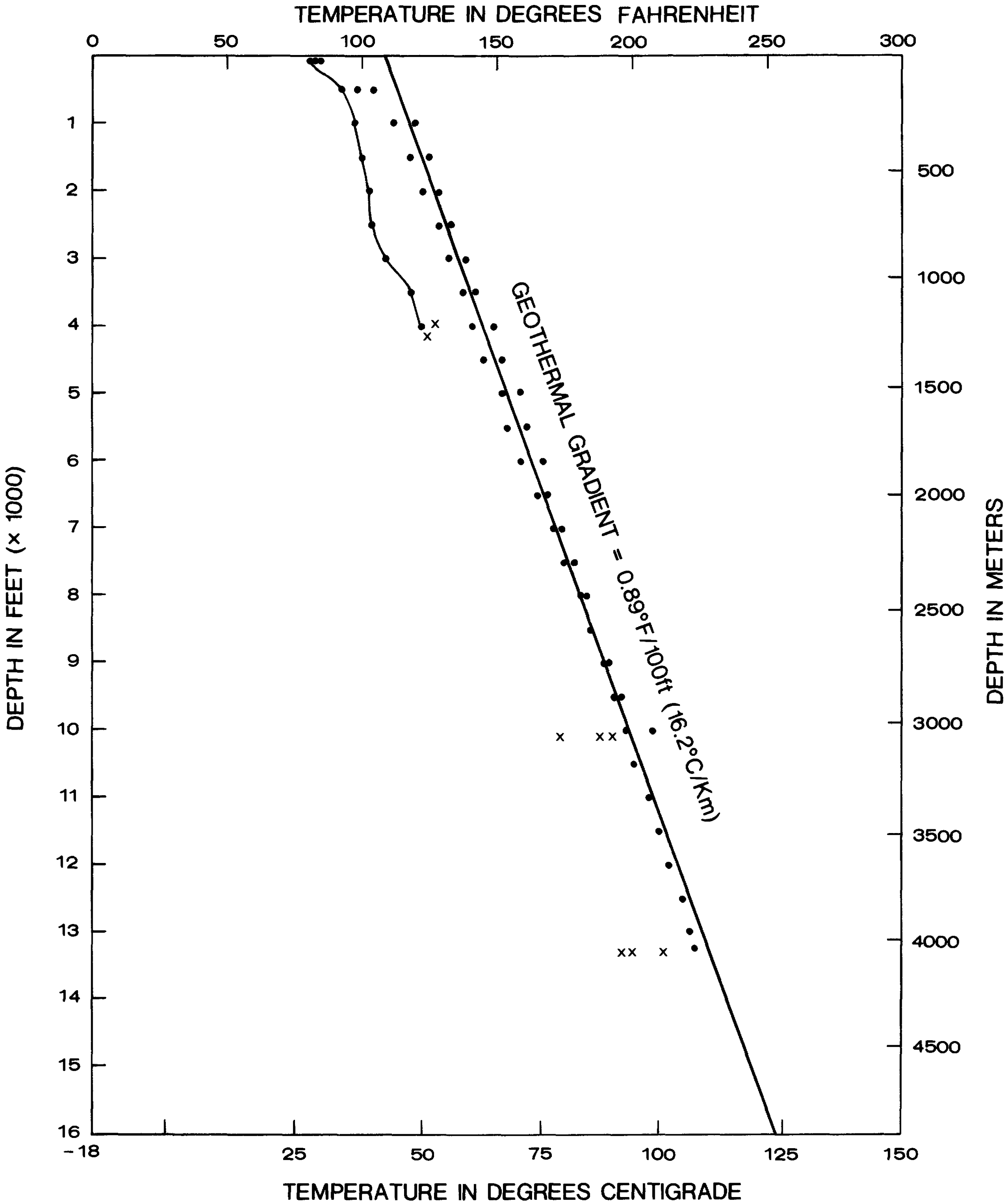


Figure 32.--Present-day temperature data for the COST No. GE-1 well. Dots are resting temperatures taken from three available temperature logs; crosses are temperatures taken from headers of other geophysical logs. Geothermal gradient is shown as a least-squares fit to the data from the two deepest temperature logs.

ORGANIC GEOCHEMISTRY

R. E. Miller, D. M. Schultz, G. E. Claypool, M. A. Smith, H. E. Lerch, D. Ligon, C. Gary, and D. K Owings

Purpose and Scope

The COST No. GE-1 well was drilled largely for the purpose of evaluating the petroleum potential of the Southeast Georgia Embayment. To aid in this evaluation, the following objectives were established: (1) characterize any rocks that might be considered prospective of petroleum and natural gas; and (2) determine and identify, where possible, the apparent influence of drilling-mud additives on the true hydrocarbon-source character.

Organic geochemical studies of GE-1 well cuttings were carried out by USGS offices in Reston, Va., and Denver, Colo. The geochemical analyses employed in these studies of sedimentary rocks measure (1) total organic carbon content by wet oxidation and combustion, (2) extractable hydrocarbons by solvent soxhlet extraction and chromatographic analyses, and (3) hydrocarbon-generating capacity of solid organic matter by pyrolysis. The interpretation of such measurements normally assumes the organic substances detected to be indigenous to the sediment composing the stratigraphic unit sampled. However, in the COST No. GE-1 well, loss of mud circulation at approximately 2,800 ft (850 m) resulted in the need for mud additives such as IMCO "free pipe," walnut husks, mica, and possibly diesel fuel to be added to the mud system in order to restore circulation and free the drill string. The effect of these mud additives seriously complicates a true interpretation of these source-rock parameters by masking, either totally or partially, the indigenous hydrocarbon characteristics.

In this present study, the USGS analyzed two sets of well cuttings samples from 570 to 10,370 ft (174-3,161 m) for their $C_{15}+$ hydrocarbon type, amount, and composition. The first set of samples included the coarse- and fine-sediment-size fractions (Tyler No. 10 to 100 mesh size), and also contained varying amounts of "free pipe" and diesel-stained walnut husks, mica flakes, and some traces of iron filings. The second set of samples analyzed, upon which the quantitative source-rock richness and maturity discussion are based, consisted only of rock chips larger than Tyler 10 to 20 mesh from which all the diesel-stained walnut husks and mica were physically removed. Although the solid contaminants were removed, some of the rock chip samples were very likely still contaminated from the liquid "free pipe" and possibly diesel added to the mud circulation system. Organic-carbon and thermal-pyrolytic analyses were performed by the USGS on 27 unwashed and unpicked well cuttings ranging in depth from 450 to 13,220 ft (137-4,029 m). These analyses were used to supplement the organic-richness and thermal-maturation interpretation derived from the composition and amount of extractable organic matter.

Terms and Definitions

The terminology used in this report to describe the petroleum source-rock potential of the COST No. GE-1 area follows, in general, the concepts of organic richness and maturity expressed in the COST No. B-2 well studies by Claypool and others (1977). The organic richness of a source bed and its petroleum potential may be measured by (1) a minimum amount of total organic carbon on a weight-percent basis (0.7-1.0 percent for argillaceous rocks); (2) pyrolytic oil yields in excess of 0.2-0.3 percent; and (3) solvent-extractable hydrocarbon concentrations in excess of 100-500 ppm. The maturity of a source bed is a term that expresses the degree to which the convertibility of organic matter to petroleum hydrocarbons has progressed through temperature- and time-dependent kinetic reactions. An important point to be considered is that some source beds must contain more organic carbon than normal to be considered possible source rocks. This arises from the much poorer conversion capability of some types of organic matter such as humic and lignin compounds. The availability of hydrogen and the molecular structure of the organic constituents will influence the degree of convertibility of organic matter to petroleum; therefore, the type of organic matter is important to source-bed performance and evaluation.

Organic-rich sedimentary rocks are defined as immature when the petroleum-generating reactions have not altered the organic matter to the point at which a minimum amount of petroleum has been thermochemically generated and physically expelled. Furthermore, those sedimentary rocks that contain predominantly biochemically derived hydrocarbons in low concentrations but yet are shown to be capable of generating petroleum hydrocarbons by pyrolysis are described as immature.

The term mature may be used to describe those source beds in which the thermochemical conversion of the organic matter disseminated in argillaceous sediments has occurred to the extent that oil expulsion could have taken place. The principal criteria used to define the degree of thermochemical conversion of the organic matter to oil are the molecular composition and relative concentration of indigenous extractable hydrocarbons. When the extractable hydrocarbons are present in amounts of about 1-2 percent of the total organic carbon and the hydrocarbons are chemically identical with petroleum, then the source beds are described as being mature.

The terms potential source and possible source rock are used in the same context as that defined by Claypool and others (1977, p. 46): potential source rock--"A sedimentary rock that is rich in organic matter, and that is immature." Possible source rock--"A sedimentary rock that is rich in organic matter, and that is mature."

Analytical Procedure

In the thermal-analysis studies, unwashed and unpicked samples of wet drill cuttings and mud were freeze-dried and analyzed for organic carbon by wet oxidation and for hydrocarbon yield by thermal-evolution analysis. Organic carbon was determined by Rinehart Laboratories, Arvada, Colo. using a chemical (chromic acid) oxidation technique modified from Bush (1970). Thermal analysis was done in the manner described by Claypool and Reed (1976), except that the response of the flame ionization detector was calibrated by analysis of a synthetic standard ($\underline{n}$-$C_{20}H_{42}$ at 4.24 percent on Al_2O_3). Total pyrolytic hydrocarbon yield (weight percent) is the integrated response of the flame ionization detector converted to an equivalent weight of hydrocarbon as $\underline{n}$-$C_{20}H_{42}$ during the time that the rock sample is heated in a flowing stream of helium from about 120° to 1,330°F (50°-720°C) at 72°F (40°C) per minute. Volatile hydrocarbon content is the component (ppm) of the total pyrolytic hydrocarbon yield that is obtained from the rock at lower temperatures (<600°F (<320°C)). The ratio of pyrolytic hydrocarbon yield to organic carbon, in percent, is a measure of the convertibility of the organic matter to hydrocarbons. Also reported is the temperature at which the yield of volatile organic compounds produced by pyrolysis of the solid organic matter is at a maximum.

In the extractable-heavy-hydrocarbon (C_{15}+) portion of this study, unwashed well cuttings from approximately 570 to 10,370 ft (175-3,160 m) were removed from their plastic storage bags; and the drilling mud was carefully removed, as well as possible, from each rock chip by thoroughly washing the sample under running water through a Tyler number 100 mesh screen. The sediment retained on the screen was air-and oven-dried at 95°-104°F (35°-40°C). Each washed and dried sample was then carefully examined under a binocular microscope and lithologically described, and all "foreign material" including string, rubber, and plastic was removed. The lithologic descriptions of the samples analyzed are shown in table 9.

In addition to the "foreign material," the binocular examination of the samples showed the presence of variable amounts of mud additives such as walnut husks and mica flakes. The organic composition of the husks was confirmed by burning the husk to form a soft, gray-white, fluffy ash. These walnut husks have a deceiving crystalline appearance similar in some regards to that of rock fragments; they were darkly stained around their edges, probably by diesel or IMCO "free pipe." In an effort to identify the possible effects of the mud additives on the gas-chromatographic character of the saturated hydrocarbons, separate sets of samples were analyzed. One set was composed only of those rock chips larger than 10 to 20 Tyler mesh and from which all the walnut husks and mica flakes had been physically removed by sieving and visual hand picking of the samples. The other set contained all the sediment-size fractions larger than 100 Tyler mesh and included the walnut husks, mica flakes, and some traces of iron filings. Both sample sets were then ground using mortar and pestle to pass through a 60 Tyler mesh screen and weighed.

The solvent-extraction technique and liquid-column- and gas-chromatography methods were adopted and modified from the procedures described by Miller and others (1976). The ground sediment samples were soxhlet-extracted for 24 hours using redistilled chloroform. If elemental sulfur was found to be present in the extract, a column of activated copper was employed to remove the sulfur. Each extract was separated into paraffin-naphthene, aromatic, and NSO fractions by elution-column chromatography using Bio-Sil HA, 100 to 200-mesh, silica gel as the solid support. The liquid-solid chromatography columns employed were approximately 8 in. (20 cm) long by 0.4 in. (1 cm) in interior diameter.

The saturated (paraffin-naphthene) fractions were analyzed on Perkin Elmer 3920 gas chromatographs. Each saturated hydrocarbon fraction was analyzed for both qualitative and quantitative information. The qualitative

Table 9.--Lithologic descriptions of COST No. GE-1 well cuttings used for organic geochemical analyses

Sample No.	Depth interval Feet	Depth interval Meters	Lithology
7	570-600	174 - 183	Shell fragments (micro and macro), whitish-gray oolites, biomicrite and trace sparite and sand, clear and frosted (45 percent). Globigerinid ooze (55 percent).
22	1,020-1,050	311 - 320	Limestone, whitish-tan, soft, finely crystalline, slightly fossiliferous (95 percent: sand, clear to frosted, subangular to subrounded (5 percent).
37	1,470-1,500	448 - 457	Soft limestone, fragments of calcarenite plus ooids, chalk (biomicrite) (70 percent); trace of chert, subangular to subrounded; Foraminifera (30 percent).
48	1,800-1,830	549 - 558	Limestone (biomicrite), argillaceous, traces of dense, crypto-crystalline dolomite (100 percent).
76	2,640-2,670	805 - 814	Limestone (chalk-biomicrite), slightly argillaceous, moderately soft (60 percent); chert, dense, brownish-gray (40 percent).
98	3,300-3,330	1,006-1,015	White, soft, argillaceous limestone with traces of pyrite and dense, brown chert (100 percent). Mud additives: mica, light-brown, angular to subangular walnut husks; iron fillings. Diesel-fuel odor in unwashed samples.
101	3,390-3420	1,033-1,042	White, soft, argillaceous limestone (70 percent); grayish-tan, dense chert and traces of possible glauconite (30 percent). Drilling mud, walnut husks, iron fillings, mica; diesel-fuel odor in unwashed samples.
110	3,660-3,690	1,116-1,125	Calcareous shale grading to soft blocky limestone (70 percent), calcareous clays, limonitic staining, traces of quartz (30 percent). Abundant drilling mud, mica, light-brown angular walnut husks.
148-149	4,280-4,300	1,305-1311	Very poor sample recovery. Light-gray calcareous shale, fossiliferous; white micrite pellets; abundant drilling mud.
156-158	4,360-4,390	1,329-1,338	Soft to moderately soft chalk or biomicrite (100 percent), with traces of clear quartz, pyrite, limonite staining, and glauconite.
194-196	4,740-4,770	1,445-1,454	Very argillaceous biomicrite, light gray to yellow, with limonite staining (100 percent). Abundant drilling mud; light-brown angular walnut husks; mica.
216-218	4,960-4,990	1,512-1,521	Very poor sample recovery. Soft biomicrite; fossiliferous shale; glassy spheres; traces of aragonite. Abundant drilling mud; light-brown angular walnut husks; mica.
254-256	5,340-5,370	1,628-1,637	Light gray shale, very calcareous and silty (100 percent); slight amount of carbonaceous material: traces of pyrite. Abundant drilling mud; light-brown walnut husks: mica.
350-353	6,300-6,330	1,920-1,929	Light- to pale-pinkish-red limestone (oomicrite), some sparite in packstone and grapestone (60 percent); shale, hard to medium, gray (40 percent). Light-brown walnut husks, mica.
467	7,470-7,480	2,277-2,280	Reddish-brown shale with traces of pink clay (5 percent); small amounts of carbonaceous, coaly shale; calcareous, dense sandstone (30 percent); calcareous shale (20 percent).
578-580	8,580-8,610	2,615-2,624	Frosted quartz sandstone with carbonate cement (65 percent). Shale, slightly calcareous, small amount of light-red to medium-gray silt (35 percent): Trace coaly organic matter. Light-brown walnut husks.
656-658	9,360-9,390	2,853-2,862	Coarse- to medium-grained, carbonate-cemented sandstone (75 percent); quartz grains are frosted; slightly calcareous shale, silty shales, light-gray to red (25 percent); trace chalk.
755-757	10,350-10,380	3,155-3,164	Reddish-brown to pale-gray shale with traces of cryptocrystalline anhydrite (90 percent); approximately 1 percent dark-brown dolomite, 2 percent siltstone, and 6 percent quartz sandstone.
805-807	10,850-10,880	3,307-3,316	Sandstone, silica-cemented, gray to light-red, with some conglomerate fragments (75 percent); gray shale with siltsone (25 percent); gray shale with black crypto-crystalline dolomite (6 percent); coaly, carbonaceous organic matter (4 percent).

analyses were performed on a 12.5 ft x 0.09 in. (3.8 m x 0.236 cm) stainless steel column, packed with 5 percent OV-1, 80- to 100-mesh CW-H.P. The helium flow rate was 1.8 in.^{3}/min (30 ml/min). The instrument temperature was programed from 176°F (80°C) at injection at 29°F/min (16°C/min) for 8 minutes; it was ten temperature programmed at 14°F/min (8°C/min) to a final temperature of 572°F (300°C). A OV-1, 66-ft (20-m) SCOT column was employed for the quantitative determinations. The column conditions were 212°F (100°C) at injection and were held isothermally for 1 minute; they were then temperature programed at 7°F/min (4°C/min) to a final temperature of 473°F (245°C) and held at this temperature until n-C_{32} eluted.

The determination of total organic carbon content of the rock samples involved first drying, then grinding the sample to less than 60 mesh. A weighed aliquot of approximately 0.2 g was then digested in hot, 6-Normal hydrochloric acid to remove the carbonates and dried. The dried samples were then reweighed and combusted in a F and M Model 185 Carbon, Hydrogen, Nitrogen Analyzer. Duplicate splits of the sample were analyzed for total organic carbon content.

The following expression, modified from Hunt (1974), was used to calculate the Carbon Preference Index (CPI):

$$CPI = \frac{\dfrac{(\%nC_{25} + \%nC_{27} + \%nC_{29} + \%nC_{31})}{(\%nC_{24} + \%nC_{26} + \%nC_{28} + \%nC_{30})} + \dfrac{(\%nC_{25} + \%nC_{27} + \%nC_{29} + \%nC_{31})}{(\%nC_{26} + \%nC_{28} + \%nC_{30} + \%nC_{32})}}{2} .$$

Results and Discussion

Tertiary.--The Tertiary section in the COST No. GE-1 well, 390-3,570 ft (118 to 1,088 m), consists largely of unconsolidated, moderate- to deep-water, chalky, cherty, and shaly limestones grading into calcareous shales at about 3,090 ft (942 m) (Amato and Bebout, 1978).

The data for total pyrolytic hydrocarbon yield, total extractable hydrocarbon, and total organic carbon (weight percent), shown in tables 10 and 11, suggest a very organic-lean Tertiary section. The average total organic carbon for this interval is 0.16 percent, considerably less than the worldwide average of 0.27 percent for carbonate rocks (Hunt, 1961; Gehman, 1962). The extractable C_{15}+ hydrocarbon content averages 32 ppm for the Tertiary, which is below the limiting range (50 ppm) needed for a poor or adequate petroleum source bed (Philippi, 1957; Baker, 1972).

A seemingly mature character of the C_{15}+ hydrocarbons in the interval from 600 to 2,800 ft (183-853 m) in the Tertiary is suggested by the comparatively high values of the saturated paraffin-napthene-to-aromatic ratio, which

Table 10.--Organic-carbon and thermal-evolution analyses, COST No. GE-1 well

[Leaders (--), no data available; (*) indicates oil staining or contamination present]

Bag No.	Sample depth interval: Feet	Sample depth interval: Meters	Total organic carbon (weight percent)	Pyrolytic hydrocarbon yield (weight percent)	Volatile hydrocarbon content (ppm)	Temperature of maximum pyrolysis yield (°C)	Pyrolytic hydrocarbon / total organic carbon ratio (percent)
3	450- 480	137-146	0.13	0.007	9	508	5.4
21	990-1,020	302-311	0.39	0.081	105	472	20.8
36	1,440-1,470	439-448	0.16	0.028	31	484	17.5
51	1,890-1,920	576-585	0.17	0.035	47	500	20.6
66	2,340-2,370	713-722	0.13	0.038	30	483	29.2
81	2,780-2,820	847-860	12.1	4.03	16,000 *	--	33.3
96	3,240-3,270	988-997	0.41	0.14	290 *	464	33.1
111	3,690-3,720	1,125-1,134	1.19	0.72	1,230 *	--	60.5
138	4,180-4,190	1,274-1,277	1.15	0.38	720 *	458	33.0
189	4,690-4,700	1,430-1,433	0.25	0.037	60	446	14.6
240	5,200-5,210	1,585-1,588	14.5	5.35	17,000 *	--	36.9
291	5,710-5,720	1,740-1,743	0.63	0.14	185	484	22.2
342	6,220-6,230	1,896-1,899	0.18	0.017	19	520	9.4
393	6,730-6,740	2,051-2,054	0.20	0.017	20	512	8.5
444	7,240-7,250	2,207-2,210	0.34	0.015	18	472	4.4
495	7,750-7,760	2,362-2,365	0.50	0.029	44	476	5.8
546	8,260-8,270	2,518-2,521	0.47	0.052	65 *	-	11.1
597	8,770-8,780	2,673-2,676	0.31	0.027	50	470	8.7
648	9,280-9,290	2,829-2,832	0.14	0.010	22	476	7.1
699	9,780-9,800	2,981-2,987	0.10	0.019	36	446	19.0
750	10,300-10,310	3,139-3,142	0.08	0.006	27	--	7.5
800	10,800-10,810	3,292-3,295	0.17	0.010	10	470	5.9
850	11,300-11,310	3,444-3,447	0.08	0.010	12	480	12.5
900	11,800-11,810	3,597-3,600	0.13	0.004	7	492	3.1
950	12,300-12,316	3,749-3,754	0.08	0.003	11	490	3.8
1,000	12,800-12,810	3,901-3,904	0.12	0.002	3	495	1.7
1,042	13,220-13,230	4,029-4,032	0.12	0.002	5	492	1.7

Table 11.-- Organic carbon and extractable organic matter, COST No. GE-1 well
[Leaders (--) indicate no data available]

Well Interval		Organic carbon	Total hydrocarbons	Hydrocarbon Organic carbon ratio	Hydrocarbon Extractable Organic matter ratio	Saturated Aromatic ratio	CPI
Feet	Meters	(percent)	(ppm)	(percent)			
570- 600	174- 183	0.20	25	1.26	0.43	2.63	1.08
1,470-1,500	448- 457	0.04	6	1.60	0.13	1.23	1.17
1,800-1,830	549- 558	0.15	15	1.00	0.24	1.82	1.00
2,040-2,070	622- 631	0.10	26	2.60	0.25	1.76	1.24
2,640-2,670	805- 814	0.07	46	6.63	0.28	2.16	0.90
3,300-3,330	1,006-1,015	0.09	61	6.79	0.39	1.30	1.93
3,390-3,420	1,033-1,042	0.32	43	1.35	0.17	1.22	--
4,280-4,300	1,305-1,311	0.15	360	23.90	0.37	0.29	1.09
4,360-4,390	1,329-1,338	0.46	410	8.91	0.62	1.89	0.85
4,670-4,700	1,423-1,433	0.09	40	4.39	0.15	0.40	0.97
4,960-4,990	1,512-1,521	4.30	95	0.22	0.20	0.33	0.92
5,340-5,370	1,628-1,637	1.20	175	1.46	0.25	0.29	1.23
6,300-6,330	1,920-1,929	0.28	23	0.80	0.35	0.55	1.51
7,470-7,490	2,277-2,280	0.35	32	0.92	0.14	0.22	1.47
8,580-8,610	2,615-2,624	0.18	9	0.49	0.05	2.00	1.55
9,360-9,390	2,853-2,862	0.01	6	6.24	0.06	1.75	1.14
10,350-10,370	3,155-3,161	0.02	3	1.59	0.04	6.95	1.26

ranges from 2.63 to 1.22. The relative concentration of saturated paraffin-naphthene-to-aromatic hydrocarbons is sensitive to the thermal history, type and percent of organic matter of a sample, and preferential destruction of aromatic hydrocarbons (Baker, 1972; Baker and Claypool, 1970; Louis and Tissot, 1967). More recently it has been suggested that thermally immature sediments may have paraffin-naphthene-to-aromatic ratios of less than 0.5 and a hydrocarbon-to-organic carbon ratio less than 0.8 percent (Claypool and others, 1978). In addition, it has been shown that hydrocarbon-to-total-organic-carbon ratios of more than 1 percent may indicate that hydrocarbon generation by thermal alteration has occurred (Philippi, 1965; Claypool and others, 1978). If the hydrocarbons in these Tertiary rocks (600-2,800 ft (183-853 m)) are truly indigenous, then the high proportion of total hydrocarbon to total extract (bitumen), a saturated paraffin-naphthene-to-aromatic ratio of greater than 1.0, and hydrocarbon-to-organic-carbon values that range from 1.0 to 6.8 (table 10) would seem to imply that the hydrocarbons are mature and that hydrocarbon generation had occurred. However, the high proportion of the extractable hydrocarbons (ppm) relative to the very low percentage of total organic carbon would probably imply a nonindigenous origin for the greater part of the C_{15}+ hydrocarbons present in these rocks. Because of the effect that small absolute concentration values, either in the denominator or numerator, may have on specific geochemical ratios, this factor must be taken into consideration in the interpretation of the geochemical significance of these ratios (Swetland and others, 1978).

With the exception of one sample interval, 2,780-2,820 ft (847 to 860 m), the total organic carbon (weight percent) and total pyrolytic hydrocarbon yield for these Tertiary rocks correlate well with the interpretation of a very lean to poor source-rock character. The pyrolytic hydrocarbon-to-total-organic-carbon ratio averages 23.3 for these Tertiary sed-iments, and may reflect the convertibility of the more lipoidal, hydrogen-rich, marine amorphous kerogens present in these rocks (tables 9, 10).

Figures 33 and 34 show a series of gas chromatograms of the saturated paraffin-naphthene hydrocarbons representing the Tertiary interval. The unresolved complex mixture is equal to or predominates, in most cases, over the resolved aliphatic peaks, a characteristic that is usually associated with thermally immature hydrocarbon extract compositions. In contrast, however, the CPI ratios for the resolved alkanes are in the range from 0.9 to 1.24. These CPI values may not be reliable because of the limited range of the C_{15} to C_{22} hydrocarbons and their low concentrations (table 11). The isoprenoids (pristane and phytane) are, however, dominated slightly by the resolved normal alkanes, a characteristic that is usually associated with mature saturated hydrocarbons. The limited range of the resolved alkanes (C_{15} to C_{22}) is inconsistent with an immature hydrocarbon assemblage, but does closely resemble both refined diesel fuel and the commercial mud additive IMCO "free pipe."

The probability that nonindigenous hydrocarbons in this Tertiary interval are a result of up-dip migration seems remote considering the low geothermal gradient and regional structure. This Tertiary interval from 600 to

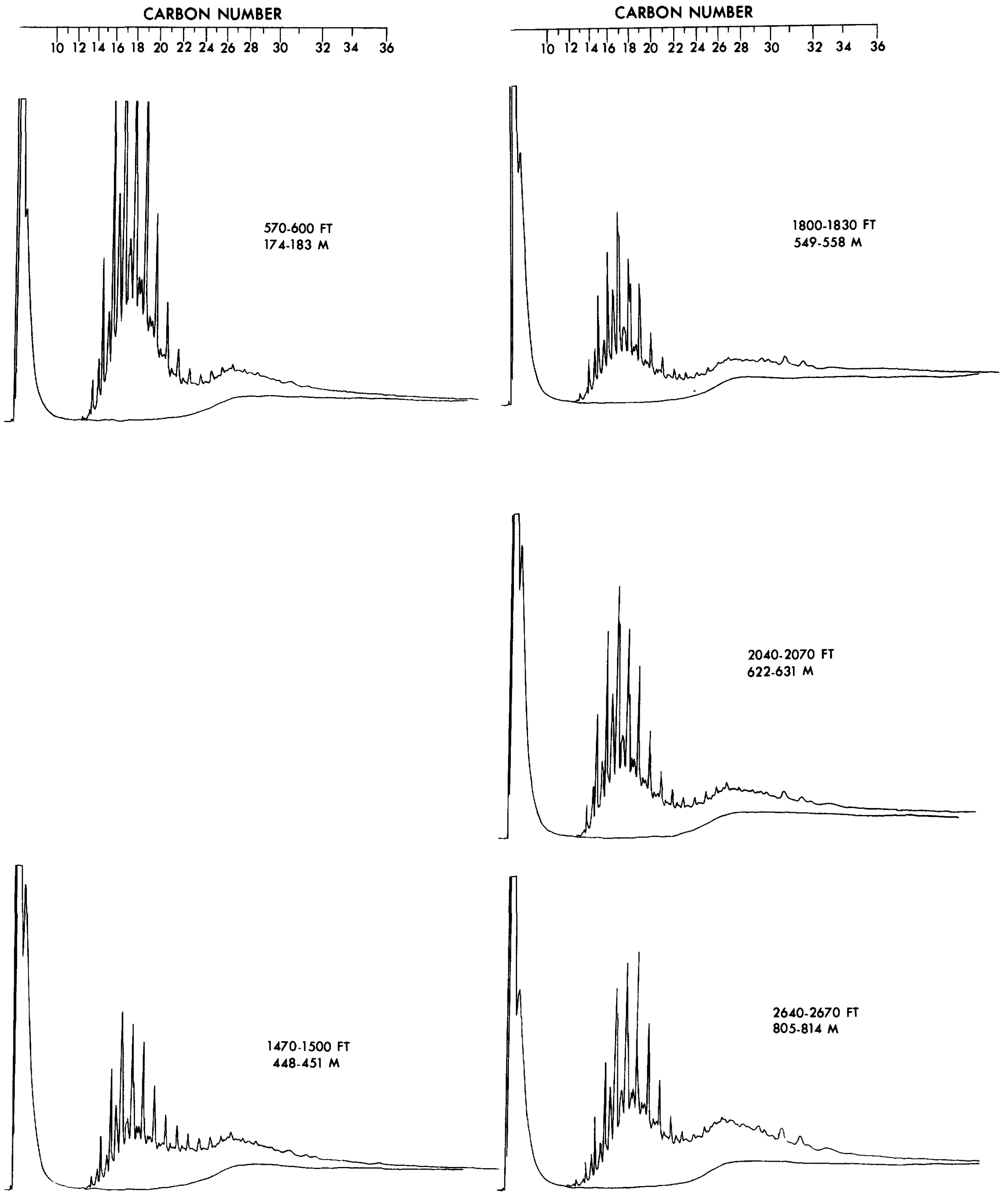


Figure 33.--Gas-chromatographic analyses of saturated paraffin-naphthene hydrocarbons of Tertiary rocks above 3,300 ft (1,000 m), COST No. GE-1 well.

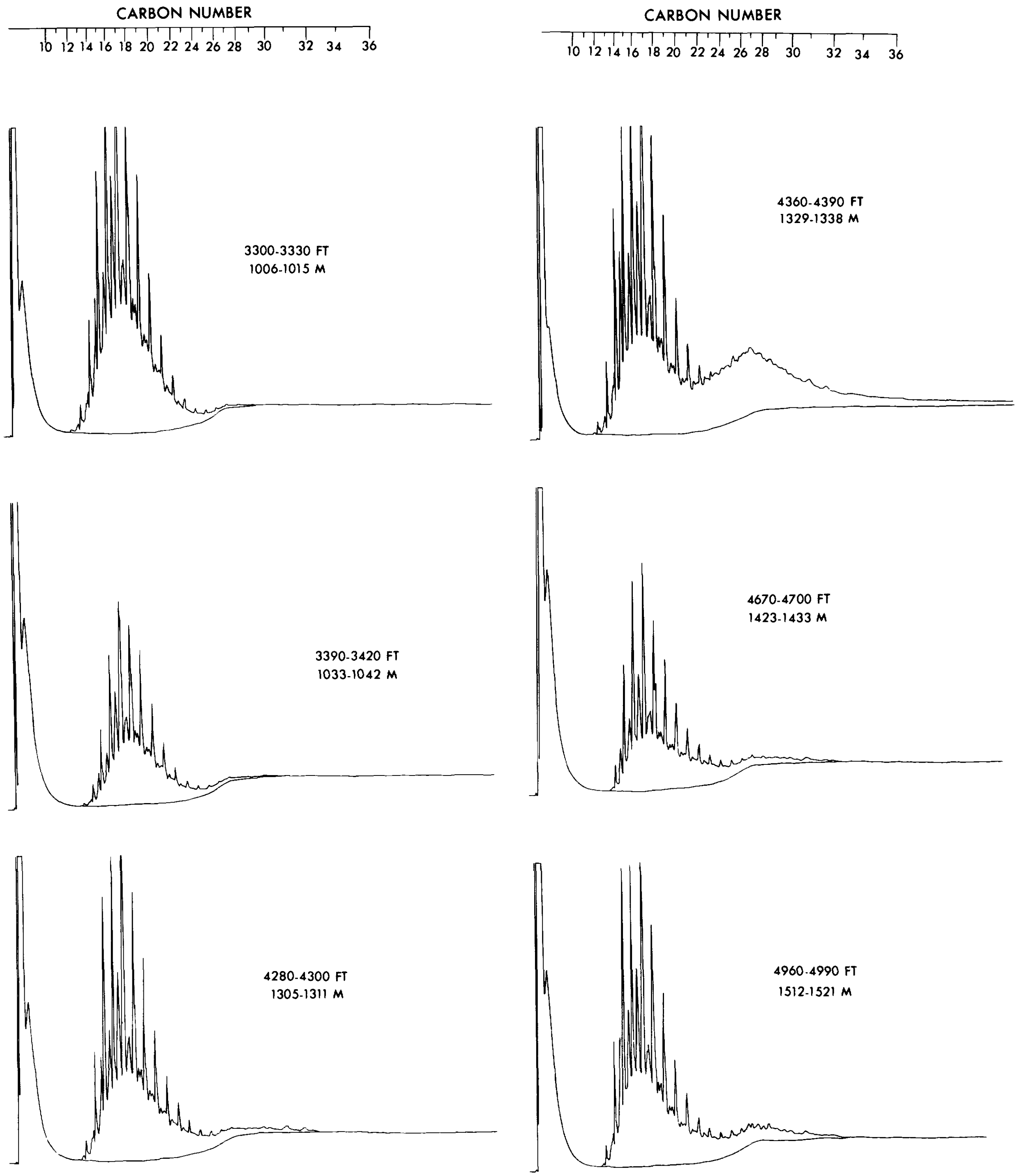


Figure 34.--Gas-chromatographic analyses of saturated paraffin-naphthene hydrocarbons of Tertiary and Upper Cretaceous rocks below 3,300 ft (1,000 m), COST No. GE-1 well.

2,800 ft (183-853 m) is believed to contain low amounts of indigenous hydrocarbons of marine biogenic origin that are not related, for the main part, to a thermal-chemical history. In addition, this low-level biogenic background may have been strongly influenced by nonindigneous, possibly anthropogenic, hydrocarbons that impart a more mature signature and more restricted range to the extractable C + hydrocarbons than would be expected normally.

Upper Cretaceous.--The Upper Cretaceous interval from 3,570 to 5,950 ft (1,088-1,814 m), a section of gray, calcareous deepwater shales, contains the zone of highest organic carbon (average 1.24 weight percent) and the highest total extractables (981 ppm), paraffin-naphthenes (268 ppm), aromatic hydrocarbons (278 ppm), NSO's (416 ppm), and pyrolytic hydrocarbon yield present in the COST No. GE-1 well (tables 10, 11; fig. 36).

The interval from 3,570 to 4,800 ft (1,088-1,463 m) contains dark-gray to light-gray, calcareous claystones of Maestrichtian, Campanian, and Santonian age. These sediments are believed to have been deposited in dominantly outer-shelf environments (Amato and Bebout, 1978). In this sequence of rocks, the total organic carbon content is about the same as that of the Tertiary rocks and averages 0.23 weight percent but, in contrast to the Tertiary, has an unusually high proportion of total hydrocarbon to total organic carbon (4.39-23.94 percent). The saturated paraffin-naphthene-to-aromatic ratio varies from 0.29 to 1.89, and the CPI values range from 0.85 to 1.23. The abnormally high hydrocarbon-to-total-organic-carbon values and the unusually high saturated paraffin-naphthene-to-aromatic ratio for the interval from 4,360 to 4,390 ft (1,329-1,338 m) probably signify the presence of nonindigenous hydrocarbons (table 11).

The saturated-hydrocarbon gas chromatograms for the 3,570- to 4,800-ft (1,088- to 1,543-m) interval of the Upper Cretaceous are shown in figure 34. For the 4,280- to 4,300-ft (1,305- to 1,310-m) and 4,670- to 4,700-ft (1,423- to 1,433-m) intervals, the resolved normal alkanes are very comparable to the unresolved complex mixture; and, furthermore, the isoprenoids pristane and phytane are dominated by the normal alkanes that occur in a limited range from C_{14} to C_{24}. Such saturated-hydrocarbon chromatogram characteristics would seem to imply a mature assemblage of petroleum hydrocarbons. In comparison, however, the 4,360- to 4,390-ft (1,328- to 1,338-m) interval tends to show a much stronger bimodal paraffin-naphthene character relative to the unresolved aliphatics, a signature that may imply the presence of thermally immature hydrocarbons. However, in this same hydrocarbon mixture, the resolved normal alkanes continue to dominate the isoprenoids, a characteristic that is consistent with a mature hydrocarbon assemblage. This seemingly inconsistent behavior in the maturation character of the saturated-hydrocarbon chromatograms tends to support the notion that the assemblage of extractable, resolved saturated hydrocarbons in these samples probably reflects the effects of drilling-mud additives; therefore, an interpretation of thermal maturity and organic richness based only on the distribution and composition of extractable hydrocarbons may be overly optimistic.

The Upper Cretaceous interval shows a comparatively reasonable and consistent agreement in degree of increase between the total organic carbon (weight percent), total extractables (ppm), total hydrocarbons $C_{15}+$ (ppm), and total eluted NSO's (ppm). The saturated-hydrocarbon chromatograms for this interval continue to show a strong paraffin-naphthene character relative to the resolved alkanes, and the pristane and phytane isoprenoid hydrocarbons continue to be dominated by the resolved normal alkanes (figs. 34, 35). The low concentrations and restricted boiling-point range serve to limit the CPI-value (0.9 to 1.2) interpretations, but would tend to suggest a mature hydrocarbon assemblage. The saturated paraffin-naphthene-to-aromatic ratio varies from 0.33 to 0.29, and the hydrocarbon-to-organic-carbon ratio ranges from 0.22 to 1.46 percent (average 0.8 percent), thus implying that thermally immature to moderately immature, soluble hydrocarbons are present (table 11).

The pyrolytic hydrocarbon yields (weight percent) in the Upper Cretaceous section range from 0.72 to 0.037 percent, while the pyrolytic hydrocarbon-to-organic-carbon (weight percent) ratios range from 60.5 to 14.8 percent for the intervals from 3,690 to 3,720 ft (1,125-1,134 m) and 4,690 to 4,700 ft (1,430-1,433 m), respectively (table 10). The pyrolytic hydrocarbon-to-organic-carbon ratio of 60.5 may reflect the high convertibility and greater hydrogen content of the dominant type of kerogen present in this interval, which is the amorphous-algal-marine variety, as well as the probable presence of mud-additive contaminants such as walnut husks. The value of 14.8 probably signifies the comparatively hydrogen-poor character of the more woody types of kerogen.

Lower Cretaceous (5,950-11,000 ft (1,814-3,353 m)).--Albian sedimentary rocks, 5,950-7,500 ft (1,813-2,286 m), are characterized by deposition in shallow-shelf and terrestrial environments. The rocks of Aptian and older(?) age, 7,500-11,000 ft (2,286-3,353 m), are dominantly continental but are intercalated with marine carbonates and sands.

The total organic carbon for the Aptian and Albian rocks, down to 8,900 ft, (2,713 m) averages 0.27 percent (by weight), and the total extractable hydrocarbons are very low, ranging from 9 to 32 ppm (by weight). The pyrolytic hydrocarbon yield and volatile-hydrocarbon

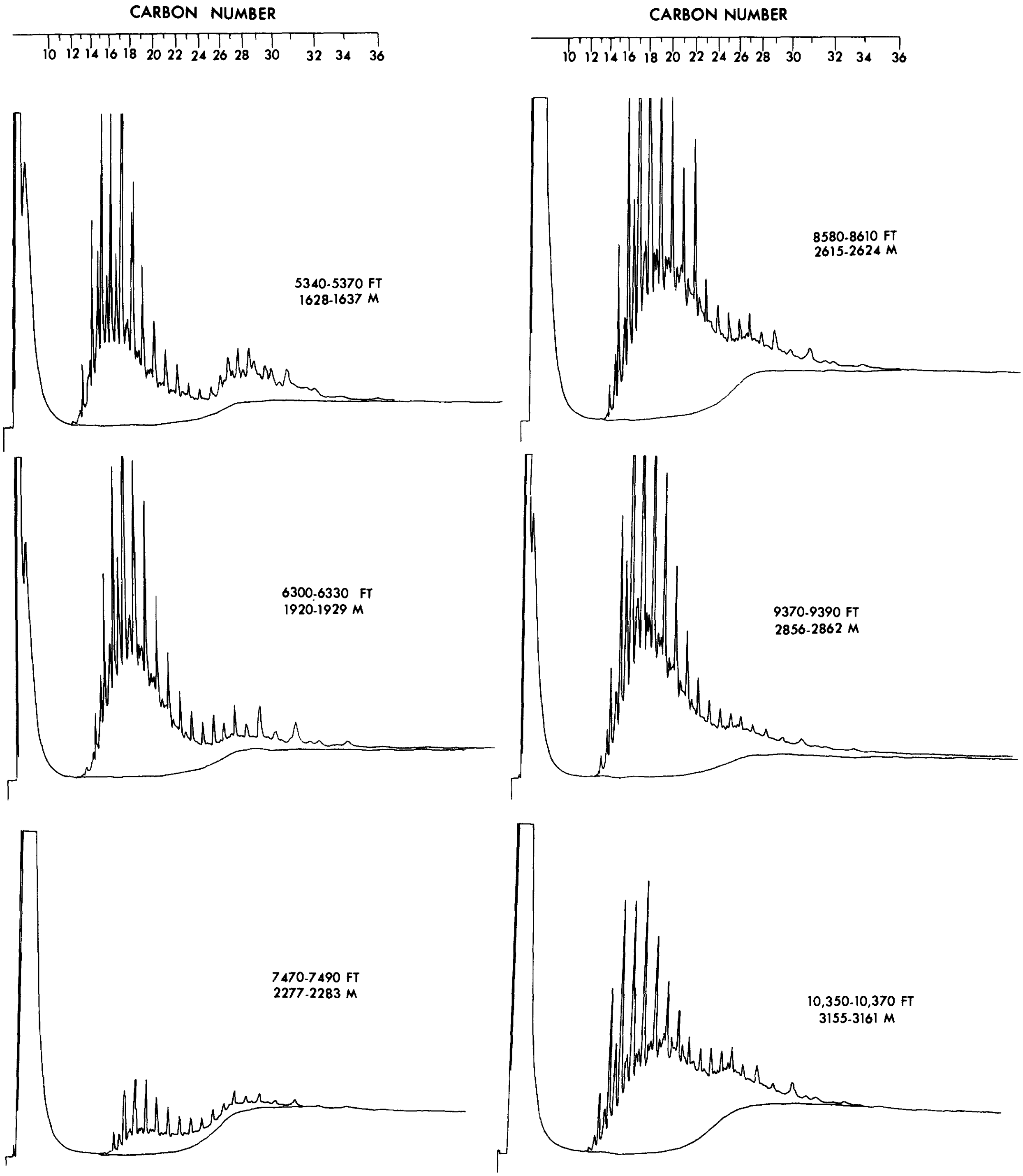


Figure 35.--Gas-chromatographic analyses of saturated paraffin-naphthene hydrocarbons of Upper Cretaceous and Lower Cretaceous rocks, COST No. GE-1 well.

content are in the range from 0.015 to 0.052 weight percent and from 19 to 85 ppm, respectively. Each of these organic-richness parameters indicates a poor source-rock quality for these Lower Cretaceous rocks (tables 10, 11).

The saturated paraffin-naphthene-to-aromatic ratio varies from 0.22 to 2.0, and the hydrocarbon-to-organic-carbon ratio ranges from 0.92 percent to 0.49 percent, respectively, for the Albian (7,470-7,490 ft (2,276-2,283 m)) and part of the Aptian (8,580 to 8,610 ft; (2,615 to 2,624 m)). The gas chromatograms of the resolved alkanes for this interval show an increase in the n-C_{24} to n-C_{32} hydrocarbons, which may be indicative of increasing amounts of terrestrial organic matter. The resolved normal alkanes are predominant over the isoprenoids pristane and phytane. With the exception of the 7,470- to 7,490-ft (2,276- to 2,283-m) interval in which the resolved alkanes are dominant, the unresolved complex mixture of branched and cyclic paraffins continues to be comparable with the resolved normal alkanes (fig. 35). Thermal-pyrolysis analyses indicate that the nonvolatile organic matter decomposed thermally at temperatures ranging from 968°F (520°C) at 6,220-6,230 ft (1,896-1,899 m) to 878°C (470°C) at 8,770-8,780 ft (2,673-2,676 m) (table 10). The reason for the seemingly inverse gradient is not known; however, the organically lean nature of these rocks may be a limiting factor in the pyrolysis method for evaluating maturity.

These Lower Cretaceous sedimentary units have organic-richness characteristics that are associated with very poor source beds for liquid-petroleum hydrocarbons and, in addition, probably have an immature to moderately immature time-temperature history. The oil-generating potential, or convertibility, of the kerogen in these Lower Cretaceous rocks has decreased primarily because of the apparent lower hydrogen content due to the more terrestrial nature of the kerogen. The probability is good that the geothermal history of this Lower Cretaceous interval has been insufficient to have generated and expulsed significant quantities of liquid-petroleum hydrocarbons or natural gas from the organic matter present in these sediments.

The 8,900- to 11,000-ft (2,712- to 3,353-m) section of the well has not been definitively dated. This interval has, however, been tentatively described as Lower Cretaceous (probably Valanginian to Aptian) by Poag and Hall (this volume). For the greater part, these rocks are fluvial and intertidal, grading into continental red beds. Occasional marine intercalations occur, however, indicated by carbonate beds.

At a depth of about 9,000 ft (2,743 m), the hydrocarbon-to-organic-carbon ratios increase from values of less than one in samples at depths shallower than 9,000 ft (2,743 m) to values of greater than one (6.2, 1.6) in samples below that level. In similar fashion, the CPI decreases from 1.5 to 1.1, the saturated-to-aromatic-hydrocarbon ratio increases from less than one to greater than one, and the proportion of volatile hydrocarbons in the total pyrolytic hydrocarbon yield increases from 0.1 to 0.2, all over the same depth interval (tables 10, 11). These measurements all suggest that if rocks containing a sufficient amount of hydrogen-rich organic matter had been present in the section below 9,000 ft (2,743 m), they might have generated petroleum hydrocarbons. The organic carbon content (weight percent) for the rocks deeper than 9,000 ft (2,743 m) is very low, generally less than 0.1 percent by weight, with total hydrocarbons averaging about 5.0 ppm. The interval from 9,600 to 10,800 ft (2,926-3,292 m) also shows high relative contents of amorphous kerogen; but, except for one sample, this increased relative percentage of apparently hydrogen-rich kerogen types is not reflected by increased pyrolytic-hydrocarbon-to-organic-carbon ratios.

Because of the very organic-lean nature of these sediments, very small differences in concentrations can cause significant changes in the value of a given ratio; therefore, any interpretation based on such ratios must take this factor into consideration. These probable Lower Cretaceous rocks are believed to have very little or no potential as liquid-petroleum or gas source rocks because of inadequate amounts of organic matter.

Comparison of Geochemical Measurements and the Possible Effects of Mud Additives on Source-Rock Interpretation.--Figure 36 shows a comparison between the COST No. GE-1 well analyses performed by the contract-service research company, Geochem Laboratories, Inc., and similar analyses carried out by the USGS. The parameters that were compared are the total extractables (ppm), paraffin-naphthene hydrocarbons (ppm), aromatic hydrocarbons (ppm), eluted NSO's (ppm), total organic carbon (weight percent), and total-hydrocarbon-to-total-extractables, paraffin-naphthene-to-total-extract, total-hydrocarbon-to-total-organic-carbon, and paraffin-to-aromatic ratios.

Good agreement exists between the analytical values reported by the USGS and those reported by Geochem Laboratories, Inc., in terms of "numerical tracking;" that is, at a given sample depth, when one value is high, both analyses are high, and, conversely, when a value is low, both analyses are low. In terms of absolute quantitative recoveries, the USGS values are consistently lower than those reported by Geochem Laboratories, Inc., but are relatively close in numerical value, as indicated by the paraffin-naphthene, aromatic hydrocarbons, eluted NSO's, and total hydrocarbon-to-total-organic-carbon, total-hydrocarbon-to-total-extract, and paraffin-naphthene-to-total-extract ratios. A similar relationship exists for the total-organic-carbon measure-

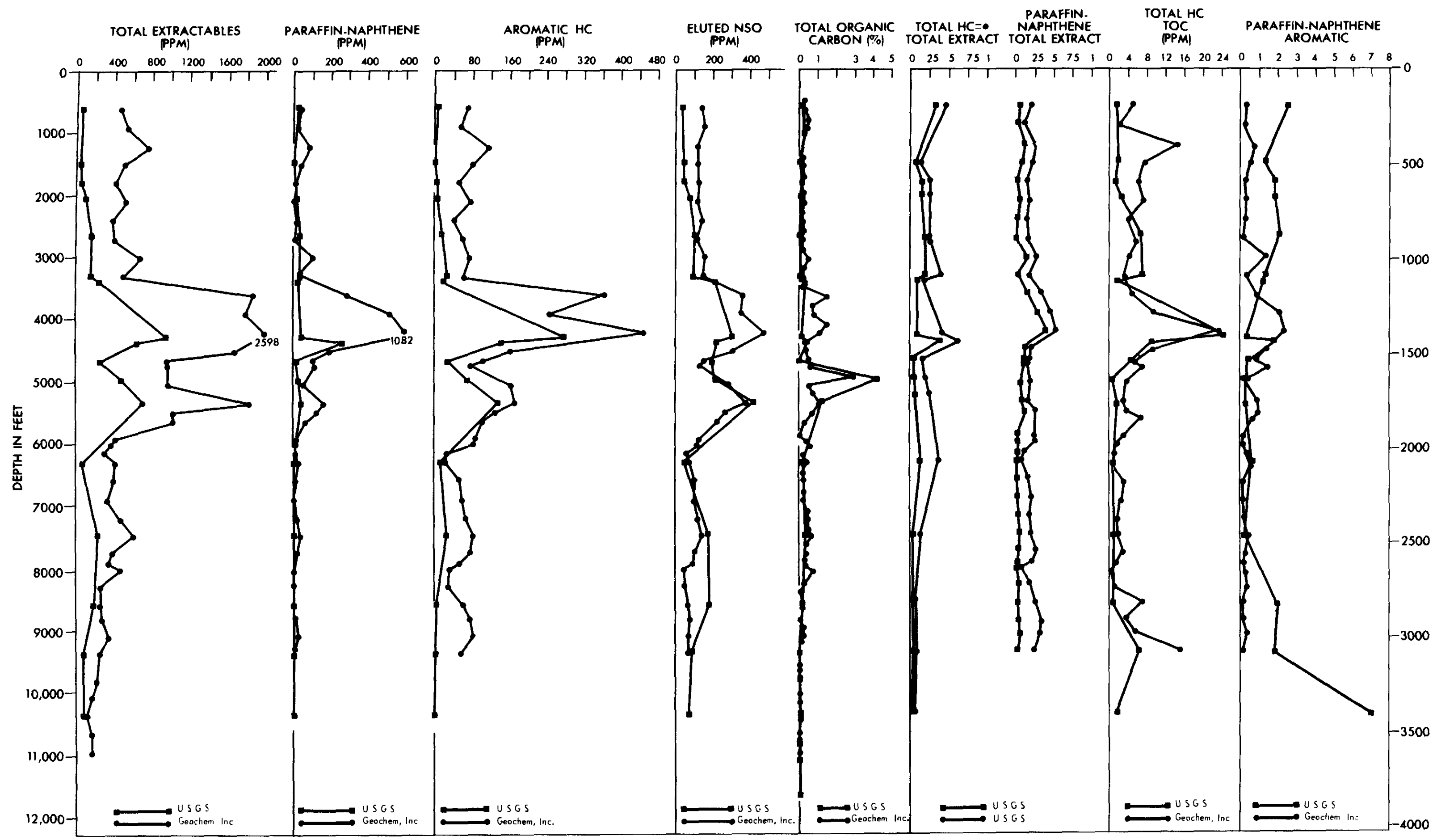


Figure 36.--Summary and comparison of organic-richness analyses on the C_{15}+ hydrocarbon extractables of samples from the COST No. GE-1 well. USGS data are shown by crosses, whereas Geochem Laboratories, Inc., (1977) data are shown as circles.

ments: the USGS values are slightly less than, but of the same order of magnitude as, those reported by Geochem Laboratories, Inc. The largest spread in the analytical determinations occurs in the interval from 3,600 to 5,400 ft (1,097-1,646 m), where the total extractable yields differ by a factor of three. The saturated paraffin-naphthene-to-aromatic ratios obtained by the USGS are consistently higher than those from Geochem Laboratories, Inc., as are the NSO values for the interval from 4,500 to 10,200 ft (1,372-3,109 m). The total extractable hydrocarbon values reported by the USGS are generally less than those of Geochem Laboratories, Inc., and may be the result of the difference between sample splits and method of storage (canned for Geochem Laboratories, Inc., and bagged for USGS). In general, the quantitative analytical differences are relatively small, with the possible exception of source-rock richness for the interval from 3,600 to 5,400 ft (1,097-1,646 m).

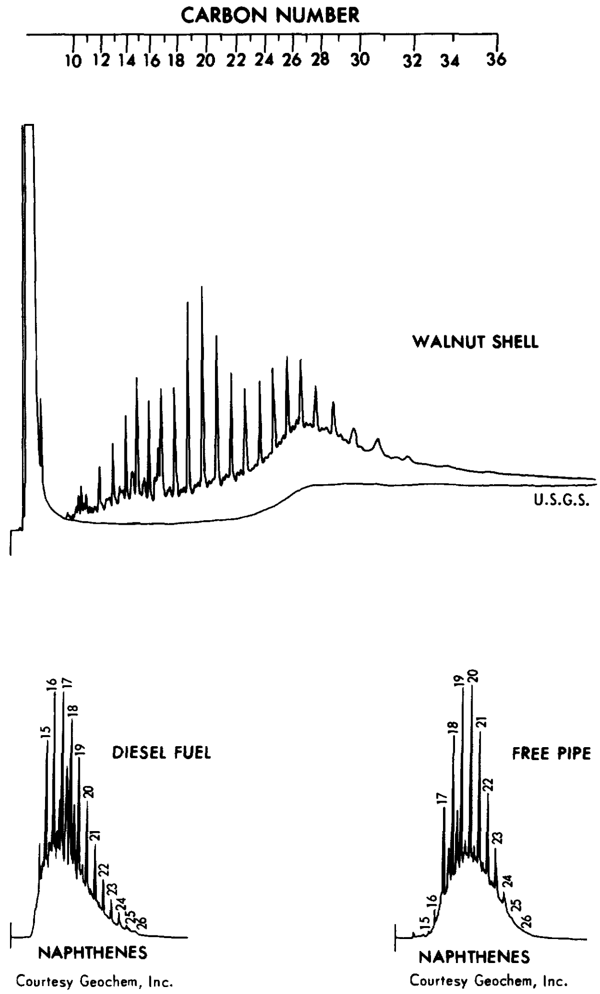


Figure 37.--Gas-chromatographic analyses of additives to the mud drilling system, COST No. GE-1 well. Analyses performed by Geochem Laboratories, Inc.

The possible effect that mud additives may have on the extractable hydrocarbon analyses and the subsequent source-rock interpretation must be given ample consideration, especially for the middle Tertiary to Lower Cretaceous interval from approximately 2,000 to 6,300 ft (600-1,900 m). Gas chromatograms of the saturated paraffin-naphthene hydrocarbons for such additives as IMCO "free pipe," stained and crushed walnut husks, and diesel fuel (IMCO Services) are shown in figure 37. Seven gas chromatograms were made (fig. 38) of the saturated paraffin-naphthene hydrocarbon fractions of well-cutting samples from 2,040 to 6,300 ft (622-1,929 m), in which no attempt was made to separate the "rock chips" (Tyler 10 to 20 mesh) from the mica, fine-clay fractions, and crushed walnut husks. The gas chromatograms of the saturated paraffin-naphthene hydrocarbons in these unfractionated sediment samples show significant differences when compared to the saturated-hydrocarbon gas chromatograms of the fractionated samples that are composed only of "rock chips." The gas chromatograms of the saturated hydrocarbons of the fractionated samples are shown in figures 33, 34, and 35. The most apparent difference in the gas chromatograms is the presence of higher-boiling-point resolved normal alkanes (C_{24} to C_{32}) in the unfractionated samples as compared with the predominance of a restricted range of the major components of resolved normal alkanes (C_{15} to C_{24}) in the fractionated "rock-chip" samples. Because these sediment samples are predominantly marine calcareous shales deposited in an outer-shelf environment with no nearby source of terrigenous-plant-wax hydrocarbons, the longer-chain normal aliphatic hydrocarbons (C_{24} to C_{32}) present in this interval may be, in part, derived from the lipids of the walnut husks, as well as from a petroleum-derived mud additive.

In the fractionated samples containing only the "rock chips," the restricted range and the continued comparability of the unresolved branch and cyclic paraffins to the resolved aliphatic compounds may be, in part, the result of the liquid-hydrocarbon mud additives (free pipe and diesel fuel) adsorbed on the "rock-chip," cutting samples. Because of the similarity in molecular composition and restricted range of the dominant resolved aliphatics (C_{15} to C_{24}) of the mud additives to both the unfractionated and fractionated well-cutting samples, it can be inferred that the mud additives IMCO "free pipe" and possibly diesel fuel may act to mask, at least partially, the indigenous saturated paraffin-naphthene source-rock character of the middle Tertiary to Lower Cretaceous sediments.

The preliminary thermal-pyrolysis analyses of unwashed, unpicked drill cuttings from the COST No. GE-1 well indicate the presence of sedimentary rocks which are generally low in organic matter content, except in the interval

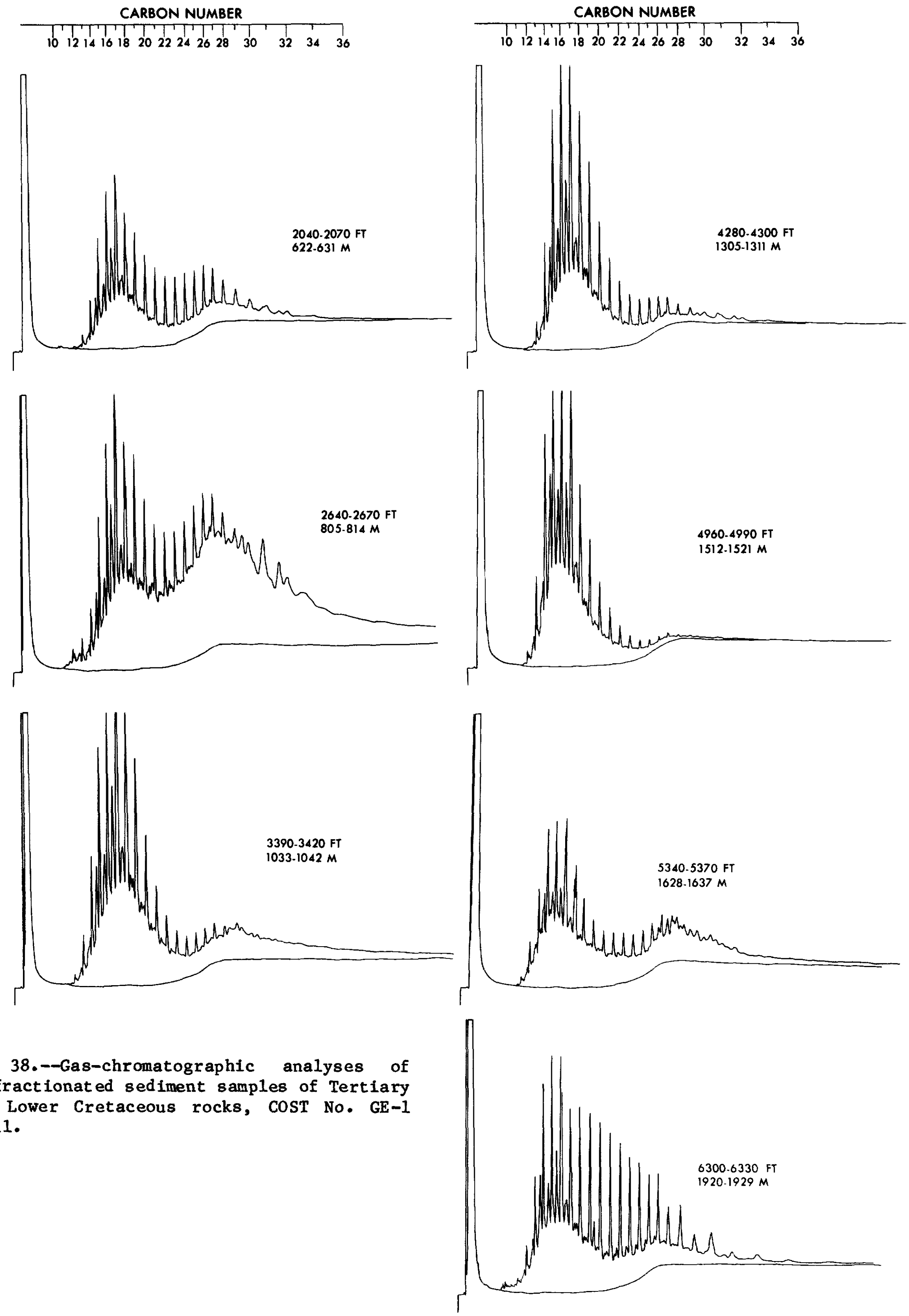


Figure 38.--Gas-chromatographic analyses of unfractionated sediment samples of Tertiary to Lower Cretaceous rocks, COST No. GE-1 well.

from 2,780 to 5,210 ft (847-1,588 m), which is believed to be contaminated by organic substances added to the drilling mud.

Determinations of organic carbon content and pyrolytic hydrocarbon yield for the unwashed and unpicked samples from the COST No. GE-1 well are reported in table 10. These preliminary analyses suggest that at least some of the samples contain large amount of nonindigenous organic matter. In particular, about half of each sample from the intervals 2,780-2,820 ft (847-860 m) and 5,200-5,210 ft (1,585-1,588 m) consisted of seemingly tar-stained, brown, angular fragments which were later determined to be walnut husks. Excluding those samples in the interval from 2,780 to 5,210 ft (847-1,588 m) that were believed to be contaminated, only one sample, at 5,710-5,720 ft (1,740-1,743 m), contained sufficient organic matter (0.63 percent organic carbon, 0.14 percent total pyrolytic hydrocarbon yield) to be considered even marginally adequate as a potential or possible petroleum source rock.

Within the 4,180- to 4,190-ft (1,274- to 1,277-m) interval, rocks with marginally adequate petroleum source-rock capability may be present. If the organic carbon contents and the pyrolysis characteristics of this interval are due primarily to the indigenous solid organic matter, then some rocks within this interval may contain a sufficient (1.15 percent organic carbon) quantity of hydrogen-rich (pyrolytic-hydrocarbon-to-organic-carbon ratio of 33 percent) organic matter to be considered as potential source rocks of petroleum (table 10).

The apparent degree of thermal maturity based on the results given in table 10 is higher than would be expected considering the stratigraphic ages and burial depths of the samples taken from less than 800-ft (1,768-m) depth. This maturity is indicated by the relatively high proportion of volatile hydrocarbons in the total pyrolytic hydrocarbon yield and by temperatures of maximum pyrolysis yield in the range from 896^{o} to 932^{o}F (480^{o}-500^{o}C). Rather than indicating only maturity, it is very possible that the relatively high contents of volatile hydrocarbons represent low levels of drilling-mud contamination, especially for shallow depths less than 5,800 ft (1,768 m) in the COST No. GE-1 well. The temperature of maximum pyrolysis yield probably is unreliable as an indicator of thermal maturity for these samples because they have low organic carbon content and have been subjected to drilling-mud contamination.

Those stratigraphic units from approximately 6,000 to 13,200 ft (1,800-4,000 m), which contain much less than 0.6 percent organic carbon and less than 0.14 percent total pyrolytic hydrocarbon yield, are believed to be inadequate for potential or possible petroleum source rocks on the basis of insufficient organic-matter content. The effects of drilling-mud additives on the deeper strat-igraphic samples appear to be less pronounced because of the more consistent agreement between source-rock parameters; therefore, a clearer assessment may be made of the source-rock potential of the interval from 6,000 to 13,200 ft (1,800-4,000 m).

Integrated discussion of USGS geochemical analyses and measurements of the stable carbon isotopes, vitrinite, T.A.I., kerogen types, and light-hydrocarbon analyses.--In addition to the USGS studies, contract organic-geochemical data, performed for the COST Group and provided by the Conservation Division, Atlantic Resource Evaluation Office, USGS, Washington, D.C., are reported. The contractual organic-geochemical analyses reported here were carried out by Geochem Laboratories, Inc. (1977); vitrinite and T.A.I. studies, by Core Laboratories, Inc. (1977); stable-carbon-isotope analyses, by J. G. Erdman, Phillips Petroleum Company (written commun., 1978); and light-hydrocarbon analyses by K. F. Thompson, Atlantic Richfield Company, (written commun., 1977). Although the above-listed geochemical analyses were not performed in laboratories of the USGS, the interpretations of the data that are expressed here are those of the USGS.

Properties sensitive to the type of organic matter--visual kerogen abundance, pyrolytic-hydrocarbon-to-organic-carbon ratio, and stable-carbon-isotope ratio--are summarized in figure 39. In addition, those properties sensitive to the maturity of the organic matter include vitrinite-reflectance data, volatile-pyrolytic-hydrocarbon ratios, kerogen-maturation data, and CPI indices, which are summarized in figure 40.

The C_1 to C_7 hydrocarbons occur in very small amounts, usually less than 200 ppm, in the 600- to 2,800 ft (180- to 850-m) interval of the Tertiary, indicating poor source quality (richness) and thermally immature, non-generative conditions. The normal C_4 (butane) -to-normal-C_7 (heptane) ratio (fig. 41) is less than unity and may suggest diesel contamination (K. F. Thompson, written commun., 1977) throughout this interval, whereas the kerogen-color maturation rank suggests the organic matter to be thermally immature and capable of producing only biogenic methane. Vitrinite-reflectance values average about 0.2 and are consistent with an interpretation of thermal immaturity. An inconsistency exists, however, between the apparent thermal immaturity of the organic matter inferred from the visual-kerogen-maturity rank, vitrinite-reflectance values, and low amounts of C_1 to C_7 hydrocarbons, in comparison with the apparently mature character of the gas chromatograms of the saturated paraffin-napthene hydrocarbon mixture (figs. 33-35, 40, 41).

The environment in which organic matter is generated by photosynthesis and the nature of the source of this organic matter can be characterized by stable-carbon-isotope ratios. The stable carbon-isotope ratio, $^{13}C/^{12}C$, for

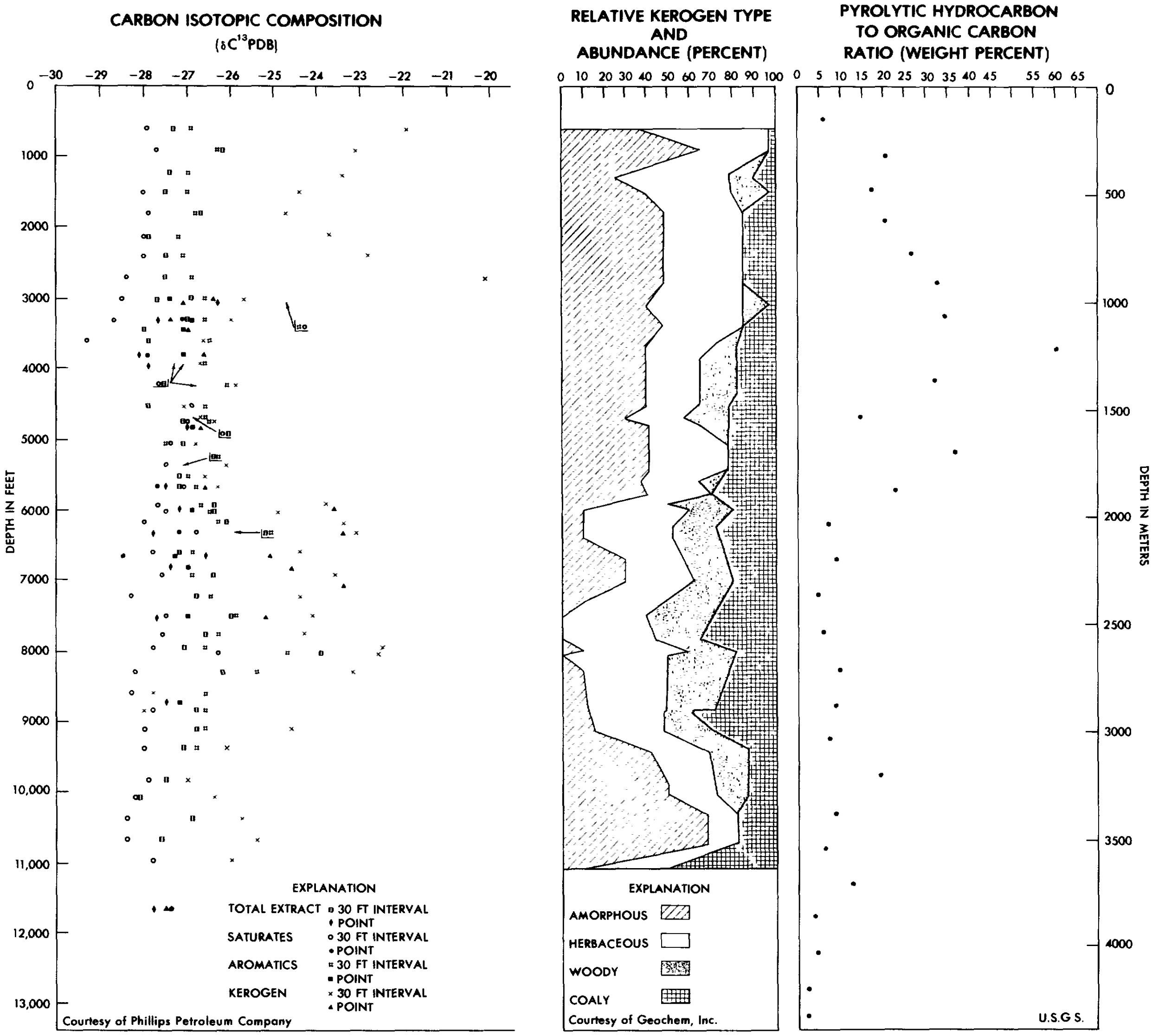


Figure 39.--Summary profiles of types of organic matter present in the COST No. GE-1 well. Relative-kerogen-type and abundance data from Geochem Laboratories, Inc., (1977); carbon isotopic composition provided by G. Erdman, Phillips Petroleum Corp. (written commun., 1978); pyrolytic hydrocarbon to organic carbon (weight percent) from G. C. Claypool, USGS (written commun., 1978).

the Tertiary interval, 600-2,800 ft, (183-853 m)), is shown in figure 39 in parts per thousand (permil) deviations from the $^{13}C/^{12}C$ ratio of the PDB carbonate standard. The stable-carbon-isotope analyses reported here were conducted by Phillips Petroleum Company (J. G. Erdman, written commun., 1977) on total hydrocarbon extracts, paraffin-naphthene, aromatic, and kerogen sample splits prepared by Geochem Laboratories, Inc. The well-cutting sample intervals analyzed are nearly identical with those reported by the USGS; and, therefore, a reasonably good comparison between USGS, Geochem Laboratories, Inc., and Phillips Petroleum Company data can be made.

A genetic relationship can be inferred from the spread (permil) between the kerogen (solvent-insoluble organic matter), total-extractable- (bitumen), saturated-paraffin-naphthene, and aromatic-hydrocarbon fractions. Theoretical considerations suggest that as the spread (permil) between fractions decreases, the potential increases for the extractable hydrocarbons to be genetically derived from the kerogen by thermal-chemical diagenesis. Conversely, when the spread (permil) increases, the

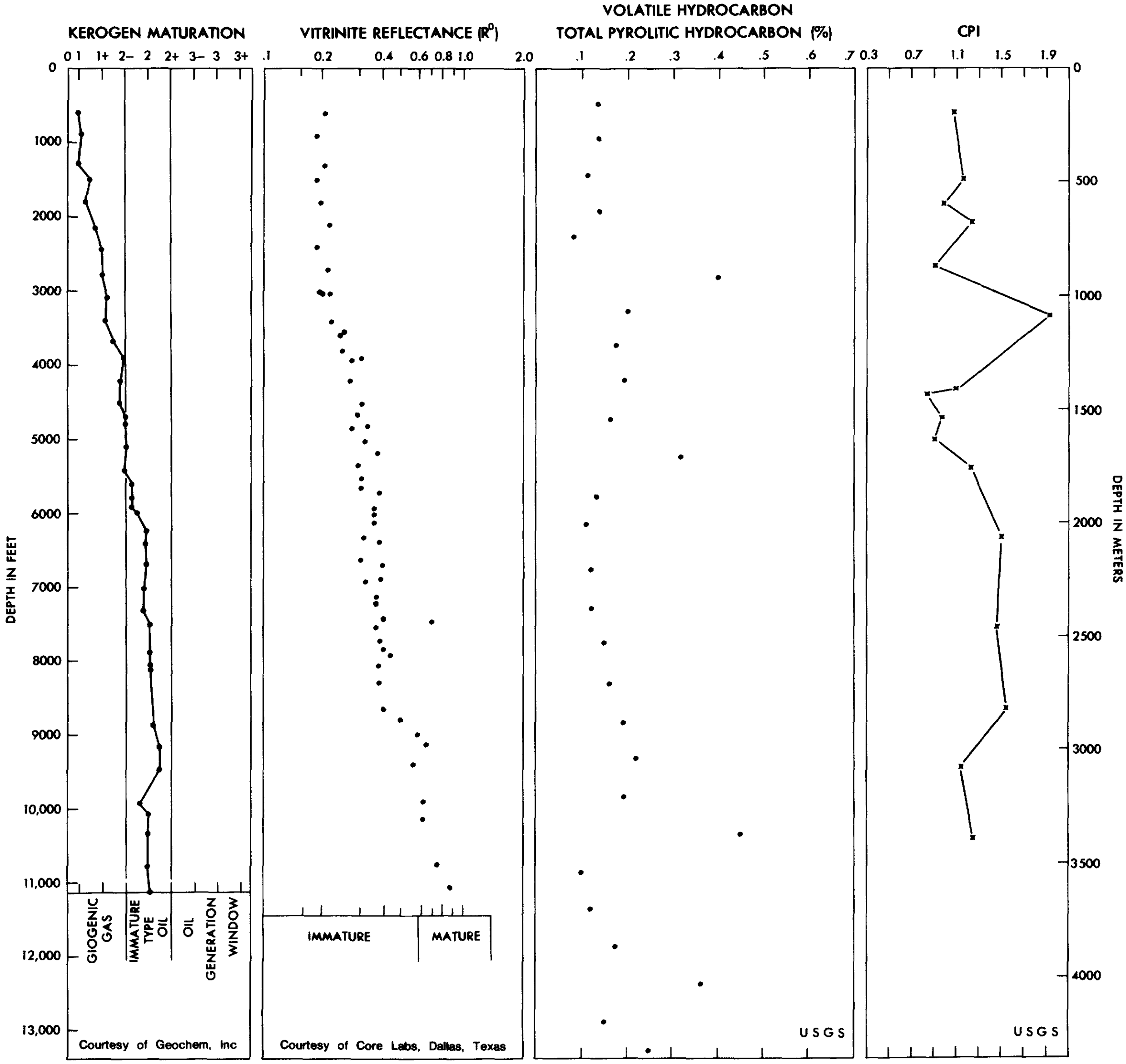


Figure 40.--Maturity profiles of organic matter in samples from the COST No. GE-1 well. Vitrinite-reflectance data (Core Laboratories, 1977); volatile-pyrolytic-hydrocarbon ratios (USGS); kerogen-maturation data (Geochem Laboratories, Inc., 1977); CPI values (Geochem Laboratories, Inc., 1977; and USGS). Where comparisons are shown, crosses identify USGS data and dots signify Geochem Laboratories, Inc., data.

potential decreases for the saturated paraffin-naphthene, aromatic and total-extractable hydrocarbons to be derived from the solid, solvent-insoluble organic matter. The stable-carbon-isotope values shown in figure 39 indicate a wide spread of 3-7 permil between the kerogen, the total extractables, the paraffin-naphthene, and the aromatic hydrocarbons for the interval from 600 to 2,800 ft (180-850 m). This would indicate that the saturated paraffin-naphthene, aromatic fractions, and total extractables are, for the greater part, genetically unrelated to the kerogen and, therefore, are not the product of in situ thermal-chemical diagenesis but most likely have a low-temperature biogenic, and possible anthropogenic, origin.

The Tertiary sequence from 2,800 to 3,570 ft (853-1,088 m) follows a geochemical pattern similar to that described for the overlying part of the Tertiary, with the noticeable exceptions of the increase in the C_5 to C_7 gasoline-range

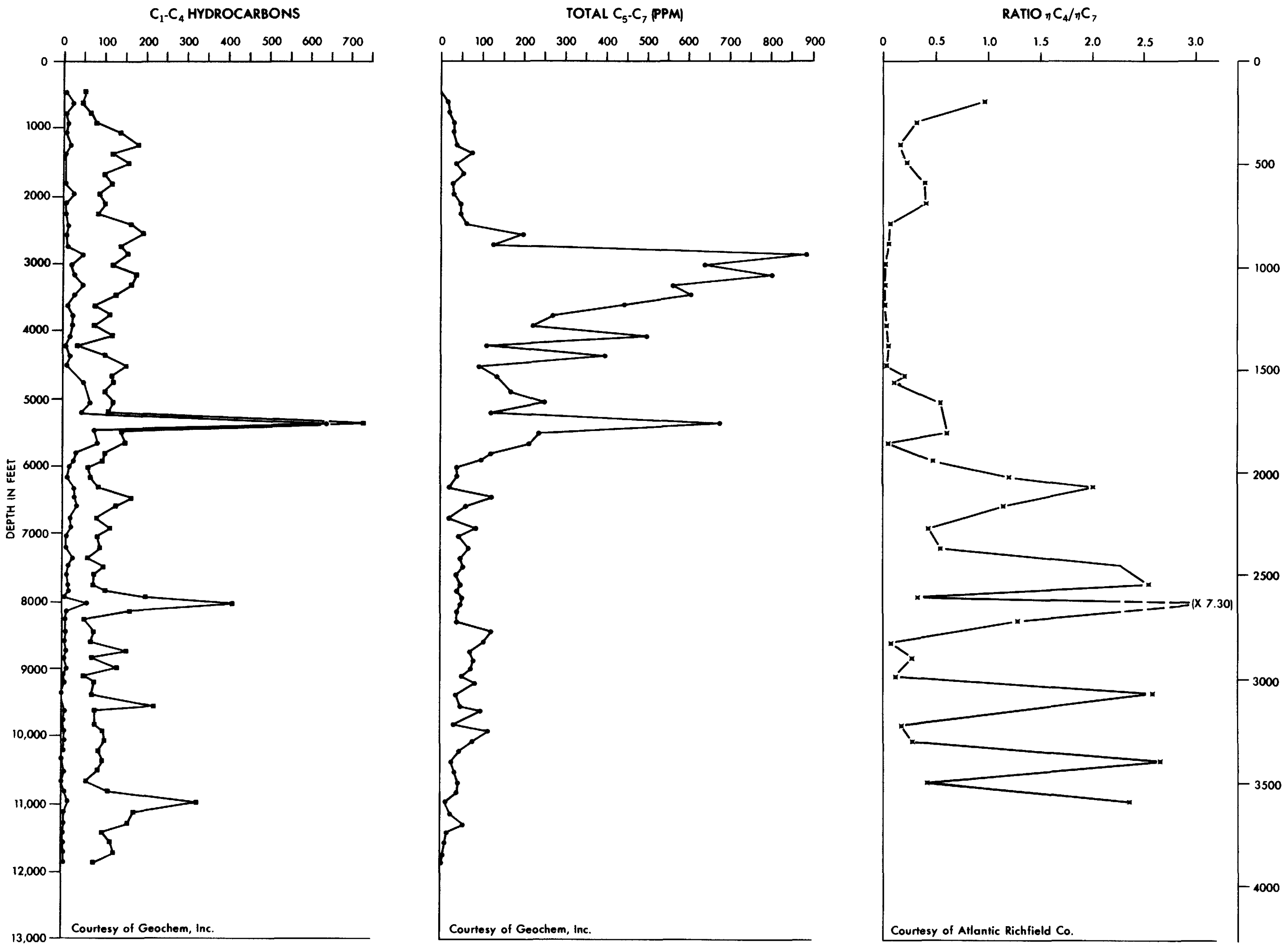


Figure 41.--Summary of light-hydrocarbon analyses of samples from the COST No. GE-1 well. Data from Geochem Laboratories, Inc. (1977), and Atlantic Richfield Co. (written commun., 1977).

hydrocarbons and a smaller spread between the $\delta^{13}C$ value of the kerogen and the extractable organic matter. These exceptions generally correlate with the depth at which the drilling operations encountered a loss in mud-fluid circulation. These parameters may reflect both the influence of drilling-mud additives and the indigenous nature of the extractable hydrocarbons.

The vitrinite-reflectance (R_o) values for the 3,570- to 4,800-ft (1,090- to 1,450-m) interval are in the immature range from 0.2 to 0.3 and are consistent with the kerogen-maturation rank of 1- to 2-, indicating that the solid organic matter in these Upper Cretaceous rocks probably has not experienced sufficient thermal alteration to form and expulse mature liquid-petroleum hydrocarbons (fig. 40). The spread of $^{13}C/^{12}C$ ratios between the kerogen-saturated-, aromatic-, and total-hydrocarbon extracts is about 2 permil, which tends to suggest that the kerogen and extractable hydrocarbons are probably, for the major part, genetically unrelated. To further amplify this point, the C_5 to C_7 gasoline-range hydrocarbons show a significant increase while the C_1 to C_4 light hydrocarbons are very low and the normal-butane-to-normal-heptane ratio is less than unity (fig. 41). This apparent inconsistency, in the proportions of the C_1 to C_4 and C_5 to C_7 hydrocarbon amounts, relative to the spread in the stable-isotope values between the kerogen and extractable hydrocarbons, suggests that these hydrocarbons were not generated totally _in situ_ by geothermal-maturation processes but rather may reflect the signature of hydrocarbons possibly related to mud additives.

In contrast to the much wider spread of about 2 permil for the $^{13}C/^{12}C$ ratio in the 3,570- to 4,800-ft (1,090- to 1,450-m) interval, a more narrow range (1 permil) exists for the 4,800- to 5,700-ft (1,463- to 1,737-m) interval between the kerogen, total-extractable, saturated, and aromatic hydrocarbons, which may indicate that the presence of liquid hydrocarbons is related, at least in part, to the kerogen. In addition, a comparatively reasonable and consistent agreement exists in the degree of increase between the total organic carbon, total extractables, total C_{15}+ hydrocarbons, total eluted NSO's, C_1 to C_4 content, and total C_5 to C_7. The kerogens of this Upper Cretaceous interval are composed of approximately 40 percent of the amorphous-algal-marine type and have a kerogen maturation rank of 2-. The R_o values are in the 0.35 range and imply immaturity. The saturated-hydrocarbon chromatograms continue to show maturation inconsistencies. However, because of the comparatively consistent agreement between the richness and type characteristics, a high probability exists that the extractable liquid hydrocarbons in this interval are, at least in part, indigenous and may be genetically related to the hydrogen-rich, amorphous-algal-marine kerogen (figs. 34, 35, 39).

The small amounts of C_1 to C_4 and C_5 to C_7 hydrocarbons present in the upper part of the Lower Cretaceous interval, 5,950-8,900 ft, (1,814-2,713 m) may suggest a relatively low time-temperature diagenetic history for these rocks, although the small increase in the C_1 to C_4 content (ppm) and a normal butane-to-normal-pentane ratio of about 7.0 at about 8,000 ft (2,450 m) may indicate that generation of traces of natural gas may have started. The R_o values are in the 0.40 to 0.45 range, while the kerogen-alteration rank occurs in the 2- to 2 range (figs. 40, 41).

The stable-carbon-isotope ratios for the part of the Lower Cretaceous interval from 5,950 to 8,900 ft (1,814-2,713 m) show a relatively wide spread in the $\delta^{13}C$ values between the kerogen-, saturated-, aromatic-, and total-hydrocarbon extracts that would suggest, first, that a thermal genetic relationship probably does not exist between the soluble hydrocarbons and the kerogen and, second, that a change is occurring in the type of kerogen. The type of kerogen present in these Lower Cretaceous rocks shows a significant trend towards smaller amounts of amorphous-algal-marine material and an increase in the relative abundances of herbaceous and woody forms (fig. 39).

The various fractions of the organic matter in sedimentary rocks of probable Early Cretaceous age below 8,900 ft (2,700 m) have a somewhat narrower range of $\delta^{13}C$ values. In some of these samples, carbon-isotope ratios might support the interpretation of a general relationship between the hydrocarbons and the solid organic matter. Each of the maturity indicators shown in figure 40 indicates similar trends that are generally consistent with a transition from immature to marginally mature with respect to generation of petroleum. However, because the organic matter content is so low, these rocks are inadequate as potential or possible source rocks.

Summary and Conclusions

The organic geochemical parameters of source-rock richness and maturity suggest that the Tertiary interval from 390 to 3,570 ft (119-1,088 m) probably contains very low concentrations of indigenous hydrocarbons of biogenic origin that are not related to a thermal-chemical history. In the lower part of this interval, the influence of the drilling-mud additives is believed to have significantly influenced the C_{15}+ extractable-hydrocarbon signatures of maturity and richness to the point that an interpretation of source-rock potential based on the extractable-hydrocarbon character alone is misleading.

The Upper Cretaceous interval from 3,570 to 5,950 ft (1,088-1,814 m) contains the zone of highest organic carbon (average 1.24 weight percent), total extractables (981 ppm), paraffin-naphthenes (268 ppm), aromatics (278 ppm), and NSO's (416 ppm) present in COST No. GE-1. Although the influence of mud additives on the extractable hydrocarbons is still present and significant in the zone from 3,570 to 4,800 ft (1,090-1,460 m), Upper Cretaceous sedimentary units from 4,800 to 5,700 ft (1,469-1,740 m) show relatively consistent agreement between the source-rock parameters, lending support to the view that the extractable C_{15}+ hydrocarbons in this interval are probably not all the products of contamination. They may be, at least in part, indigenous and may possibly be genetically related to the hydrogen-rich amorphous-marine kerogens. The kerogen-maturation rank of 2- and R_o values (0.35) still, however, imply thermal immaturity. Interpretation of maturity based on relative concentrations of extractable or volatile hydrocarbons is susceptible to interference because of the presence of mud additives or other sources of nonindigenous hydrocarbons. Such interference appears to be a significant factor that affects analyses of sediments from most of the upper half of the COST No. GE-1 well. Thus, high ratios of volatile to pyrolytic hydrocarbons, and extractable hydrocarbons to organic carbon at depths of 5,300 ft (1,615 m) and shallower may indicate contamination.

Visual-kerogen analyses show high relative contents of hydrogen-rich, "oil-prone" kerogen types in the upper 5,800 ft (1,770 m) of the section. This is also indicated by pyrolytic-hydrocarbon-to-organic-carbon ratios generally greater than 20 percent in this same interval.

The Lower Cretaceous sediments from 5,950 to 8,900 ft (1,814-2,713 m) show an increase in hydrogen-deficient types of kerogens. This increase correlates with pyrolytic-hydrocarbon-to-organic-carbon ratios of 10 percent or less and, in this same interval, with geochemical characteristics that are associated with very poor source beds for liquid-petroleum hydrocarbons. These rocks appear to have an immature to moderately immature time-temperature history that probably has been inadequate to have generated expulsed-liquid-or gaseous-petroleum hydrocarbons.

Vitrinite-reflectance and kerogen-color-alteration values apparently were not affected severely by the contamination problem. Both of these maturity indicators exhibit fairly gradual increase with increasing depth of burial in the well. The onset of petroleum-hydrocarbon generation at geologically significant rates is believed to coincide with R_o values of 0.6 percent and kerogen-color-alteration values of 2+. These values are reached or approached in samples of the COST No. GE-1 well at depths of about 9,000 ft (2,750 m).

The interval from 8,900 to 10,370 ft (2,710-3,160 m) (probable Lower Cretaceous) contains sediments which for the greater part are fluvial to intertidal grading to continental red beds; because of their very low organic-matter content, they possess little or no potential as petroleum source rocks.

GEOPHYSICAL STUDIES

R. C. Anderson and D. J. Taylor

Velocity information obtained from the interval transit-time log of the COST No. GE-1 well was used to generate synthetic seismograms and plots of vertical depth, average velocity, and root-mean-square (RMS) velocity versus two-way travel time. Manual digitizing of the well-log data was performed by visually averaging zones of constant-interval transit times, producing an irregularly sampled digital curve. Values from this curve were entered in a computerized synthetic-seismogram package, producing the results shown in figure 42. The program was restricted to velocity information only. Density data from the well were not incorporated into the construction of the synthetic seismogram because, in the majority of rock sequences, the reflection coefficient depends primarily on changes in velocity rather than in density.

The synthetic-seismogram program assumes a normal-incident, plane-wave model and computes the reflection coefficient as the ratio of the amplitude of the reflected wave to the amplitude of the normal-incident wave. The reflection coefficient is computed according to the formula:

$$RC = \frac{V_{i+1} - V_i}{V_{i+1} + V_i}$$

where V represents wave velocity. The subscripts "i" and "i + 1" denote the rock layer above and below the reflecting interface respectively. To complete the synthetic seismogram, an approximation of the Earth's impulse response is then applied to the reflection coefficients. The resulting seismogram can be used to correlate geologic intervals to their corresponding expression on a seismic trace.

Figure 42 shows three synthetic seismograms obtained by applying three bandpass wavelets with different frequency ranges. The bandpass wavelet represents an approximation of the Earth's impulse response to a seismic wave. Bandpass wavelets of 8-30 and 8-40 Hz were assumed to best match the typical frequency range of normally processed marine seismic data (fig. 42). The 8-70 Hz synthetic seismogram (fig. 42) shows the additional resolution that might be obtained with further processing of the seismic data.

The interval-velocity curve in figure 42 shows the velocity distribution as a function of time plotted linearly, and can be used to correlate stratigraphic changes with reflections.

Velocity informaton from the interval transit-time log is also useful for converting seismic travel times to depth. The relationship between two-way travel time and vertical depth is shown plotted in figure 43. From this information, three types of velocity functions can be generated: interval velocity (already shown in fig. 42), average velocity, and RMS velocity. These velocities have been tabulated in table 12 for every 164 ft (50 m) of vertical depth. The interval velocity is shown in figure 42 as a function of two-way travel time plotted linearly. The average velocity curve is shown by the heavy line in figure 44. The average velocity can be used in seismic data processing for time-to-depth conversion and for migration.

Finally, the RMS velocity, V_{RMS}, is a good approximation to stacking velocity in areas of gentle regional dip. The stacking velocity is used for correcting the hyperbolic moveout of common-depth-point (CDP) seismic-data traces prior to stacking. This velocity function is given by

$$V_{RMS} = \frac{\sum_{i=1}^{N} V_i \, \Delta Z^{1/2}}{\sum_{i=1}^{N} \frac{\Delta Z}{V_i}}$$

and is shown in figure 44. The V_{RMS} velocity is useful for checking the accuracy of stacking velocities that have been derived strictly from the seismic data.

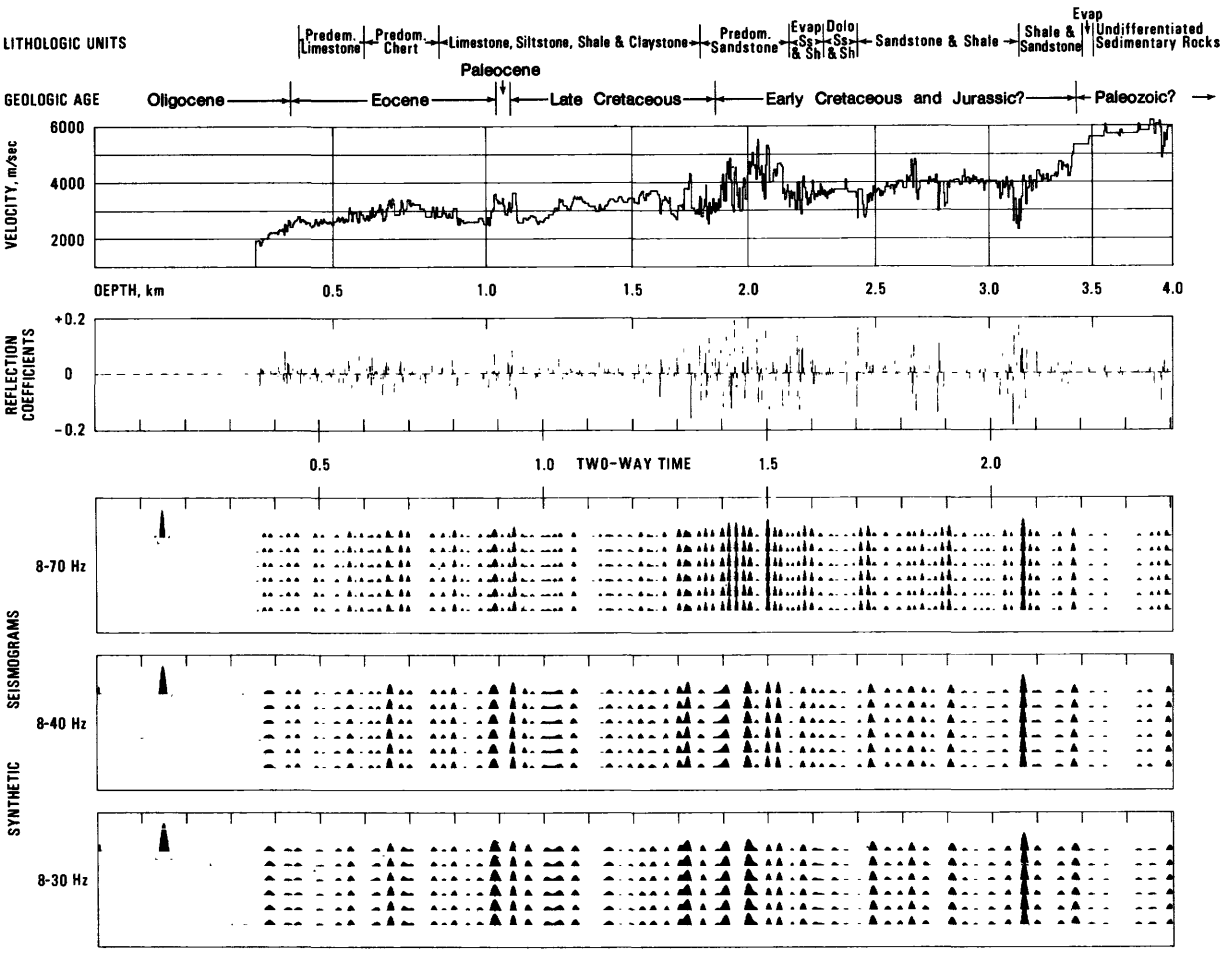


Figure 42.--One-dimensional synthetic seismograms derived from the interval transit-time curve of the COST No. GE-1 well. All data are displayed in linear time.

Table 12.--Velocity data from the COST No. GE-1 well

Depth		Two-way travel time (seconds)	Interval velocity (m/s)	Average velocity (m/s)	RMS velocity (m/s)
Feet	Meters				
951	290	0.359	1,954	1,616	1,616
984	300	0.369	1,792	1,625	1,625
1,148	350	0.416	2,309	1,684	1,693
1,312	400	0.456	2,796	1,756	1,781
1,476	450	0.494	2,746	1,822	1,858
1,640	500	0.532	2,540	1,879	1,923
1,804	550	0.569	3,208	1,933	1,984
1,968	600	0.604	2,697	1,987	2,046
2,133	650	0.638	3,048	2,037	2,103
2,297	700	0.670	2,903	2,088	2,162
2,461	750	0.703	3,243	2,134	2,214
2,625	800	0.734	3,110	2,180	2,266
2,789	850	0.768	2,822	2,213	2,299
2,953	900	0.802	3,110	2,242	2,328
3,116	950	0.839	2,605	2,263	2,346
3,281	1,000	0.877	2,771	2,279	2,359
3,445	1,050	0.909	3,243	2,309	2,392
3,609	1,100	0.940	3,672	2,340	2,425
3,773	1,150	0.977	2,849	2,354	2,437
3,937	1,200	1.014	2,876	2,367	2,448
4,101	1,250	1.046	3,208	2,389	2,470
4,265	1,300	1.077	3,503	2,414	2,496
4,429	1,350	1.106	3,175	2,439	2,523
4,593	1,400	1.139	3,079	2,458	2,542
4,757	1,450	1.169	3,349	2,481	2,565
4,921	1,500	1.198	3,464	2,503	2,589
5,085	1,550	1.227	3,387	2,526	2,613
5,249	1,600	1.254	3,717	2,550	2,640
5,413	1,650	1.284	3,503	2,570	2,660
5,577	1,700	1.317	3,810	2,581	2,670
5,741	1,750	1.345	3,048	2,600	2,692
5,905	1,800	1.377	2,650	2,612	2,703
6,070	1,850	1.408	4,618	2,629	2,721
6,234	1,900	1.432	4,549	2,654	2,751
6,398	1,950	1.460	4,763	2,672	2,772
6,562	2,000	1.481	5,080	2,701	2,808
6,726	2,050	1.503	5,347	2,727	2,841
6,890	2,100	1.526	4,689	2,752	2,871
7,054	2,150	1.551	3,277	2,772	2,895
7,218	2,200	1.580	4,762	2,784	2,905
7,382	2,250	1.608	3,386	2,799	2,920
7,546	2,300	1.635	3,349	2,813	2,934
7,710	2,350	1.662	3,763	2,827	2,948
7,874	2,400	1.689	3,674	2,842	2,962
8,038	2,450	1.717	3,208	2,854	2,973
8,202	2,500	1.747	3,672	2,863	2,982
8,366	2,550	1.773	3,858	2,875	2,994
8,530	2,600	1.799	4,064	2,890	3,009
8,694	2,650	1.824	4,996	2,906	3,025
8,858	2,700	1.848	4,064	2,922	3,043
9,022	2,750	1.872	4,118	2,937	3,059
9,186	2,800	1.898	3,242	2,942	3,072
9,350	2,850	1.924	4,118	2,962	3,084
9,514	2,900	1.948	4,175	2,976	3,099
9,678	2,950	1.972	4,064	2,991	3,115
9,843	3,000	1.997	4,064	3,003	3,127
10,006	3,050	2.022	3,424	3,015	3,139
10,170	3,100	2.048	4,064	3,026	3,149
10,335	3,150	2.079	4,064	3,031	3,154
10,499	3,200	2.104	4,417	3,042	3,164
10,663	3,250	2.127	4,354	3,055	3,178
10,827	3,300	2.152	4,482	3,068	3,192
10,991	3,350	2.173	4,064	3,084	3,209
11,155	3,400	2.193	5,347	3,101	3,230
11,319	3,450	2.212	5,347	3,120	3,253
11,483	3,500	2.230	5,644	3,139	3,278
11,647	3,550	2.248	5,644	3,159	3,304
11,811	3,600	2.265	5,751	3,179	3,303
11,975	3,650	2.282	5,751	3,199	3,355
12,139	3,700	2.299	5,751	3,218	3,379
12,303	3,750	2.317	5,751	3,237	3,403
12,467	3,800	2.334	5,861	3,256	3,428
12,631	3,850	2.351	5,862	3,276	3,452
12,795	3,900	2.367	6,096	3,294	3,477
12,959	3,950	2.385	5,080	3,313	3,499
13,123	4,000	2.402	5,977	3,331	3,521

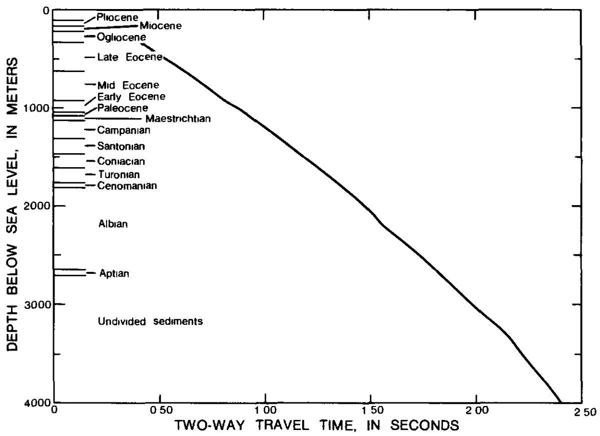


Figure 43.--Depth, measured from sea-level datum, versus two-way vertical travel time. Geologic age boundaries are approximate.

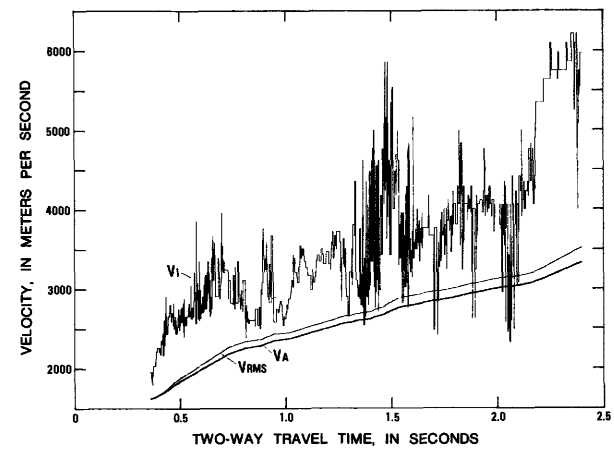


Figure 44.--Interval velocity, V_I; average velocity, V_A; and RMS velocity, V_{RMS}, cross-plotted against vertical two-way travel time. Light line is V_{RMS}.

STRUCTURE OF THE CONTINENTAL MARGIN NEAR THE COST NO. GE-1 DRILL SITE FROM A COMMON DEPTH-POINT SEISMIC-REFLECTION PROFILE

William P. Dillon, Charles K. Paull,
Alfred G. Dahl, and William C. Patterson

INTRODUCTION

A deep-penetration, CDP seismic profile has been recorded for the USGS along a track which passes through the site of the COST No. GE-1 well (fig. 2). The line, recorded under contract by Teledyne Exploration Company, is part of a grid of seismic profiles totalling 5,200 mi (8,400 km) that have been recorded south of Cape Hatteras in order to examine the structure, history, and resource potential of the Continental Margin. In addition to crossing the COST No. GE-1 location, the line crosses the Atlantic Slope Project (ASP) 3 and Deep Sea Drilling Project (DSDP) 390 drill sites on the outer Blake Plateau (fig. 45). The seaward end of the line, in the Blake-Bahama Basin, can be tied to the DSDP 391 drill site through other profiles of our grid. Thus, the profile affords one of the best opportunities on the United States eastern Continental Margin to correlate reflectors and sampled horizons along a profile from the shelf to the deep sea.

Older regional seismic-reflection profiles reported for the United States southeastern Continental Margin have been single-channel data, with limited penetration (Ewing and others, 1966; Emery and Zarudzki, 1967; Uchupi and Emery, 1967; Uchupi, 1970). CDP reflection data, which achieve deeper penetration, have been reported in more recent publications (Dillon and others, 1976; Dillon and Paull, 1978; Shipley and others, 1978; Buffler and others, 1978; Dillon and others, in press; Buffler and others, in press).

METHODS

The seismic source consisted of four 540-$in.^3$ (8,850-cm^3) airguns towed abreast, 13 ft (4 m) apart and at a depth of 26 ft (8 m) ± 10 percent. Firing pressure was 2,000 psi (13,800 kPa) ± 10 percent. The multichannel streamer cable was 2.2 mi (3.6 km) long and contained 48 hydrophone groups. The hydrophone-group spacing nearest the ship was 165 ft (50 m), and the far spacing was 330 ft (100 m). The streamer was towed 985 ft (300 m) behind the seismic source at a depth of 30 ft (10 m). A pass band of 8-124 Hz was applied during field recording on a Texas Instruments DFS IV system. Shot-point interval was 165 ft (50 m) for most of the line. However, the shoreward part of the profile (shelf and slope at water depths less than about 1.0 s) was shot at 330-ft (100-m) intervals. This was necessary because of the impossibility of steaming slow enough to fire at 165-ft (50-m) intervals while maintaining a straight cable in the strong flow of the Gulf Stream. The seaward end of the line, at water depths of more than about 3.6 s, was also shot at 330-ft (100-m) intervals in order to allow sufficient recording time between shots.

The line was processed by Teledyne Exploration Co. in their Houston processing center. The data were demultiplexed, and parameter selection (such as filter tests, deconvolution tests, scaling tests, and so forth) were completed. Then basic processing was applied, including binary-gain recovery, spherical-divergence correction, predictive deconvolution, velocity analysis at 2-mi (3-km) intervals, normal-moveout correction, 48-fold CDP stack, post-stack time-variant deconvolution, and time-variant filtering and scaling. The parts of the line with 330-ft (100-m) shot-point intervals were stacked 24-fold.

Special processing was applied to a 6-mi (10-km) section of the profile landward of the COST No. GE-1 well. For this part of the profile, continuous velocity analysis was performed by Teledyne. The USGS seismic processing center then applied multi-pass predictive deconvolution, a technique designed to attack individual pegleg or interbed multiples that interfere with primary events. Subsequently, both F-K migration and wave-equation (finite-difference) migration were used. All special processing was aimed at improving the signal-to-noise ratio in the region of basement reflections.

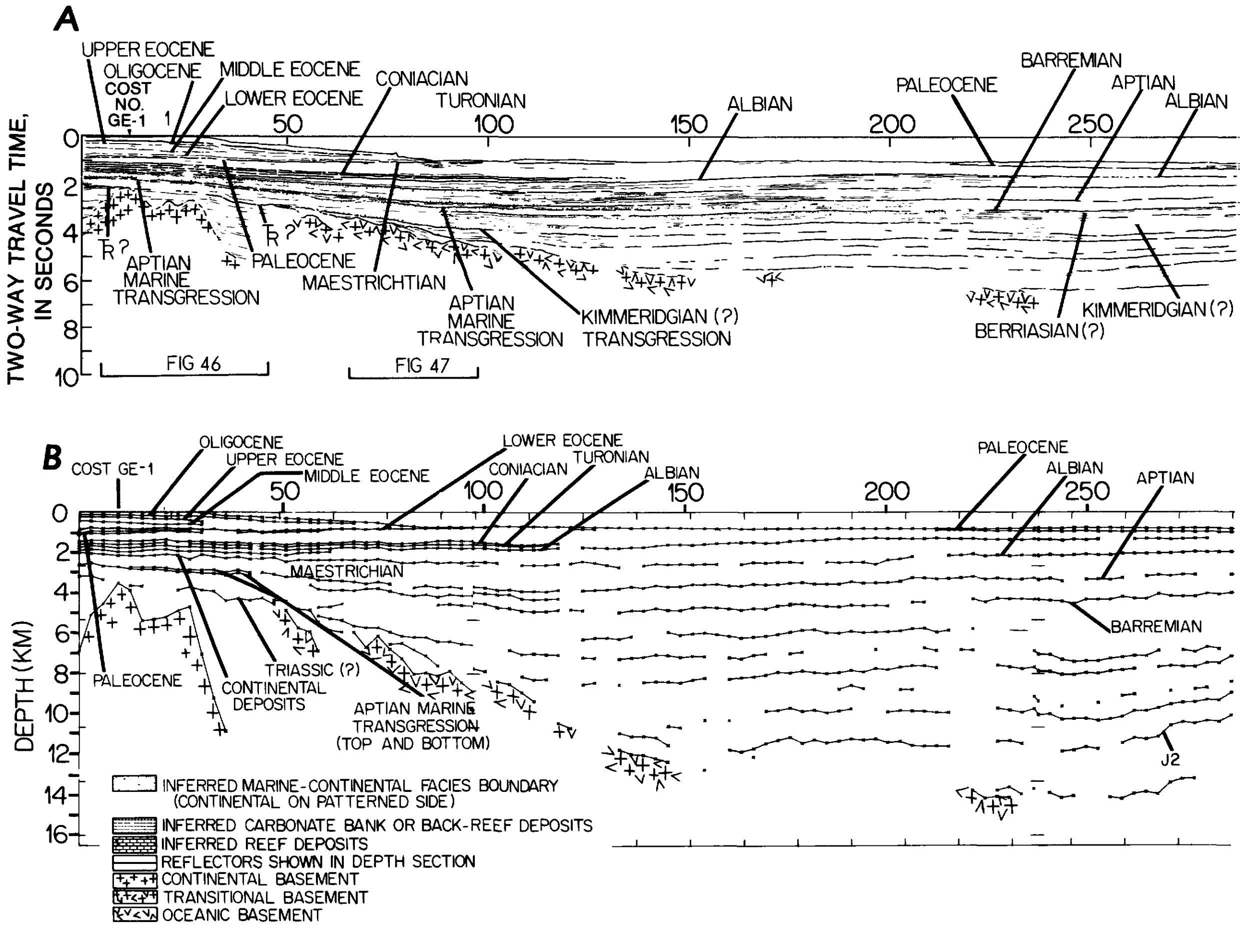


Figure 45.--Line-drawing interpretation and depth section calculated from the interpretation of seismic profile (location of profile shown in fig. 2). Heavy lines indicate reflectors used brackets beneath the profile. B, Depth section.

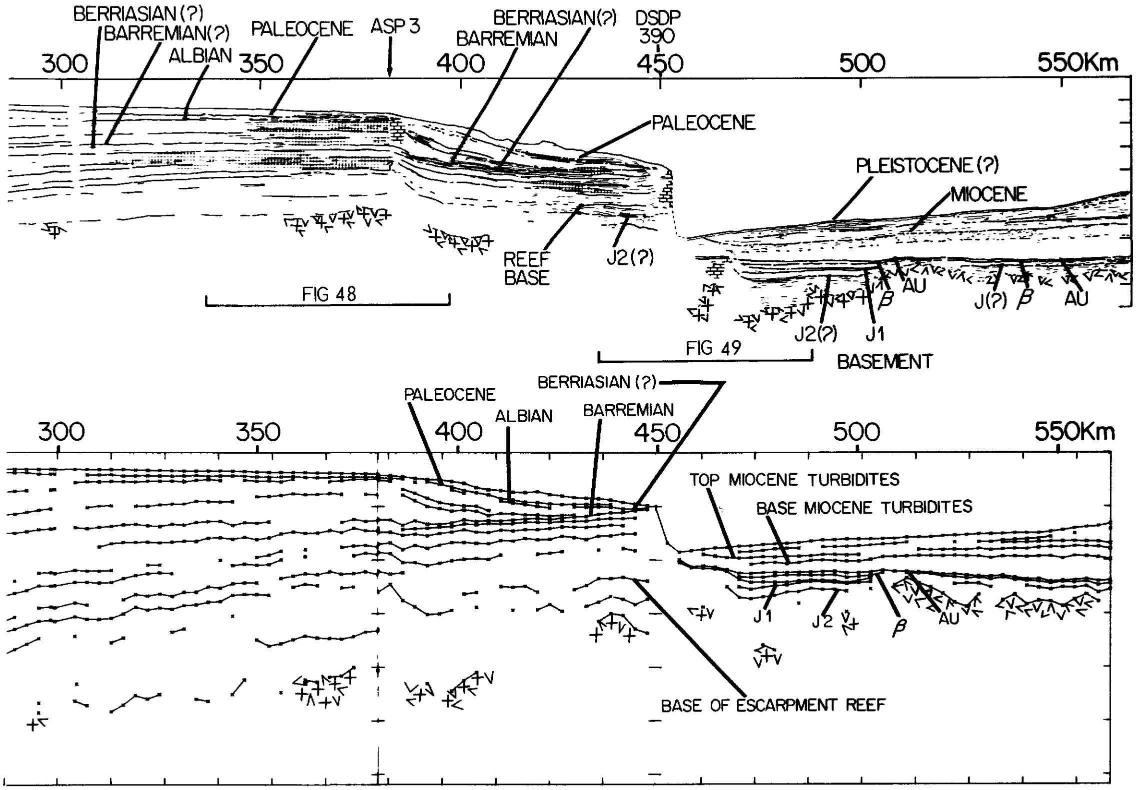
Stratigraphic horizons determined paleontologically (Amato and Bebout, 1978; Poag and Hall, this volume; Valentine, this volume) and seismic reflectors were correlated using a con-version table produced by Schlumberger, Inc. For the conversion table, velocities were determined both by conventional down-hole logging (by Schlumberger) and by measuring arrival times of waves originating at a seismic source at the water surface to a sensor in the hole (by Seismic Reference Service, Inc.).

The profile is presented as a line drawing (fig. 45) intended to display selected reflectors as accurately as possible. Estimated ages corresponding to selected reflectors and possible environments of deposition are also included. Depths to some of the reflectors shown in figure 45A were calculated by the method of Taner and Koehler (1969) and are presented in the form of a companion profile (fig. 46B). Heavy lines in figure 45A indicate the reflectors for which depths were calculated and which therefore correspond to the lines in figure 45B.

DESCRIPTION OF THE SEISMIC PROFILE AND ESTIMATESOF AGES OF REFLECTORS

Continental Shelf, mi 0-25 (km 0-41)

Correlation of reflectors and stratigraphy is most satisfactory beneath the Continental Shelf, where reflectors can be related to strata of known age penetrated in the COST No. GE-1 well. This part of the profile and our interpretation are shown in figure 46. Basement rocks penetrated in the GE-1 well have been identified as quartzites and argillites (Halley, this volume) and have been radiometrically dated as Devonian (Simonis, this volume). This basement surface apparently does not produce a strong reflection event in the seismic record,



USGS seismic profile across Southeast Georgia Embayment. A, Line-drawing interpretation of
to construct the depth section. Locations of photographs shown in figures 46-49B by

presumably due to the small change in acoustic impedance between the oldest Mesozoic sedimentary units and the underlying Paleozoic rocks. Reflections from within the basement, however, are discernible (fig. 46). The irregular basement surface probably results from faulting and erosion during Triassic rifting; and, therefore, we assume that at least some of the sediments filling the resultant grabens are of Triassic age. An unconformity which may represent the top of Triassic deposits is observed (figs. 45, 46), but was not penetrated in the drilling.

Lower Cretaceous (pre-Albian) deposits at the drill site are mostly continental, except for those corresponding to a brief marine transgression in the Aptian (Poag and Hall, this volume; Valentine, this volume). These continental facies appear in the seismic profile (figs. 46, 47) as zones of low reflector continuity and variable amplitude, a pattern characteristic of such deposits (Sangree and Widmier, 1977). The Albian marine limestone and sandstone above the continental terrigenous section are characterized by strong and distinctly more continuous reflectors, as is the Aptian transgressive unit. This good correlation of reflector characteristics and facies at the drill site has encouraged us to estimate the marine-continental facies boundary in the profile as shown in figure 45A.

The Upper Cretaceous marine shaly chalks (Halley, this volume) drilled at GE-1 were deposited in a deepening-outer-shelf to upper-slope environment (Poag and Hall, this volume; Valentine, this volume). On the profile these Upper Cretaceous deposits, which were laid down in an upper-slope environment, are characterized by a set of continuous but very weak reflectors. The small amplitude of the reflections attests to the homogeneity of the section. The entire Upper Cretaceous section assumes this

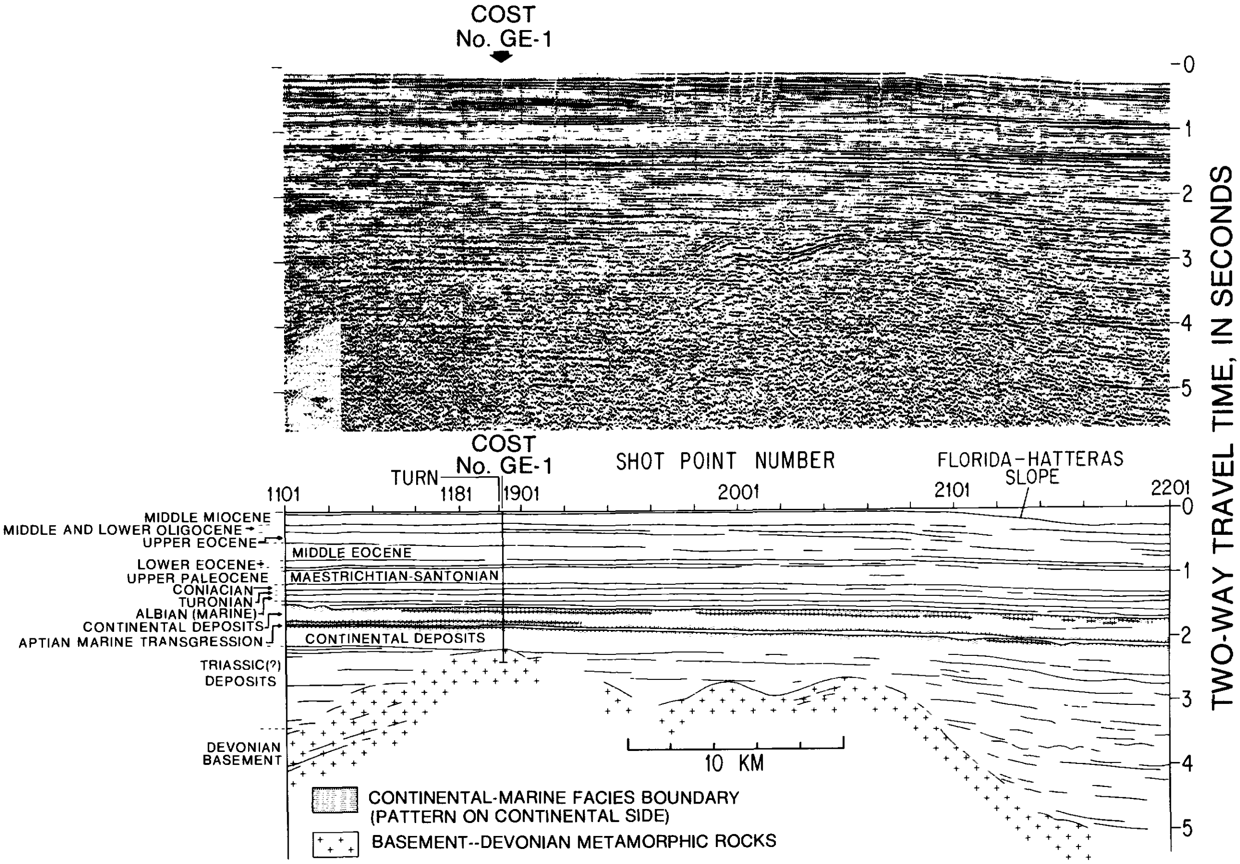


Figure 46.--Section of the profile through the COST No. GE-1 drill site crossing the Continental Shelf and upper Florida-Hatteras Slope and a line-drawing interpretation, both at the same scale. Correlations of reflectors to stratigraphy, as derived from the well, are shown to the left of the interpretation. Location shown in figure 45A.

pattern farther seaward (fig. 47), and we conclude that much of this section was deposited across the Blake Plateau as a homogeneous shaly chalk at water depths greater than those presently characteristic of continental shelves. The Paleocene strata produce strong, distinctly continuous reflections, even though their environment of deposition is not considered to be greatly different from that of the underlying Upper Cretaceous strata.

Reflections from the Eocene interval suggest a progradational filling by sediments of a restricted area of subsidence in the center of the Southeast Georgia Embayment (Charles K. Paull, unpublished data, 1978). The Eocene wedge is covered by a fairly uniform blanket of upper Tertiary and Quaternary deposits.

Florida-Hatteras Slope and inner Blake Plateau, mi 25-149 (km 41-240)

In the inner part of this zone beneath the Florida-Hatteras Slope (near mi 37 (km 60), fig. 45), the basement probably changes from block-faulted, continental Paleozoic rocks to a transitional basement that was formed during the earliest part of the rift stage. The basement rocks are inferred to underlie all of the Blake Plateau (Klitgord and Behrendt, in press) and to be composed of a mixture of mantle-derived mafic igneous rock and continent-derived sediments, perhaps including some fragments of old continental basement. Maximum depth to basement, at about mi 137-143 (km 220-230) along the line, appears to exceed 8 mi (13 km).

We have made tentative age estimates of several horizons beneath the Blake Plateau that are stratigraphically lower than any beds drilled at the COST No. GE-1 well. The deepest of these is the J2 horizon, which has been identified beneath the Blake Basin to seaward; its origin and age, about 175 m.y., will be discussed in the section on the Blake Basin part of the line. The correlation of the J2 horizons beneath the Blake Plateau and Blake Basin is based on structural character. Faults break the strata below J2 in the deep sea but not above; and a similar structural pattern, with faults

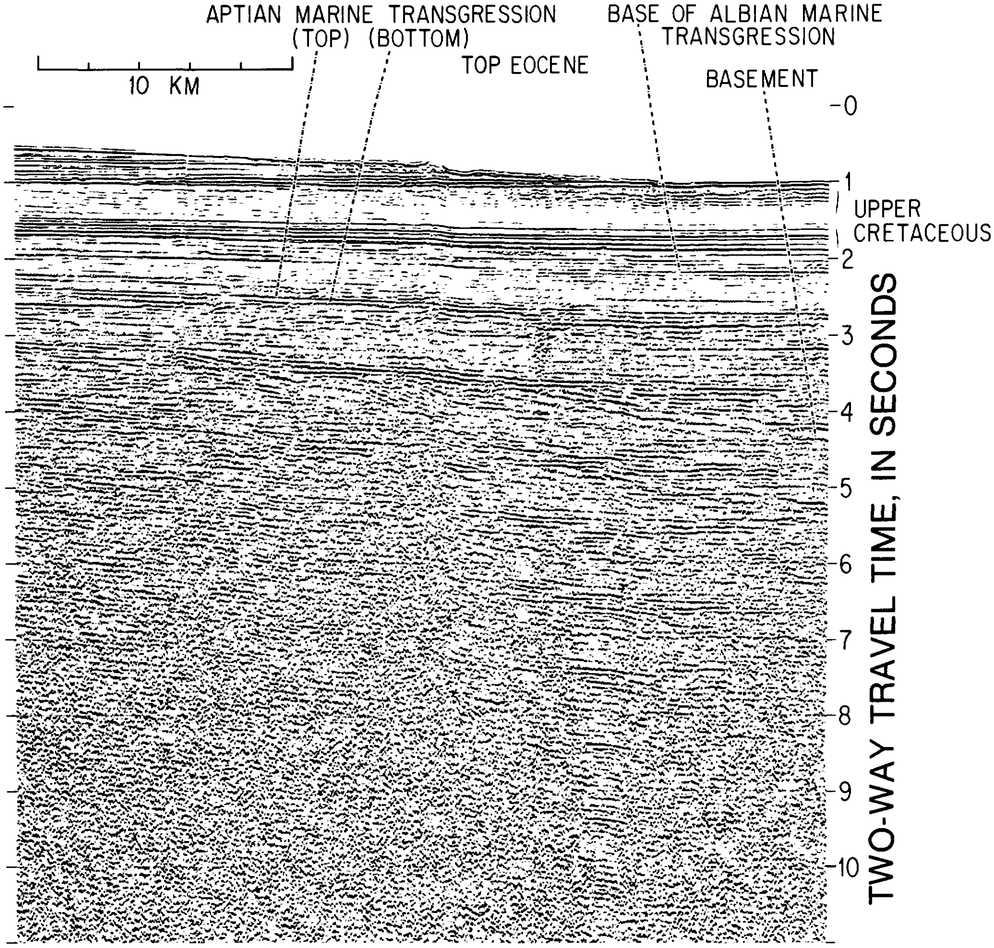


Figure 47.--Part of the profile showing the lower Florida-Hatteras Slope and inner Blake Plateau. Location shown in figure 45A.

terminating upward at a horizon, is seen beneath the Blake Plateau. Therefore, because we assume tectonic episodes to be regional events, we conclude that the two horizons may be of the same age.

Two younger horizons, Kimmeridgian(?) and Berriasian(?) (fig. 45), have been tentatively identified by correlating the pattern of transgressions and regressions which were observed at the GE-1 well with the transgression-regression sequence on a global cycle, as proposed by Vail and others (1977b, fig. 2). Agreement between the general pattern of Vail's idealized sea-level curve and that derived from the well is excellent down to the Aptian (Poag and Hall, this volume). Therefore, our tentative Kimmeridgian Age appears to be on safer ground than it would be without the GE-1 well control. Our Kimmeridgian(?) top is assumed to correspond to a regression, shown by Vail and others (1977a, b) to occur at about 141 m.y. The Berriasian(?) top is assumed to correspond to another regression at about 130 m.y. (the latter also recognizable as an unconformity).

One other horizon, the top of the Barremian, has been traced on the seismic record across the Plateau from DSDP drill te 390 located on the seaward side of the Blake Spur (Benson and others, 1976). DSDP 390 also provides control for correlating Albian and Paleocene strata to reflectors that have been carried seaward from the COST No. GE-1 location. The Paleocene also was penetrated at the ASP 3 site (fig. 45).

The general structure of the sedimentary deposits beneath the inner Blake Plateau is that of an onlapping wedge modified by transgressions and regrssions (fig. 45). The Upper Cretaceous chalks and calcareous shales (Halley, this volume) become more acoustically homogeneous ("transparent") in a seaward direction and perhaps more carbonate rich. On that part of the seismic record corresponding to this layer, small breaks appear in the weak reflectors at the foot of the Florida-Hatteras Slope (fig. 47) and CDP-determined interval velocities increase from about 2.4 km/s beneath the inner Blake Plateau to about 3.2 km/s as the layer becomes thinner beneath the Continental Shelf. This change in velocity probably is due to compaction by the weight of Cenozoic sediment forming the shelf, and the small breaks in reflectors may represent small faults resulting from variation in the amounts of compaction.

The lower Florida-Hatteras Slope and inner Blake Plateau appear to be zones of scour, where the Paleocene top is truncated and Cretaceous rocks are exposed. Dredge hauls of Cretaceous rocks from the Plateau confirm this (Uchupi, 1967, 1970).

Outer Blake Plateau, mi 149-233 (km 240-375)

Beneath the outer Blake Plateau, the basement rises irregularly toward the east from a depth of about 9 mi (14 km) to about 7 mi (11 km) (fig. 45B) Reflectors below the Tertiary show a consistent westward dip following the basement trend, indicating that maximum overall subsidence occurred beneath the western part of the Plateau. However, the locus of subsidence, defined on the basis of maximum interval thickness (fig. 45B), has migrated considerably during the Cenozoic and late Mesozoic. The thickest interval between basement and the J2 horizon (probably of late Early Jurassic age) occurs at mi 186-196 (km 300-315). Based on interval thickness between J2 and a probable middle Upper Jurassic reflector, the depocenter apparently was located at mi 137-143 (km 220-230). Between this reflector and one inferred to be near the Jurassic-Cretaceous boundary, the thickest interval occurs at about mi 87-93 (km 140-150). Lower Cretaceous rocks are almost uniform in thickness, with a poorly defined maximum at about mi 75-118 (km 120-190), whereas the Upper Cretaceous maximum thickness occurs at mi 62-75 (km 100-120). Maximum subsidence during most of the Cenozoic, as measured from the top of the lower Eocene to the sea surface, occurred at mi 25-34 (km 40-55), but again, as in the Cretaceous, the subsidence was very broad and the depocenter poorly defined. We therefore see a pattern in which the locus of maximum subsidence shifted landward through time, accompanied by a broadening of the area of subsidence.

The outer Blake Plateau is covered by a thin, seaward-thickening wedge of Cenozoic deposits. At the ASP 3 drill site an apparently complete Tertiary section from Paleocene to the Miocene, except for the Oligocene, was penetrated. The absence of Oligocene, however, might have resulted from a sampling gap of 46 ft (14 m) between lower Miocene and upper Eocene (Page Valentine, oral commun., 1978). This Tertiary section probably was deposited under fairly energetic current conditions, as broad crossbedding and some cut-and-fill structures are displayed in nearby high-resolution profiles.

Shipley and others (1978) discussed a multichannel seismic profile that intersects our line at mi 173 (km 279 or shot point 4630). We estimate the tops of Upper and Lower Cretaceous to occur slightly shallower at the intersection than they estimate by 650-980 ft (200-300 m). Our Aptian top is deeper by 2,000-2,300 ft (600-700 m), but we are in quite close agreement on the placement of the Barremian. Our interpretation shows basement at considerably deeper depth than Shipley's by 2-3 mi (3-4 km).

Beneath the outer Blake Plateau, the seismic profile contains several zones that we have interpreted as representing reflections from carbonate-bank and back-reef facies (fig. 45A). We believe that we can distinguish these features from reefs which are considered to have been "bathymetrically positive structures formed by sedentary, intergrowing organisms" (Bubb and Hatlelid, 1977, p. 185). The inferred carbonate banks in the outer Blake Plateau appear on the seismic profile as zones in which reflectors abruptly disappear or become very weak (fig. 48). The zones generally have a sigmoidal lense shape and rise in the section toward land. The inferred back-reef deposits are distinguished from the carbonate banks only by their location directly landward of reef structures.

Blake Spur, mi 233-283 (km 375-455)

The Blake Spur (fig. 2) is a seaward-projecting rampart which forms the northward termination of the Blake Escarpment. Its surface dips rather gently between water depths of 3,600 and 9,500 ft (1,100-2,900 m). At a water depth of about 9,500 ft (2,900 m), the dip steepens abruptly, assuming an angle similar to that of the Blake Escarpment to the south (fig. 45).

Basement rises toward the east beneath the Blake Spur from 5 to 7 mi (8-11 km) (fig. 46), continuing the general trend of basement reflectors becoming more shallow seaward, noted beneath the outer Blake Plateau. Internal basement reflectors dip seaward beneath the outer Blake Spur (fig. 45), attesting to the layered nature, at least in part, of this transitional basement. Although we have not applied migration, we believe that these are truly intrabasement reflectors because diffractions, which are also observed originating from the basement surface, assumed a considerably steeper apparent dip.

The Blake Spur is bounded and structurally controlled by a pair of reefs (fig. 45A). The reef situated at the seaward margin of the spur developed first. The base of a reef commonly is difficult to observe in seismic profiles, whereas fore-reef and back-reef deposits are much easier to penetrate. Therefore, we have

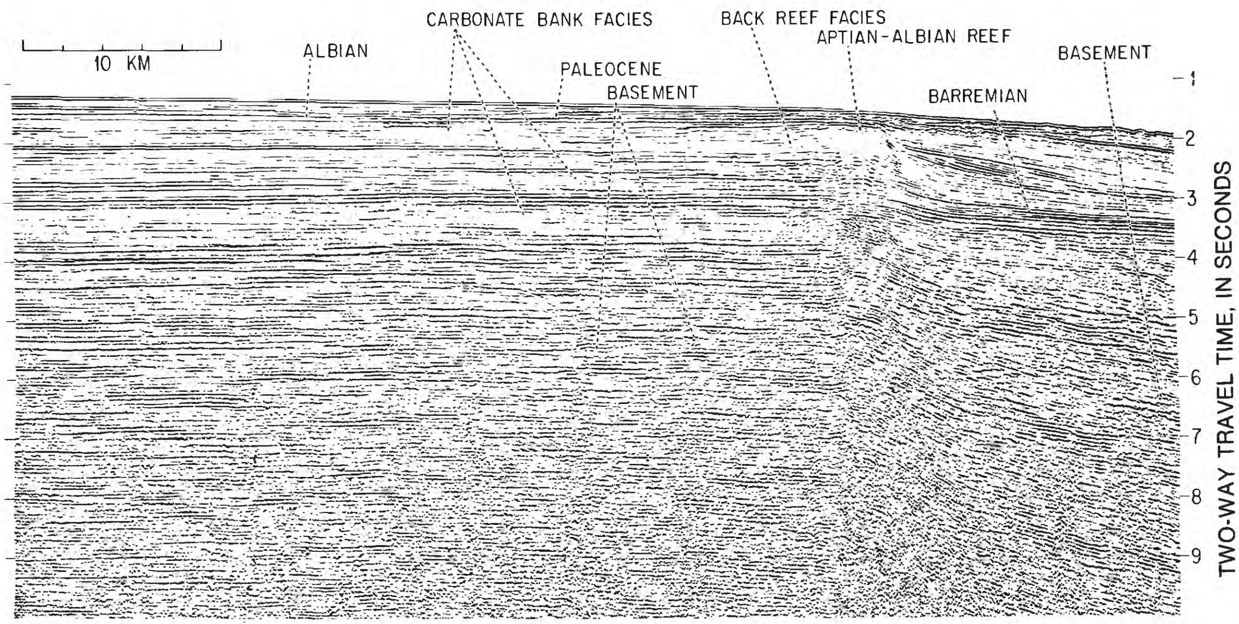


Figure 48.--Photograph of part of the profile, showing the outer Blake Plateau and inner Blake Spur. Location shown in figure 45A.

selected the subhorizontal reflector directly below the base of relatively steeply dipping fore-reef or back-reef facies as a horizon equivalent in age to onset of reef development. By this criterion, it appears that the outer reef (mi 278-281 (km 448-453)) did not become well established until more than 6,600 ft (2,000 m) of sediments had accumulated above basement, although unidentified patch reefs or carbonate banks may have existed which cannot be observed at that depth. Onset of true reef development occurred after the formation of the reflector that is presumed to be equivalent to the J2 horizon of the deep sea (figs. 45, 49). If the assumed age of the J2 horizon is approximately correct (about 175 m.y.), then true reef construction probably began at the outer edge of the Blake Spur in Middle to early Late Jurassic time. The death of this reef is well documented by studies of samples from DSDP holes 390 and 392 (Benson and others, 1976) showing that reef or carbonate-bank limestones of Neocomian-Barremian Age occur beneath an eroded surface covered by Barremian-Albian deepwater oozes. Apparently, the reef died in Barremian time. Our correlation of reflectors to the drilled stratigraphic horizons (DSDP 390) also suggests this time for the cessation of reef growth. The deepest coherent reflector that crosses the reef occurs just 0.08 s beneath the top of the Barremian (fig. 49).

The reef that forms the landward boundary of the Blake Spur (km 382-386) apparently began to form just after the end of the Barremian. Its base occurs about 0.10 s (about 650 ft (200 m)) above the top of the Barremian as traced on seismic section from the DSDP 390 drill site. The reef seems to have died by the end of Albian time, as the Albian reflector, traced both from the DSDP 390 and COST No. GE-1 wells, extends across the top of the reef. During the life of this landward reef, the Blake Spur was covered by seaward-dipping fore-reef deposits. Previously, beds were deposited horizontally, trapped by the older reef to seaward. After the death of the landward reef, the spur was covered by pelagic oozes, deposited at least through the middle Eocene (Benson and others, 1976; DSDP 390). A fairly complete Cenozoic section, except perhaps for the Oligocene, was penetrated at the ASP 3 well (Page Valentine, oral commun., 1978) (fig. 45), and rather thick remnants of Cenozoic deposits are present on the Blake Spur as compared to the inner Blake Plateau. This indicates that the major erosion which is indicated by the scoured topography of the spur (fig. 45) is the result of post-Eocene changes in deep-sea current activity perhaps related to major changes in sea level in Pliocene and Pleistocene time (Vail and others, 1977b).

Blake Basin, mi 283-352 (km 455-567)

Based on seismic interpretation, basement just seaward of the Blake Escarpment is believed to be relatively shallow (4.6-5 mi (7.5-8 km)) (figs. 45A, B), but it drops abruptly into a basin at least 6 mi (10 km) deep farther to seaward. This basin, interrupted by a small basement peak on the line of profile, becomes

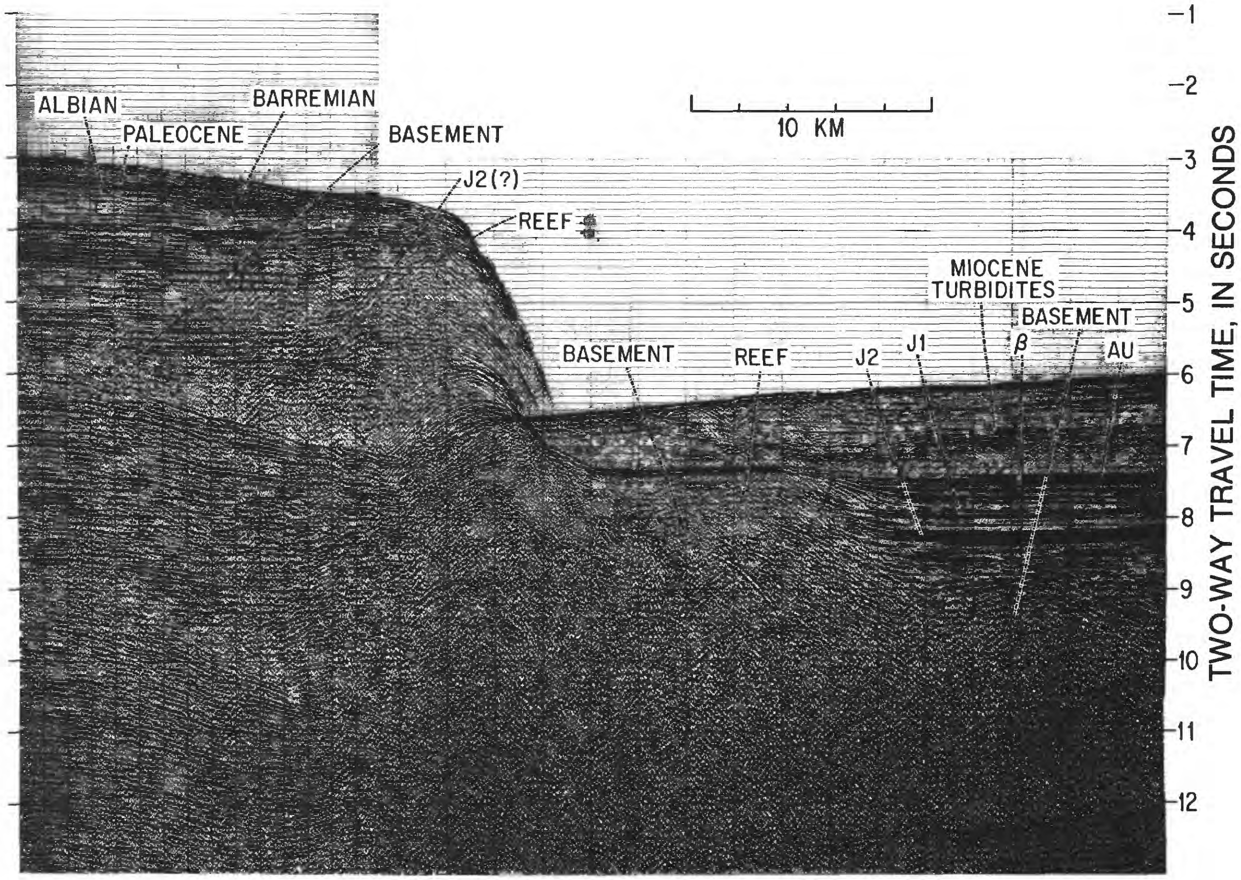


Figure 49.--Photograph of part of the profile showing the outer Blake Spur and western Blake Basin. Location shown in figure 45A.

shallower to seaward and is bounded by a broad basement high-centered at about mi 320 (km 515). This broad high is associated with a magnetic anomaly related to the opening of the Atlantic, the Blake Spur anomaly (Vogt, 1973; Klitgord and Behrendt, 1979). Seaward of the Blake Spur anomaly, basement remains at a depth of about 4.0-4.6 mi (6.5-7.5 km) and is believed to be of normal oceanic composition and thickness. The change from transitional basement (modified oceanic) beneath the Blake Plateau to oceanic crust is gradual, no doubt, but we considered it to be completed at the location of the Blake Spur anomaly because the anomaly is continuous and associated with the ocean opening.

The J2 reflector (fig. 45) pinches out against the basement high believed to be the source of the Blake Spur anomaly. Because this basement material is considered to be 175 m.y. old (Klitgord and Behrendt, 1979), the J2 reflector is considered to be approximately the same age. The sedimentary section directly above basement and below the J2 horizon appears on the seismic section to be extensively fractured west of the Blake Spur anomaly. An eastward jump of the oceanic spreading center to the Blake Spur anomaly location 175 m.y. ago has been proposed (Vogt, 1973), and this assumption seems to result in the best reconstruction of early spreading events. If such an eastward jump did occur, then fracturing of the sedimentary layers in the region between the old and new spreading centers might be anticipated. We believe that this may account for the faults which extend upward to the J2 reflector. We have previously mentioned that a deep reflector beneath the Blake Plateau overlies a similarly faulted sedimentary section, and using the assumption that tectonic episodes probably represent regional events, we have tentatively correlated that deep reflector with the horizon identified as J2.

A buried Jurassic reef formed on basement has been identified at the foot of the Blake Escarpment (fig. 45). This reef may have died at J2 time, but subsequently another smaller reef appears to have been initiated slightly eastward of the older reef. The younger reef grew atop the latter's fore-reef talus. This interruption in reef development might also be related to tectonic events that occurred about 175 m.y. ago. The younger reef subsequently died and was covered by the time of formation of the strong reflector located between horizons J1 and Beta.

Horizon J1 has been traced from a seismic profile presented by K. Klitgord and J. Grow (written commun., 1978). They consider this reflector to represent a 140-m.y.-old stratum because it pinches out against basement that is estimated to be of this age. Their interpretation was based on magnetic-anomaly patterns. The unit bounded by J1 and J2 is unfaulted in the Blake Basin west of the Blake Spur anomaly. Some small breaks in the unit to the east are attributed to compaction over a rough basement. The J1 and J2 horizons probably were not penetrated at DSDP site 391 in the Blake Basin.

Horizons Beta and AU and a Miocene turbidite were, however, penetrated at DSDP site 391 (Benson and others, 1976) and have been traced to the profile along connecting seismic lines. Horizon Beta is presumed to correlate with the transition from Aptian clays to Neocomian limestone. At DSDP site 391, horizon AU represents an unconformity between Miocene turbidites and unfossiliferous Cretaceous claystones. The Miocene carbonate turbidites at that drill site are similar to those cored just east of the Blake Escarpment by Sheridan and others (1974). The Miocene turbidites in our profile apparently are represented by discontinuous, irregular, strong reflectors (figs. 45, 49). Below these reflectors and above AU is a section of very weakly reflective or acoustically transparent material that may represent sedimentary deposits equivalent to the Miocene hemipelagic deposits drilled on the Blake Ridge at DSDP site 101 (Hollister and others, 1972a) and at site 102 (Hollister and others, 1972b).

Above the Miocene turbidites, two unconformities are present at depths of approximately 0.05 and 0.4 s sub-bottom, both of which roughly parallel the sea floor. Either of these might be the Pliocene-Holocene contact as drilled at nearby locations.

HISTORY OF THE CONTINENTAL MARGIN

Pre-185 m.y. ago

Development of the Continental Margin at the latitude of the COST No. GE-1 well began in the Triassic, presumably with rifting and thinning by fracture of the continental crust. The irregular, blocky nature of the Devonian (and older) basement seen in the profile (fig. 45) probably results from this faulting. The crustal extension would have resulted in considerable volcanic activity. The grabens would then have filled rapidly with continental terrigenous deposits, similar to those found in Triassic basins all along the U.S. east coast.

185 to 175 m.y. ago

In Early Jurassic time, perhaps 180-185 m.y. ago (Vogt, 1973), rifting of continental basement slowed, as thinning of this material approached a limit, and intrusions of mafic mantle material began to fill the gap between the separating continents. The oceanward limit of rifted continental crust probably occurs beneath the Florida-Hatteras Slope. The mantle material which welled up in the gap between continental masses was, no doubt, extensively mixed with sediment shed from the nearby, still-rugged continents and may have included sizable fragments of continental rocks. Therefore, we refer to this as transitional or rift-stage crust (Klitgord and Behrendt, 1979). Although Sheridan (1974, 1976) originally referred to the basement as oceanic, he pointed out (1974, p. 399; 1978) that it has intermediate seismic velocity and mantle depth and should be considered a "rift crust" (1978). Tarr (1969) noted that the Rayleigh wave-dispersion curve for this region is intermediate between theoretical curves for oceanic and continental crust and that this might be accounted for by the presence of a variety of crustal types. However, it is also consistent with a tran-Ositional type of basement, as pointed out by Sheridan (1974). A basement beneath the southern Blake Plateau derived mostly of mantle material was proposed by Dietz and others (1970) on the basis of an overlap in a pre-rift fit of the continents. Recent, improved fits are somewhat different (Le Pichon and others, 1977; Schouten and Klitgord, written commun., 1978); but the overlap at continental closure, as well as the nature of basement estimated from magnetic anomaly patterns (Klitgord and Behrendt, 1979) still precludes the presence of continental basement beneath the Blake Plateau. Sheridan (1974, 1976) has proposed a narrow, high, continental basement beneath the Blake Escarpment, which our profile does not show.

Early in the Jurassic (185-175 m.y. ago), in conjunction with the development of transitional basement, the grabens became filled with continental deposits, extensional movement on the faults ceased, and a smooth subaerial surface developed. This is interpreted as the unconformity shown as the top of Triassic deposits in the profile. This post-rift unconformity surface probably did not develop until Early Jurassic time. On the eastern (African) side of the rift basin, a reef, now in the Blake Basin at the foot of the Escarpment, began to develop on the transitional basement.

175 to 140 m.y. ago

Approximately 175 m.y. ago, a reorganization of plate movement occurred (Vogt, 1973; Klitgord and Behrendt, 1979) and the spreading center jumped eastward by about 120 mi (200 km) on this profile. The change in depth of basement just west of the Blake Spur anomaly is considered to be the contact between older crust to the west and younger (170-175 m.y. old) crust to the east. The younger basement was hotter and therefore formed at a shallower level than the older, cooler, and more dense basement to the west. Although both crusts are now old enough, and therefore cool enough, to have reached nearly their maximum subsidence, the step was frozen into the basement topography and so remains (Klitgord, oral commun., 1978). The "jump" in spreading center referred to above certainly was not an instantaneous leap, and it is probable that considerable faulting of the basement and sediments took place. We correlate the extensive fracturing of the deepest strata in the western Blake Basin (fig. 45) to the time of spreading-center jump. These deposits are covered by a quite undisturbed reflector, J2. The episode of readjustment of plate movement may also be related to a period of Early Jurassic basaltic intrusion and volcanism around the North Atlantic basin. Dikes and flows of this age have been distinguished paleomagnetically by deBoer (1967) in eastern North America and by their inferred stress pattern by May (1971) around the North Atlantic. Extensive volcanic flows occur near this profile, directly overlying the post-rift unconformity (Dillon and others, 1979). These have shown a range of dates of 162-204 m.y. (Gohn and others, 1978) but probably represent volcanic activity associated with stresses involved in the spreading-center jump. The oldest reef observed in this profile (at the foot of the Blake Escarpment) apparently died at about this time, or slightly later.

140 to 130 m.y.

During the time represented by the J2-J1 interval (about 175-140 m.y. ago), no reef building appears evident in the profile; but after J1 time, a small reef began to grow in the Blake Basin, atop the fore-reef talus of the previous reef. At about the same depth (4 mi (6.5 km)) and somewhat to the west, we find the probable base of the reef structure that forms the Blake Escarpment. The Blake Basin reef survived only briefly, but the Blake Escarpment reef survived until perhaps as late as Barremian time, about 115 m.y. ago (Benson and others, 1976). These two structures may have begun to form simultaneously during an episode of renewed reef growth, or the escarpment reef may represent a site of reef development initiated after the death of the basin reef. Based on character of the seismic reflections (fig. 45), the most extensive development of carbonate banks on the outer shelf occurred during this period (Tithonian-Berriasian).

130-115 m.y. ago

The end of this period is characterized by a major regression. The shoreline apparently moved farther seaward than ever before, and the related unconformity extended far seaward across the plateau. The escarpment reef died at this time, possibly as a result of the regression.

115-100 m.y. ago

In Aptian-Albian time, reef growth abruptly recommenced 40 mi (70 km) to landward of the Blake Escarpment, resulting in development of a small reef just seaward of the ASP 3 drill site (fig. 45). The present Blake Spur then became a zone of deposition of fore-reef talus, and a broad zone of back-reef deposits and carbonate banks appears to have extended about 25 mi (40 km) behind the reef, westward beneath the Blake Plateau. Beneath the present shelf at the GE-1 site and beneath the inner Blake Plateau, a period of continental terrigenous sedimentation was interrupted by a brief Aptian transgression and regression, followed by a major transgression in the Albian. The reef on the outer Blake Plateau died by the end of Albian time, perhaps drowned by this transgression.

In the deep waters of the Blake Bahama Basin and generally in the western North Atlantic, anoxic conditions prevailed, resulting in the deposition of carbonaceous clays between horizons Beta and AU (fig. 45) (Ewing and Hollister, 1972; Benson and others, 1976).

100 to 55 m.y.

During Late Cretaceous to Paleocene time, submergence exceeded deposition and a general deepening of the Blake Plateau took place. The plateau previously had been a shallow carbonate shelf. At the COST No. GE-1 site, the argillaceous chalks and calcareous shales of this interval are indicative of paleobathymetric environments that increased from shelf to slope depths (Poag and Hall, this volume); however, these strata remained relatively flat-lying, both beneath the present shelf and the Blake Plateau. Presumably a shelf was present to the west. The weak acoustic layering of the Upper Cretaceous and Paleocene at the GE-1 well changes to an almost acoustically transparent signature farther seaward, beneath the plateau, showing that the unit becomes even more homogeneous to the east. The deposition of such homogeneous, fine-grained deposits suggests that quiet current conditions existed across the present Blake Plateau at the time. During the Late Cretaceous and Paleocene, the area of maximum subsidence was beneath the inner Blake Plateau, as shown by the location of maximum sediment thickness there as well as the presence of a sag at the base of the unit in that region.

55 to 0 m.y.

High-resolution airgun profiles in the study area show that extensive erosion took place near the end of Paleocene time. Paleocene and Eocene strata on both sides of the unconformity were deposited at middle- to outer-shelf water depths at the well site (Poag and Hall, this volume), and no significant regression was proposed by Vail and others (1977b, fig. 2). Therefore, we believe that at the end of the Paleocene, the Gulf Stream, which previously probably flowed northward along the Blake Escarpment, changed its location and began to flow through the Straits of Florida and across the western Blake Plateau. The post-Paleocene depositional history of the area is characterized by the seaward progradation of the Continental Shelf against the flank of this fast-moving current and of scour beneath the Gulf Stream on the inner Blake Plateau.

The maximum development of the present Continental Shelf occurred during the Eocene as sediments prograded in a wedge from the west. Within the resolution of this profile, the reflectors seem to prograde smoothly with no contemporaneous erosion and redeposition (fig. 46). After deposition, the Eocene deposits were extensively eroded, and differential erosion features are evident on the slope and inner Blake Plateau (fig. 47). The Gulf Stream may have migrated eastward during the Eocene, allowing the shelf to prograde seaward, and then resumed its former course to scour the Eocene deposits. Subsequently this current prevented any further progradation of the shelf, eroded the inner Blake Plateau, and swept away most of the sediment that otherwise could have built up the plateau.

On the outer Blake Plateau, seaward of the main zone of Gulf Stream influence, a condensed wedge of Cenozoic strata is present which underwent extensive sediment migration during deposition. The profile (fig. 45) shows that the Blake Spur has also been very extensively eroded. Based on ages of sediments drilled, erosion on the spur occurred after Eocene time (Benson and others, 1976). This erosion may have been related to Gulf Stream flow, although the main flow axis probably was located on the inner Blake Plateau by that time. Deep-sea deposits were extensively eroded between late Eocene and early Miocene time to form the unconformity known as AU.

At DSDP site 391, in the Blake Basin, horizon AU is formed at the contact of Miocene carbonate turbidites and Cretaceous black clays (Benson and others, 1976). The turbidites also have been cored near the escarpment (Sheridan and others, 1974). However, on the profile (fig. 45), an acoustically transparent layer which probably represents Oligocene or lower Miocene pelagic deposits occurs between the irregularly bedded, channeled, discontinuous Miocene turbidite deposits and horizon AU. This is the horizon A--reflector X unit of Markl and others (1970). Above the Miocene turbidites, probable Pliocene-Quaternary hemipelagic deposits are interrupted by at least two erosional episodes; one of these unconformities is just below the sediment surface and might be related to changes in ocean circulation associated with Pleistocene glaciation.

SUMMARY

An unprecedented opportunity to analyze the structure and development of the Continental Margin off the southeastern United States is afforded by correlation of the COST No. GE-1 stratigraphic information with data from other drill sites and with a high-quality, deep-penetration, multichannel seismic profile.

The Continental Margin is underlain by a broad, asymmetric basin and basement rocks probably consist of transitional (modified oceanic) crust; the basin's center of subsidence is located beneath the inner Blake plateau. Maximum subsidence occurred beneath the outer plateau early in margin development, and the locus of subsidence moved landward and broadened with time. The seaward limit of shelf development was set by two reefs which acted as sediment dams.

The present Continental Margin began to form in the Triassic, with rifting of continental crust. Sediments eroded from the rough, faulted topography accumulated in the grabens. In Early Jurassic time, from about 185 to 175 m.y. ago, intrusions and extrusions of mafic material, extensively mixed with continent-derived sediments, formed new transitional basement beneath the Blake Plateau. As marine water flooded the subsiding zone, reefs began to form on fault-block highs. About 175 m.y. ago, reorganization of plate movements resulted in a jump of the spreading center about 120 mi (200 km) eastward, close to the African continental block. About 140 m.y. ago, a reef began to develop at the location of the Blake Escarpment and grew upward for almost 6,600 ft (2,000 m) before dying in Berriasian time. A broad carbonate platform developed behind this reef; and when the initial reef died, another reef was initiated 40 mi (70 km) to the west, which took over the function of a sediment dam. Until the latter reef died at the end of the Early Cretaceous, the outer Blake Plateau was characterized by carbonate-bank development; to the westward, sediments were more terrigenous. During Late Cretaceous and Paleocene time, quiet-water deposition of chalk and terrigenous mud characteristic of slope water depths covered the plateau and Outer Continental Shelf area. The top of the Paleocene sediments was sharply eroded, presumably due to the onset of Gulf Stream flow across the inner Blake Plateau after the Paleocene. The present Continental Shelf has resulted from sedimentary accumulation, mostly in Eocene, restricted on the seaward side by the flank of the Gulf Stream flow.

CONCLUSIONS

1. The COST No. G-1 well penetrated 13,039 ft (3,974 m) of sedimentary and metasedimentary rocks in the Southeast Georgia Embayment of the AOCS. The age of sedimentary units was determined through the examination of Foraminifera, calcareous nannofossils, and palynomorphs. The section is Cenozoic down to about 3,500 ft (1.060 m). From 3,500 to 5,900 ft (1,060-1,800 m), the sediments are Late Cretaceous in age, whereas the interval from 5,900 to about 11,000 ft (1,800-3,350 m) consists of units of probable Early Cretaceous (Kimmeridgian?) and younger age. The section from 11,000 ft (3,350 m) to the total depth of the well (13,254 ft (4,040 m below KB)) contains metasedimentary and meta-igneous rocks which have been radiometrically dated as Devonian or older.
2. The sediments down to about 3,300 ft (1,000 m) are predominantly chalks; limestone and calcareous shales are most abundant in the underlying interval down to about 7,200 ft (2,200 m). In the 7,200- to 11,000-ft (2,200- to 3,350-m) interval, interbedded sandstones and shales (mostly red beds) are the dominant lithology, and these rocks unconformably overlie basement units at about 11,000 ft (3,350 m).
3. Oligocene and Miocene units as well as some Upper Cretaceous strata were deposited in outermost-shelf to middle-slope water depths. Pliocene, Eocene, and Paleocene beds, as well as some Upper and Lower Cretaceous units, were laid down in middle- to outer-shelf water depths. The bulk of the Lower Cretaceous rocks were deposited in inner-shelf to terrestrial environments.
4. Porosities in excess of 25 percent are present in sandstone and limestone units down to approximately 10,000 ft (3,000 m). Sandstones with reservoir-quality petrophysical properties are especially common in the 6,000- to 10,000-ft (1,800- to 3,000-m) interval. No systematic decrease of porosity or permeability appears to occur with depth. Chalks at the top of the section in the GE-1 well, although they have low permeabilities, could form adequate reservoirs, especially where fractured.
5. Petrographic analysis indicates that most of the sandstones in the COST No. GE-1 well are arkoses or subarkoses. Feldspars are generally fresh and unaltered; they neither show breakdown into pore-filling clays nor leaching to form secondary porosity.
6. The present geothermal gradient in the COST No. GE-1 well is 0.89^{o}F/100 ft (16.2^{o}C/km).
7. Organic geochemical studies, coupled with data on vitrinite reflectance and color alteration of visible organic matter, indicate poor source-rock potential for the section down to 3,600 ft (1,100 m) because of low organic-carbon contents and thermal immaturity. The section from about 3,600 to 6,000 ft (1,100-1,800 m) has the highest organic carbon content of any interval in this well but still appears to be thermally immature. This interpretation is complicated by contamination by drilling additives, however. The section from about 6,000 to 8,900 ft (1,800-2,700 m) has low levels of organic carbon, and much of this material is of the terrestrial, "gas-prone" type. The basal part of the interval does appear to be thermally mature, however. The section below 8,900 ft (2,700 m) has very low organic-carbon content and, in spite of some small gas shows, is unlikely to have any significant source-rock potential.
8. The combination of the above factors indicates that the intervals with the best reservoir rocks have generally low associated source potential. Source beds capable of generating oil or gas are present in the well, however, and where thermally mature they may have formed and expelled hydrocarbons. Lateral migration into stratigraphic traps or upward migration into overlying low-permeability but high-porosity chalks may provide potential for oil or gas production in the upper parts of the section.

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