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U.S. Geological Survey Core Drilling on the Atlantic Shelf

Geologic data were obtained at drill-core sites along the eastern U.S. continental shelf and slope.

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In 1976, the U.S. Geological Survey conducted the Atlantic Margin Coring Project (AMCOR) to obtain information on stratigraphy, hydrology and water chemistry, mineral resources other than petroleum hydrocarbons, and geotechnical engineering properties at sites widely distributed along the continental shelf and slope of the eastern United States (*1*). This program, aided in its planning by the geological surveys of the Atlantic coastal states, was directed toward determining a broad variety of sediment properties, many of them studied for the first time in this region. Previous studies of sediments recovered by core drilling in this region (Fig. 1a) were usually limited to one or two aspects of the sediment properties.

Summary. The first broad program of scientific shallow drilling on the U.S. Atlantic continental shelf has delineated rocks of Pleistocene to Late Cretaceous age, including phosphoritic Miocene strata, widespread Eocene carbonate deposits that serve as reflective seismic markers, and several regional unconformities. Two sites, off Maryland and New Jersey, showed light hydrocarbon gases having affinity to mature petroleum. Pore fluid studies showed that relatively fresh to brackish water occurs beneath much of the Atlantic continental shelf, whereas increases in salinity off Georgia and beneath the Florida-Hatteras slope suggest buried evaporitic strata. The sediment cores showed engineering properties that range from good foundation strength to a potential for severe loss of strength through interaction between sediments and man-made structures.

The AMCOR program was limited by two factors: water depth and penetration depth. Because the ship selected for the program, the *Glomar Conception*, lacked dynamic positioning capability, its anchoring capacity determined the maximum water depth in which drilling could take place. Although it was equipped to anchor in water 450 meters deep and did so successfully at one site, we attempted no drilling in water depths greater than 300 m. Strong Gulf Stream currents at the one attempted deep site (443 m) frustrated attempts to "spud in" to begin the hole. The amount of space necessary to assemble the drilling equipment imposed a lower limit of 18 m for the water depth at any site. Safety considerations limited penetration depth. Because the program involved open-hole drilling without equipment such as blowout preventers, we selected sites at locations devoid of structures capable of trapping oil or gas, and we drilled the holes no deeper than 310 m to further minimize the possibility of encountering hydrocarbon accumulations.

Holes were cored at 19 sites (Fig. 1 and Table 1) in water depths ranging from 20 to 300 m and sediments totaling 1020 m were recovered in 380 cores. We investigated a twentieth site (6003) but recovered no cores because of a resistant layer at the sea floor.

Shipboard analytical tests of the cores included visual description and photographing; measurements of the bulk density, shear strength, and electrical resistivity of the sediment and of the salinity, *p*H, alkalinity, and calcium content of the interstitial water; gas chromatography of the light hydrocarbon and hydrogen sulfide contents; and micropaleontologic analyses.

After completion of the coring operation, a subcontractor obtained logs of responses to various sensors lowered into ten boreholes, which measured spontaneous potential and resistivity, gamma ray and neutron porosity, compensated formation density, borehole diameter, temperature, and velocity of sound in the borehole. Caving, loss of downhole equipment, or sticking of the logging tools prevented complete logging of several holes.

Laboratory analyses of samples from the cores included studies of mineralogy, petrography, stratigraphy, and paleoecology, organic and interstitial water geochemistry, and geotechnical properties. In this article we present the salient results of the shipboard and laboratory studies to date (*2*).

Stratigraphy

Sedimentary rocks of Late Cretaceous through Pleistocene age were recovered, but Miocene and Pleistocene strata constitute the bulk of the cored sections (Fig. 2). Deposition in this region has been interrupted by several important hiatuses that can be correlated with low global sea levels. Biogenic calcarenites and calcilutite deposits predominate at

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core sites south of Cape Hatteras, whereas terrigenous quartzose sand, silt, and clay are the chief sedimentary components north of Cape Hatteras. The cored strata are discussed below in chronostratigraphic order. Interpretations are based principally on analyses of planktic and benthic foraminifera, calcareous nannoplankton, and diatoms.

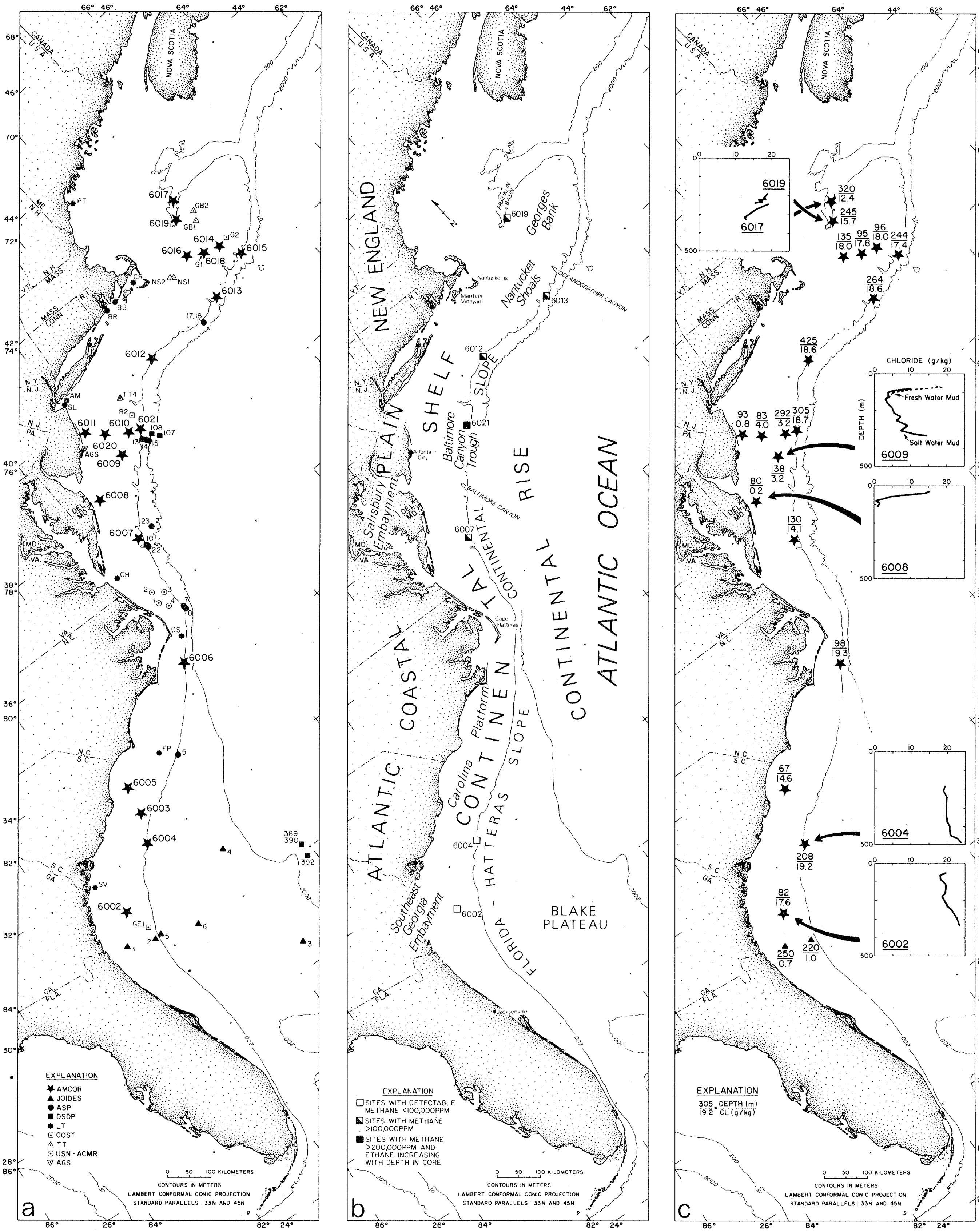


Fig. 1. (a) Locations of drilling sites on the Atlantic continental margin; see Table 2 for identification of acronyms for the various drilling programs. (b) Geographic localities and light hydrocarbon data for AMCOR sites. (c) Hydrologic data for AMCOR sites. Insets show chlorinity variations with depth below sea level of selected sites. Numbers accompanying each site show the minimum chlorinity value and the depth below sea level at which that value occurred.

Upper Cretaceous. Upper Cretaceous sedimentary rocks are widespread beneath the Atlantic coastal plain and are especially well exposed on the Carolina Platform (Fig. 1b). Among the AMCOR drill sites, however, Upper Cretaceous sediments were recovered only at site 6004. Olive gray carbonate sand and mud 18 m thick containing glauconitic and zeolitic zones range in age from late Campanian–early Maastrichtian to middle Maastrichtian (*3*) and are equivalent in age and lithology to the Peedee Formation onshore (*4*).

Paleocene. Paleocene sedimentary strata were drilled at sites 6004 and 6005. At site 6004, 105 m of richly fossiliferous, olive gray calcareous silty clay and siliceous (disordered cristobalite or opal containing interlayered cristobalite and tridymite) carbonate muds of middle Paleocene age are equivalent in age and lithology to the beds of the Black Mingo Formation onshore (*4*, *5*).

Table 1. Locations and depths of AMCOR drill holes on the Atlantic outer continental shelf and slope of the United States.

Site	Date completed, 1976	Latitude (N)	Longitude (W)	Water depth (m)	Penetration depth (m)
6002	23 July	31°08.57′	80°31.05′	32.3	304.8
6003	25 July	32°37.66′	78°48.80′	41.0	N.R.*
6004	26 July	32°03.98′	79°05.86′	173.7	307.9
6005	30 July	33°15.10′	78°44.08′	18.6	47.6
6006	2 August	34°41.4′	75°43.0′	56.1	89.3
6007	6 August	37°17.99′	74°39.16′	85.0	310.6
6008	8 August	38°24.21′	74°53.83′	20.7	119.5
6009	13 August	38°51.27′	73°35.47′	58.5	299.6
6010	15 August	39°03.70′	73°05.90′	75.9	310.6
6011	18 August	39°43.5′	73°58.6′	22.3	260.0
6012	22 August	39°59.57′	71°20.09′	262.7	303.9
6013	25 August	40°05.04′	68°52.13′	238.7	304.8
6014	27 August	40°48.33′	67°53.64′	69.8	102.4
6015	29 August	40°23.11′	67°35.85′	209.1	62.8
6016	2 September	41°09.50′	68°41.83′	66.4	68.9
6017	5 September	42°10.45′	67°57.51′	238.7	90.5
6018	7 September	40°55.90′	68°18.14′	46.3	48.5
6019	10 September	41°49.27′	68°16.39′	173.7	71.6
6020	13 September	39°25.41′	73°35.63′	39.0	43.9
6021	18 September	38°57.92′	72°49.20′	301.2	304.8

*No recovery; resistant layer at sea floor.

At site 6005, 28 m of lower to middle Paleocene sediments consist of calcareous silty clay containing disordered cristobalite and are overlain by sandy limestone. These beds are also equivalent in age and lithology to parts of the Black Mingo Formation (*4*), but microfossils are sparse and poorly preserved (*6*). Pleistocene sand overlies the Paleocene sediment at site 6005, showing that extensive erosion removed most of the Tertiary record from this nearshore locality.

Eocene. Rocks of Eocene age are more widely distributed and thicker than other Paleogene rocks beneath the Atlantic coastal plain and offshore continental margin and have been drilled at many offshore sites (*7*). We recovered Eocene rocks at sites 6002, 6011, and 6019 (Fig. 2). In core hole 6002, 150 m of light olive gray and light gray, slightly dolomitic and zeolitic, upper Eocene limestone beds are overlain by 10 m of upper Eocene phosphatic carbonate mud sequences. About 50 kilometers south of site 6002, the JOIDES program (see Table 2) encountered Eocene sediments of similar lithology and age at approximately the same depth below sea level (*8*). These strata are offshore extensions of the Ocala Limestone of Georgia and Florida (*4*, *9*) and are equivalent in age to the Santee Limestone and possibly the lower part of the Cooper Formation of South Carolina. We estimate Eocene rocks to be at least 600 m thick at site 6002.

Core hole 6011 penetrated 30 m of middle Eocene calcareous sand, silt, and clay that appear to be equivalent in age and lithology to the Shark River Formation of the New Jersey coastal plain (*10*, *11*). Farther offshore from 6011, the Eocene strata dip into the Baltimore Canyon Trough (Fig. 1b), where 247 m of Eocene calcilutite deposits are present in the COST B-2 well (*12*).

In core 6019, about 10 m of glauconitic limestone and calcilutite deposits of early and middle Eocene age contains rich assemblages of calcareous nannofossils and foraminifers (*13*). We believe that these Eocene beds are the source of the reworked Eocene fossils and lithoclasts found in Pleistocene sediments cored nearby at site 6017. The top of the Eocene strata at site 6019 corresponds to a prominent seismic reflector that is widespread beneath the northern margin of Georges Bank (*14*).

Oligocene. Rocks of Oligocene age form a relatively thin carbonate unit that is widely distributed offshore. Onshore, they are well represented beneath the Atlantic coastal plain south of Virginia (*15*) but are presumably absent or restricted to small basins beneath the northern coastal plain. We cored Oligocene sediments in core hole 6002, where 70 m of carbonate mud and calcareous silty clay are present. The Oligocene sequence appears incomplete; it is partly equivalent in age to the upper part of the Cooper Formation in South Carolina (*4*). Calcareous nannofossils and planktic foraminifers are abundant (*16*). The site is 50 to 60 km north of two other shelf core holes (JOIDES 1 and 2) that penetrated middle and lower Oligocene rocks 10 to 30 m thick. The Oligocene has also been cored at several other offshore localities (*7*).

Miocene. Offshore Miocene strata contain significantly less carbonate than the underlying Paleogene sediments. This is particularly evident north of Cape Hatteras, where rich assemblages of diatoms and radiolarians replace the calcareous nannoplankton and foraminifers. Phosphorite and glauconite grains are also notable constituents of the Miocene south of Cape Hatteras, but only the glauconite extends farther north. These latitudinal changes in fauna and sediment composition are accompanied by thickening of the Miocene sequence to the north. The AMCOR Project recovered Miocene rocks at sites 6002, 6004, 6007, 6009 to 6012, and 6016. Several of the JOIDES and ASP core holes also penetrated Miocene rocks (*7*).

AMCOR hole 6002 penetrated approximately 47 m of upper, middle, and lower Miocene phosphatic silty clay units. The lower Miocene interval contains approximately 9 m of olive silty clay (*17*). Abundant radiolarians and diatoms and sparse planktic foraminifers identify the overlying 38 m of olive silty clay as middle Miocene. Above this, 10 m of olive silty clay topped by dark grayish brown phosphatic sand contain late Miocene(?) diatoms (*18*).

On the slope off South Carolina, core holes 6004 and 6004B penetrated approximately 80 m of middle and lower(?) Miocene clay and sand. The lower 20 m of this interval is still olive gray clay containing planktic foraminifers (*19*) characteristic of the lower Miocene, but these species also range into the lower middle Miocene. The foraminiferal tests in this interval have undergone incipient chemical diagenesis. They are partly dissolved and dolomite has been precipitated as rhombohedrons that often penetrate the outer layers of the tests (see cover). Middle Miocene light olive foraminiferal sand units are 80 m thick and contain numerous diagnostic foraminifers (*20*). No upper Miocene sediments were present.

Off the Middle Atlantic States, five AMCOR core holes penetrated Miocene strata. On the inner New Jersey shelf, core hole 6011 was drilled through approximately 67 m of dark green to olive sand and sandy silt containing diatoms and radiolarians of early middle Miocene age; calcareous microfossils are rare. Below this interval, approximately 95 m of dark gray sands and silty clays are nearly barren of microfossils, although molluscan fragments are common. We have tentatively assigned this part of the section to the Miocene but have not determined its position within the Miocene.

Beneath the outer shelf of this region, Miocene strata were encountered in core holes 6007, 6009, 6010, and 6012. Core hole 6007 penetrated approximately 134 m of Miocene diatomaceous gray sand and olive silty clay. Calcareous nannoplankton and foraminifers are too sparse for reliable dating, but the abundant diatoms suggest a late Miocene age.

At site 6009, at least 130 m of dark gray and brown sand and silty clay contain a microfossil assemblage of chiefly benthic foraminifers (*21*). Nearly identical strata are 85 m thick at site 6010. About 45 km north of site 6010, the COST B-2 well completely penetrated the Miocene interval, revealing a total thickness of approximately 800 m in this part of the Baltimore Canyon Trough. The upper and middle Miocene sequences here are predominantly terrigenous and can probably be correlated with the terrigenous Miocene beds in AMCOR cores 6007, 6009, and 6010; the lower Miocene sequence, in contrast, is distinctly more calcareous in the COST B-2 well.

Off Long Island, core hole 6012 terminated in about 9 m of highly glauconitic plastic silty clay that is barren of microfossils. The lithologic similarity to Miocene rocks farther south suggests that it may be of Miocene age.

The northernmost Miocene samples come from 6016 (and 6016B) on Georges Bank. Approximately 1.2 m of dark gray clayey silt at the bottom of the core hole contained a microfossil assemblage of mainly benthic foraminifers (*22*).

Pliocene. North of Cape Hatteras, Pliocene rocks, like those of Miocene age, are terrigenous clastic sequences and contain siliceous microfossils. Core holes 6007, 6009, and 6010 from this region contain probable Pliocene intervals, but only south of Cape Hatteras, at site 6004, did the core samples contain sufficient calcareous nannofossils and planktic foraminifers to firmly establish a Pliocene age; there, about 14 m of olive sandy clay includes a typical upper Pliocene foraminiferal assemblage (*23*). Off Virginia, core holes 6007 and 6007B penetrated a 25-m section of dark gray clayey sands and silty clay containing diatoms and sparse planktic foraminifers (*24*) that suggest a Pliocene age. On the New Jersey outer shelf, core holes 6009 and 6009B penetrated 25 m of gray silty clay, sand, and gravel containing a microfossil assemblage of principally benthic foraminifers (*25*). Rare specimens of planktic forms (*26*) suggest a Pliocene age for the interval in core holes 6009

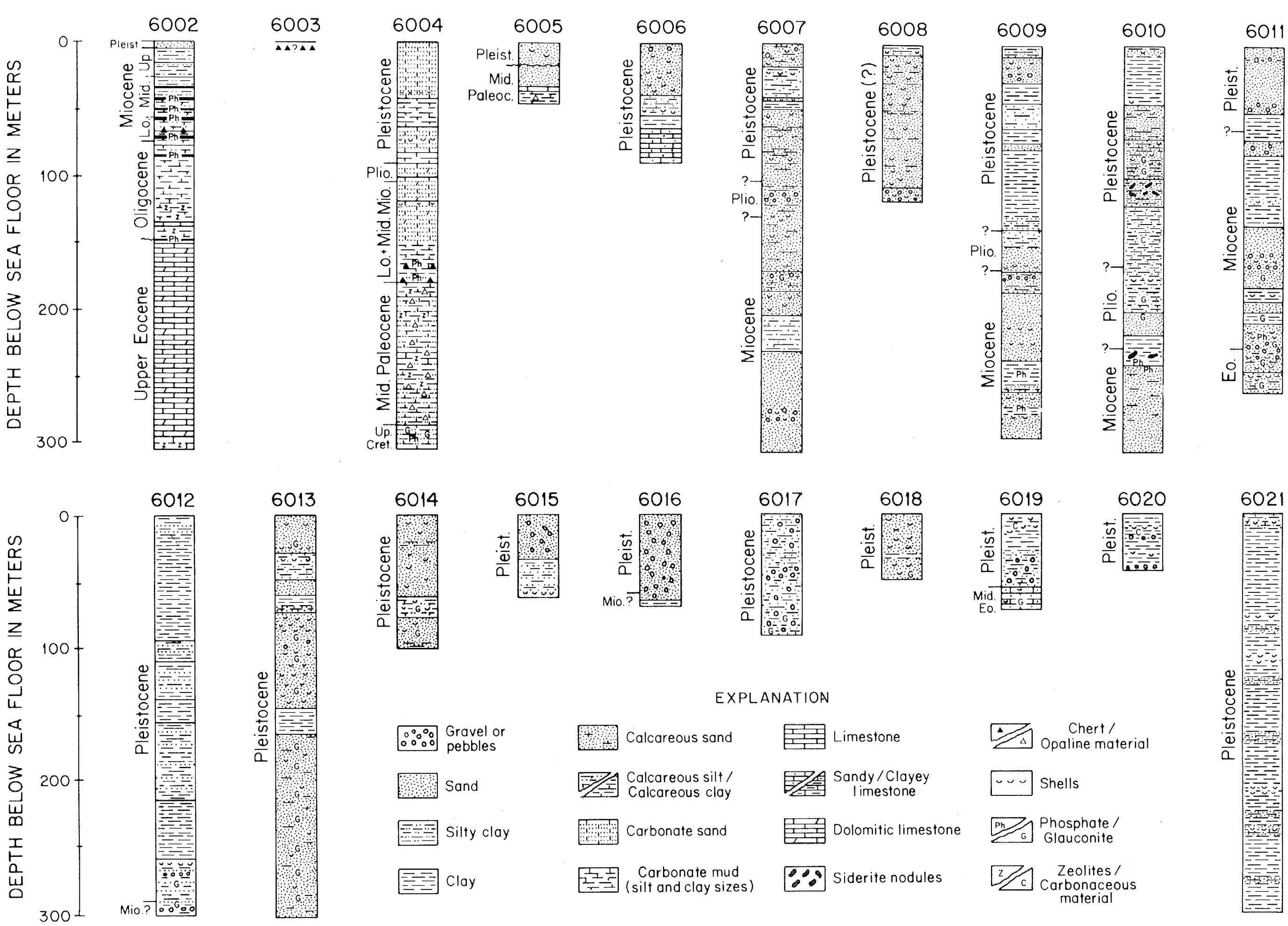


Fig. 2. Lithologic and stratigraphic columns of AMCOR sites. Site locations are shown in Fig. 1a.

Table 2. Drilling programs on the Atlantic outer continental shelf and slope before 1978 (*100*).

Year	Program	Purpose	References
1954	Texas Tower Feasibility Studies (TT)	Platform foundation investigation	(*101, 102*)
1959–1960	U.S. Coast Guard Light Tower Foundation Studies (LT)	Platform foundation investigation	(*103*)
1965	Joint Oceanographic Institutions Deep Earth Sampling (JOIDES)	Stratigraphy and geologic structures	(*8, 104*)
1967	Atlantic Stratigraphic Project (ASP)	Stratigraphic testing	(*7, 82, 105*)
1970	Deep Sea Drilling Project (DSDP), Leg 11	Stratigraphy and geologic structures	(*35*)
1973	Atlantic Generating Station studies (AGS)	Foundation investigation	(*106*)
1975	East Coast Air Maneuvering Range Studies (USN-ACMR)	Platform foundation investigation	(*107*)
1975	Deep Sea Drilling Project (DSDP), Leg 44	Stratigraphy, geologic structures, geochemistry	(*108*)
1975–	Continental Offshore Stratigraphic Testing (COST)	Deep stratigraphic testing	(*12*)
1976	Atlantic Margin Coring Project (AMCOR)	Stratigraphy, structure, geochemistry, hydrology, geotechnical properties	(*1*)

and 6009B. Planktic specimens are absent in an equivalent 65-m interval in core hole 6010 in the same region, but lithology and stratigraphic position suggest that this interval is also of Pliocene age. The nearby COST B-2 well (Fig. 1a) penetrated a Pliocene interval of similar thickness (66 m), lithology, and microfossil content (*7*).

Pleistocene. Strata of Pleistocene age were penetrated at every AMCOR site. [We include here the lower Holocene sand sheet that forms much of the seafloor surface along the Atlantic shelf (*27*).] Terrigenous clastic sediments are predominant at all sites. Carbonate in the form of fossils is common on the shelf edge off South Carolina (site 6004), but is much reduced shoreward and to the north. Glacially derived coarse detritus is abundant on Georges Bank. Thickening of the Pleistocene section northward and toward the shelf edge is illustrated in Fig. 2.

On the Georgia and South Carolina shelf, gray to white quartzose sand units constitute the Pleistocene (sites 6002 and 6005). Core hole 6005 contained 20 m of Pleistocene quartzose sand (*28*), and core hole 6002 contained 14 m of diatomaceous quartzose sand. Off South Carolina, core hole 6004 penetrated the thickest Pleistocene interval found south of Cape Hatteras (85 m). Shelly olive carbonate sand in the lower half and olive clayey sand in the upper half contain abundant calcareous nannoplankton and planktic foraminifers (*29*).

In the Cape Hatteras region and northward, the Pleistocene section thickens on the outer shelf and upper slope. Core hole 6006 off North Carolina penetrated 120 m of shelly silt, sand, clay, and limestone (*30*). Core hole 6007, on the Maryland outer shelf, contains 102 m of Pleistocene dark gray sand and silty clay with a microfauna similar to that in core hole 6006, except that planktic specimens are rare.

On the inner shelf of Maryland, core hole 6008 penetrated 120 m of dark gray, often shelly, sand, gravel, and silty clay that are nearly barren of microfossils (*31*). The lowermost 3 m, which contains coarse sand and pebble gravel, appears to be an offshore extension of the Ocean City–Manokin aquifer system that underlies the Maryland coast. Weigle (*32*) reported that the onshore strata of the aquifer are of Miocene age, but our samples contain no diagnostic fossils.

A series of nine core holes penetrated Pleistocene sediments on the New Jersey shelf and slope (Fig. 2). On the inner shelf, core hole 6011 yielded 70 m of dark olive silty clay and coarse gray sand that is barren of microfossils and is tentatively assigned to the Pleistocene. On the middle shelf core hole 6020 terminated in Pleistocene beds at 44 m (*33*), and on the outer shelf core holes 6009 and 6010 penetrated 59 and 170 m, respectively, of Pleistocene dark gray silty clay and fine sand with occasional layers of pea gravel. The microfaunas are richer in specimens than those from the shoreward core holes, but the predominant species are largely the same.

On the upper slope, core hole 6021 penetrated 305 m of Pleistocene dark to medium gray silty clay (Fig. 2). The microfaunas vary considerably, but three benthic assemblages of foraminifers are prominent (*34*). Farther down the slope, core holes ASP 14 and 15 and DSDP 108 also penetrated the Pleistocene section, which thins from 220 m at ASP 14 to around 10 m at ASP 15 and DSDP 108 (*7*). [We assume that Pleistocene strata overlie the Eocene at DSDP 108, but none were actually recovered (*35*).] The dark to medium gray silty clays at these deeper sites contain sparse benthic and planktic foraminifers of the same species that occur on the shelf. However, diatoms and radiolarians are more abundant than on the shelf.

On the upper slope off Long Island and Massachusetts, core holes 6012 and 6013 penetrated approximately 300 m of Pleistocene strata. At 6012 the sediments are largely dark gray silty clay units, but at 6013 dark silty clay alternates with dark gray silty sand and fine sand. The microfossils are similar to those from core hole 6021; *Elphidium clavatum* (Cushman) is especially prominent in the upper 100 m, and numerous intervals are rich in diatoms. The only significantly different assemblage of foraminifers is found in the bottom 30 m of core hole 6012 (*36*).

The remaining core holes (6014 to 6019) on or adjacent to Georges Bank contain chiefly Pleistocene sediments. Those on top of the bank (6016 and 6018) penetrated mainly coarse gray sand and gravel. The sediments change to dark silty clay on the flanks of the bank (6015, 6017, and 6019) (*37*). The most unusual assemblage is in the upper 16 m of core hole 6019 in the Franklin Basin north of Georges Bank. The dark gray gassy clay leaves washed residues that consist nearly entirely of diatoms and organic particles. Foraminifers, sponge spicules, echinoid remains, and mollusk shells are also present (*38*). This may be a Holocene deposit, with possibly modern constituents at the surface.

Paleoecology

Figure 3 illustrates the paleoecology of cored strata approximately along the depositional strike as inferred from the microfossil assemblages. The oldest strata, Upper Cretaceous clay units at site 6004 (Fig. 2), contain abundant planktic and deep-water benthic microfossils that indicate a slope environment of deposition; overlying faunas indicate that these conditions persisted in the Paleocene as well. The unconformity separating Maastrichtian from middle Paleocene slope deposits is therefore of submarine origin. The only other Paleocene strata encountered (core hole 6005 on the inner shelf) contained sparse benthic foraminifers of shallow marine origin.

The Eocene is characterized by well-developed middle and outer shelf car-

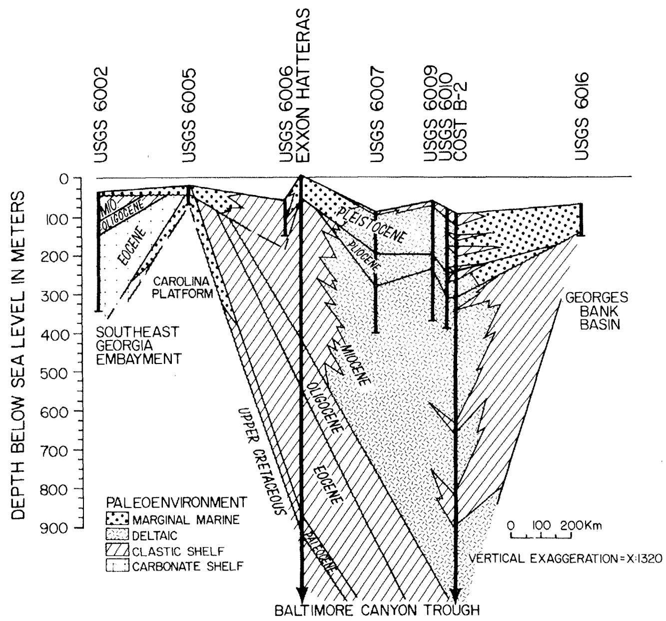


Fig. 3. Paleoecology of the Tertiary of the Atlantic continental shelf from the Southeast Georgia Embayment to the Georges Bank Basin.

bonate deposits in most of the core holes. The major latitudinal change is from carbonate platform deposits containing larger foraminifers and sparse planktic forms in the Southeast Georgia Embayment (core hole 6002) to smaller benthic foraminifers associated with planktic species to the north in the Baltimore Canyon Trough and Georges Bank Basin (core holes 6011 and 6019). As indicated by data from the COST B-2 well, the most significant marine transgression known in the Baltimore Canyon Trough took place during the Eocene (*7*).

Oligocene strata, observed only in core hole 6002, were deposited on the upper slope, where abundant planktic specimens accumulated. Similar Oligocene assemblages from the COST B-2 well suggest a similar paleoenvironment for the central Baltimore Canyon Trough.

The Miocene was a time of considerable paleoclimatic and paleoenvironmental change on the Atlantic margin. Lithofacies and biofacies became distinctly more provincial. The Miocene deposits of core hole 6004 are the deepest water deposits of this age recovered during the AMCOR drilling. The abundance of planktic and deep-water benthic foraminifers indicate slope conditions similar to those now prevailing at that site. Inner and outer shelf deposits characterize the other Miocene sites, except off Maryland and New Jersey, where sparse benthic foraminiferal assemblages, abundant nearshore and fresh-water diatoms, and prograding sediment wedges as seen on seismic reflection profiles all indicate deposition of a major Miocene deltaic complex.

Pliocene strata at site 6004 are of slope origin. As in the Miocene, however, deltaic environments persisted off the Middle Atlantic States.

The most complete paleoenvironmental changes took place during the Pleistocene. Warm-water planktic foraminifers are decidedly more abundant south of Cape Hatteras. Although a nearly complete deep-water Pleistocene stratigraphy has been established in core hole 6004, no sediments indicative of a cool-water environment were found. Perhaps the Gulf Stream, which passes just seaward of site 6004, buffered this location from the incursion of cooler-water planktic assemblages during glacial intervals.

Off New Jersey, Delaware, and Maryland, deltaic conditions persisted well into the Pleistocene. Northward on the New England upper slope, the thick Pleistocene intervals contain abundant sediments derived from the shelf, and planktic species are sparse. Alternating intervals containing shallow- and deep-water benthic microfossils are present, but we have not yet determined a detailed Pleistocene history. On Georges Bank, much of the Pleistocene sediment is glacially derived and barren of microfossils, but intervals of inner shelf, lagoonal, and near-delta or fluvial sediments were encountered. The origin of the unusual assemblage at the top of core hole 6019 is not known, but we speculate that it may have accumulated in an anoxic depression. We noted similar assemblages deeper in several other Pleistocene cores in this area.

Several depositional hiatuses at sites 6002 and 6004 provide evidence of important paleoenvironmental events (Fig. 2). At site 6002, the following intervals are missing: uppermost Eocene and lowermost Oligocene, upper Oligocene and most of the lower Miocene, and upper Miocene and all of the Pliocene. These are identical to hiatuses in JOIDES core holes 1 and 2 and in the COST GE-1 well (*39*), and all correspond to low periods of global sea level (*40*). The missing intervals appear to have been eroded subaerially. Deep-water intervals within these holes are also correlated and correspond to periods of high global sea level.

In contrast to the subaerial erosion at site 6002, submarine erosion appears to have caused the two major hiatuses at site 6004; missing sections are the uppermost Cretaceous to middle Paleocene and the upper Paleocene through lower Miocene. Both hiatuses at 6004 are marked by channeled unconformities [channeling of middle Paleocene strata is especially striking on seismic reflection profiles (*41*)], but deep-water microfaunas on either side of both unconformities suggest that shoaling was not sufficient to expose the seabed at this location.

Preliminary Organic Geochemistry

Two major types of organic geochemical studies were performed in the AMCOR program: shipboard light hydrocarbon geochemistry and detailed geochemical studies of solvent-extractable organic matter. Shipboard analyses at seven sites (Fig. 1b) showed significant concentrations of light hydrocarbons—about 200 to more than 421,000 parts per million (ppm) by volume—including, in places, methane, ethane, and propane. In contrast, the light hydrocarbons measured during the Deep Sea Drilling Project in core samples from several world ocean basins ranged in concentration from background levels, less than 50 ppm, to more than 215,000 ppm, with virtually all the reported gas being methane of biogenic origin (*42–47*). Because petroleum exploration is under way in the Baltimore Canyon Trough, we have focused particular attention on the possible origin of the methane and on the presence of the higher homologs ethane and propane in the upper continental slope sediments of Pleistocene age in this region.

As the cores were brought to the surface, gas expansion pockets formed in them. Because the gas could not be sampled at the pressures and temperatures in situ, it was not possible to relate the gas concentrations in the expansion pockets to the sediment volume. Shipboard analyses were performed by use of a gas chromatograph equipped with a molecular sieve column and a platinum hot-wire detector. A standard volume (2 milliliters) of gas at standard temperature and pressure was withdrawn from the gas pocket through a septum-clamp device attached to the core liner. This gas was analyzed with the gas chromatograph, which was calibrated in parts per million (by volume) for each specific light hydrocarbon component (Table 3). The calibration is the detector response to a standard volume of gas of known composition. An equal volume of gas from the core liner was analyzed under the same conditions. In most analyses an air peak was present but was not quantified. Approximately 200 m of sediments in core 6021-C, at depths from 101 to 291 m (below the mud line), have methane concentrations greater than 282,000 ppm, with a maximum of more than 400,000 ppm in the interval 168 to 196 m. The same core yields ethane concentrations greater than 10,000 ppm and propane concentrations greater than 1300 ppm. The Pleistocene sediments in this core are very uniform, dark gray to medium gray silty clays with pore-water salinities ranging uniformly from 32.1 to 31.9 grams per kilogram.

The sparse occurrence of nannofossils throughout the 6021-C sediments suggests that decay of marine organisms is not the major source of the methane. The occurrence of ethane and propane supports a nonbiogenic thermocatalytic origin for most of the methane. The $\delta^{13}C$ values (*48*) were −29 to −48 per mil (*49*)—the middle to lower range for methane normally associated with liquid petroleum. These results suggested the presence of natural gas accumulations in this area of the Mid-Atlantic shelf and slope (*50*). This interpretation has been borne out by the recent discovery of natural gas in commercial exploratory wells in the Baltimore Canyon Trough.

In contrast to the high concentrations of methane, ethane, and propane in core hole 6021-C, ethane was detected in only one sample (at 235 m) in core hole 6007, located in the Mid-Atlantic region near the Virginia coast. In this core, the methane concentrations reached 417,000 ppm in middle Miocene sediments at a depth of 247 m. This methane is believed to be of biogenic origin. A greenish gray silty clay formed a seal immediately overlying the methane zone. The methane-rich sediment was composed of a very rich diatom ooze. Below this ooze, in the underlying unconsolidated sands, no light hydrocarbons were detected. These results suggest that the probability of natural gas deposits in this region of the Virginia Mid-Atlantic shelf is not as great as that in the Baltimore Canyon Trough area.

Site 6004 was selected for detailed organic geochemical characterization because of its extensive stratigraphic range (Fig. 2). The concentrations of total resolved aliphatic hydrocarbons, total resolved aromatic hydrocarbons, total fatty acid methyl esters, and total organic carbon measured in the sediments are presented in Table 4. The aliphatic hydrocarbon concentrations were very low, all less than 4.0 micrograms per gram. Similarly, the aromatic hydrocarbon concentrations were less than 1.0 μg/g, and in only one sample, 6004B-4-1 (lower Miocene), was there more than 1 percent total organic carbon. Concentrations of the fatty acid methyl esters were also low, less than 2 μg/g, with the exception of sample 6004-10-3 (upper Pliocene).

The resolved aliphatic hydrocarbon pattern of the Pleistocene sample 6004-8-2, illustrated in Fig. 4, is typical of most of the core sediments. Normal alkanes with 16 to 20 carbon atoms (n-C_{16} to n-C_{20}) and the isoprenoid hydrocarbons pristane and phytane are the dominant components. Longer chain normal alkanes are present in much lower concentrations. The unresolved complex mixture in this chromatogram ranges from n-C_{14} to n-C_{28} and is unimodal in character. Two exceptions to the predominance of n-C_{16} to n-C_{20} alkanes are the lower Eocene–upper Paleocene sample 6004B-7-6 and upper middle Paleocene sample 6004B-16-3, in which the dominant components are n-C_{23} to n-C_{30} alkanes. Normal alkanes considered to be of marine origin generally show a maximum at n-C_{17} or n-C_{18} and may range from n-C_{12} to n-C_{25}, usually with no odd or even predominance. Normal alkanes that are believed to have a terrigenous source usually show a strong predominance of odd-carbon atoms and may range from n-C_{25} to n-C_{33}, with a maximum at n-C_{27} or n-C_{29} (*51–53*).

We believe that marine organic matter

Table 3. Light hydrocarbon concentrations; N.D., not detected.

Sample number	Maximum penetration depth (m)	Lithology	Concentration (ppm by volume)		
			Methane	Ethane	Propane
6007-6-3	54.3	Sticky gray clay	1,215.5	N.D.*	N.D.
6007-10-1	92.4	Gray clayey sand with shells	1,402.5	N.D.	N.D.
6007-11-2	101.8	Gray clayey sand	761.4	N.D.	N.D.
6007B-1 CC	130.5	Olive gray silty clay with shells	N.D.	N.D.	N.D.
6007B-2-3	139.3	Olive gray silty clay	N.D.	N.D.	N.D.
6007B-10-5	215.5	Olive gray silt	2,835.8	N.D.	N.D.
6007B-11-6	225.3	Greenish gray silt and clay	7,441	N.D.	N.D.
6007B-12-3	234.7	Gray silty clay	43,195	N.D.	N.D.
6007B-12-4	231.6	Gray silty clay	3,055.5	N.D.	N.D.
6007B-12-6	233.9	Gray silty clay	407,500	N.D.	N.D.
6007B-12-6	234.7	Gray silty clay	417,500	4,210	N.D.
6021C-1-3	7.6	Dark gray, laminated, sandy clay	356	N.D.	N.D.
6021C-2-4	12.2	Dark gray sandy clay	1,339	N.D.	N.D.
6021C-3-2	25.6	Dark gray sandy clay	285	N.D.	N.D.
6021C-4-1	35.1	Dark gray sandy clay	4,755	36	N.D.
6021C-6-1	54.0	Dark gray sandy clay	229,018	2,895	206
6021C-7-2	63.4	Dark gray sandy clay	81,786	2,714	81
6021C-8-3	72.8	Dark gray silty clay	19,305	542	N.D.
6021C-9-3	82.3	Dark gray silty clay	10,237	649	N.D.
6021C-10-2	91.7	Dark gray silty clay	1,997	325	N.D.
6021C-11-3	101.5	Dark gray silty clay	292,930	8,108	1,013
6021C-12-3	111.0	Dark gray silty clay	282,278	3,378	1,013
6021C-14-1	129.8	Dark gray silty clay	282,278	1,508	723
6021C-16-1	149.1	Dark gray clayey sand	282,278	2,116	429
6021C-17-1	158.5	Dark gray silty clay	287,604	2,094	404
6021C-18-2	168.0	Dark gray silty clay	410,102	10,135	1,240
6021C-19-2	177.4	Dark gray silty clay	410,102	10,135	827
6021C-21-2	196.3	Dark gray silty clay	412,765	3,137	207
6021C-23-3	215.8	Dark gray silty clay	287,760	7,239	1,240
6021C-24-1	225.6	Dark gray silty clay	287,538	7,239	1,157
6021C-25-1	235.0	Dark gray silty clay	287,604	3,378	289
6021C-26-5	244.5	Medium gray clay	286,538	10,617	1,240
6021C-27-1	253.9	Medium gray clay	284,941	6,273	1,157
6021C-28-1	263.4	Medium gray silty clay	284,941	6,273	1,034
6021C-29-2	273.1	Medium gray silty clay	287,604	5,309	1,351
6021C-39-2	282.6	Medium gray silty clay	287,604	6,604	1,240
6021C-31-1	291.7	Medium gray silty clay	290,267	7,239	1,240

is the dominant source of the hydrocarbons in the sediments of Cretaceous to Holocene age. The only exceptions are the lower Eocene–upper Paleocene interval and the upper middle Paleocene interval, which are believed to show a slightly greater input of hydrocarbons from a terrestrial source to the outer to middle shelf depositional environments. Paleogeothermal gradients in this area are unknown and present-day geothermal gradients are relatively low. These sediments and the indigenous organic matter are believed to be thermally immature because of the shallow burial depth and the low geothermal gradients.

The fatty acid methyl ester fractions consist of a small amount of monounsaturated acids $C_{16:1}$ and $C_{18:1}$, with the even-carbon saturated acids from $C_{14:0}$ to $C_{26:0}$ predominating. Marine fatty acids are usually in the range $C_{12:0}$ to $C_{20:0}$, with a strong even-carbon predominance and a maximum at $C_{16:0}$ or $C_{18:0}$. Fatty acids attributed to a terrestrial source appear mainly in the range $C_{20:0}$ to $C_{32:0}$, also showing a strong even-carbon predominance, with a maximum at $C_{24:0}$ or $C_{26:0}$ (*53*). In the core 6004 sediments the highest fatty acid concentrations are at $C_{16:0}$ and $C_{18:0}$, suggesting marine planktic and algal source. The presence of minor amounts of branched $C_{15:0}$ may indicate degradation by bacteria.

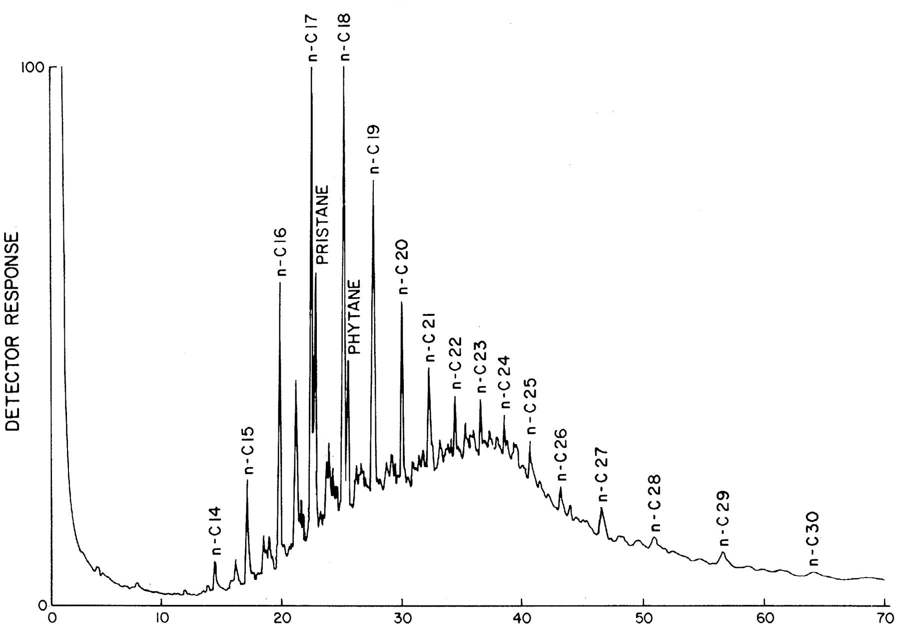


Fig. 4. Gas chromatogram of aliphatic hydrocarbons detected in sediments of early Pleistocene age from site 6004.

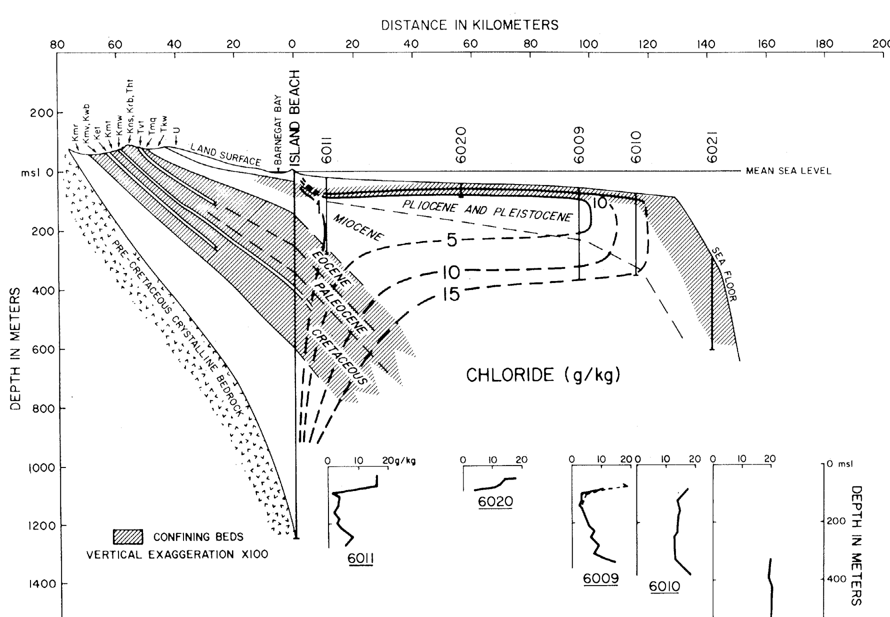


Fig. 5. Hydrologic section of the coastal plain of New Jersey and the continental shelf off Barnegat Inlet, New Jersey. Dashed contours show the chlorinity of pore water. Stratigraphic units of the New Jersey coastal plain (*63*) are: *U*, undifferentiated aquifer; *Tkw*, aquifer in Kirkwood Formation; *Tmq*, Manasquam Formation; *Tvt*, aquifer in Vincentown Formation; *Tht*, Hornerstown Sand; *Krb*, Red Bank Sand; *Kns*, Navesink Formation; *Kmw*, aquifer in Mount Laurel Sand and Wenonah Formation; *Kmt*, Marshalltown Formation; *Ket*, aquifer in Englishtown Formation; *Kwb*, Woodbury Clay; *Kmv*, Merchantville Formation; and *Kmr*, aquifer in Magothy and Raritan formations.

In general, the low concentrations of resolved hydrocarbons and fatty acids at site 6004 suggest that oxidative conditions in the water column resulted in the chemical degradation of extractable organic components before deposition. Normal productivity in the photic zone is indicated by organic carbon values near the average of 0.27 percent for carbonate sediments (*54*) and by the presence of abundant microfossils in the Tertiary and Upper Cretaceous. The organic carbon values in the lower Miocene (1.2 percent in sample 6004B-4-1) and the upper Pliocene (0.55 percent in sample 6004-10-3) indicate increased preservation of organic matter during these periods, possibly due to a more anaerobic depositional environment, an increased source of organic matter, and greater rates of sedimentation.

Analysis of organic carbon in AMCOR samples revealed anomalously high concentrations in some intervals at sites 6002 and 6019: 1 to 5.5 percent in a 122-m section of Miocene and Oligocene sediments in hole 6002, and 1 to 2 percent in the upper 30 m of Holocene to Pleistocene sediment in hole 6019. These values contrast with the low concentration and narrow range of organic carbon measured in all other samples, which averaged 0.40 ± 0.24 percent. Although there is a general correlation between the concentration of organic carbon and the proportion of clay-sized material in the sediments, the anomalously high organic carbon concentrations are much higher than could be predicted on the basis of grain size. Both sections of high organic carbon contain a faunal assemblage that represents an inner and a middle shelf paleoenvironment. As samples of similar age and similar paleoenvironment from other cores have average organic carbon levels, it appears that the anomalous values at sites 6002 and 6019 are related to a local paleoenvironment that favored the collection and preservation of organic matter.

Hydrogeology and Water Chemistry

Anomalous fresh and brackish water. One of the most significant discoveries made during the AMCOR project is that relatively fresh ground water occurs beneath much of the Atlantic continental shelf. Detailed sampling of interstitial water at each site also defined zones of high salinity, which are influenced by deeply buried evaporite deposits. Relations between alkalinity, H_2S, sulfate, and methane measured in pore fluids suggest a large-scale upward migration of gaseous hydrocarbons at some locations and, at one location, the maintenance of bacterial activity since middle Tertiary time.

Squeezing techniques (*55, 56*) were used to collect 175 interstitial water samples from sediment cores after all mud-invaded surfaces had been removed. Shipboard chemical measurements generally followed techniques used in the Deep Sea Drilling Project (*56–58*). Remaining constituents were determined at the U.S. Geological Survey National Water Quality Laboratory at Lakewood, Colorado, by micromodification of Technicon AutoAnalyzer techniques (*59*). The reproducibility of the sampling and analytical procedure can be assessed from the results for sites 6009 and 6009B, which were drilled with fresh-water mud and seawater mud, respectively (inset Fig. 1c); inexact match of sampling depths accounts for the difference between cores.

A map of minimum chlorinity values observed at the core hole sites (Fig. 1c) gives a general indication of the geographic distribution of pore-water chlorinity in sediment underlying the continental shelf and slope. In general, very low chlorinity (less than g/kg) is found at distances of less than about 16 km off the Delaware–Maryland–New Jersey coast but as much as 120 km off the Florida coast (*60*).

A sharp decrease of chlorinity was observed through a confining bed of clay in hole 6008 (inset in Fig. 1c) before the drill penetrated sand and gravel horizons at a depth of 150 m below mean sea level, equivalent to the Ocean City–Manokin aquifer on the mainland (*32*). The chlorinity profile for hole 6008 is typical of that for sites where an aquifer containing relatively fresh water underlies and is protected from rapid vertical intrusion of seawater by a confining bed of low permeability.

The general pattern of decreasing chlorinity with depth below the floor of the continental shelf was also observed on the landward side of Georges Bank about 250 km off the Massachusetts coast. Caving, or sloughing, of Pleistocene glacial-outwash sand and gravel stopped the drill at relatively shallow depth. However, minimum chlorinities of about 12.4 g/kg in hole 6017 and 15.6 g/kg at the bottom of hole 6019 [the general chlorinity of seawater in this area is about 18 g/kg (*61, 62*)] suggest that low-salinity water might also be present under Georges Bank in this far offshore area (Fig. 1c).

Table 4. Concentrations of total organic carbon, resolved aliphatic and aromatic hydrocarbons, and fatty acid methyl esters in sediment samples from site 6004.

Core	Total organic carbon (%)*	Aliphatic hydrocarbons (μg/g)†	Aromatic hydrocarbons (μg/g)†	Fatty acid methyl esters (μg/g)‡
6004-2-3	0.12	2.6137	0.1135	1.3560
6004-5-4	0.26	0.4587	0.0486	0.4952
6004-8-2	0.37	3.1610	0.4564	0.5288
6004-10-3	0.55	1.3946	0.0766	2.5587
6004-13-6	0.21	0.6085	0.0291	1.2862
6004B-2-6	0.17	0.7547	0.0160	1.0708
6004B-4-1	1.20	0.9859	0.4129	1.2841
6004B-7-6	0.24	2.2100	0.1033	0.6188
6004B-13-2	0.21	1.0716	0.4445	0.4461
6004B-16-3	0.14	0.7322	0.0909	1.2980
6004B-20-3	0.22	0.7219	0.0377	1.4923

*Calculated on the basis of sediment dry weight. †Micrograms of total resolved hydrocarbons per gram of sediment. ‡Micrograms of total fatty acid methyl esters per gram of sediment.

Salinity transect off New Jersey. The most striking documentation of low-salinity water beneath the continental shelf was obtained in a transect of five core holes across the shelf east of Barnegat Light, New Jersey. Isochlor lines in Fig. 5 show that relatively fresh ground water (5 g/kg) forms a flat-lying lens extending more than 100 km offshore. The blunt-nosed shape and estimated position of the lower isochlor lines are based in part on data from onshore observation wells (*63, 64*) and on the shape of isochlors observed in the transition zones in the Biscayne (water table) aquifer and the Floridan (artesian) aquifer of Florida, where extensive studies of salt-water encroachment have been made (*64–70*).

Overlying this lens of relatively low salinity water, which has a minimum chlorinity of 820 milligrams per kilogram, is an extremely sharp chlorinity gradient increasing toward the chlorinity of seawater in holes 6011, 6020, and 6009 (insets in Fig. 5). This high gradient occurs in the low-permeability clay in the upper part of the Miocene deposits in hole 6011 and in Pleistocene deposits in holes 6020 and 6009. The clay constitutes a confining bed for the underlying permeable beds of the Kirkwood Formation, which were under artesian pressure on the mainland prior to intensive ground-water development after 1900. Ground-water levels on the island beaches (equivalent to the "800-foot sand" at Atlantic City) have been drawn down to as much as 30 m below sea level by heavy pumping. The integrity of the confining bed is important as it is an impediment to rapid downward infiltration of seawater into mainland well fields. An implication of the present work is that salt-water intrusion would have taken place long before now if it had not been for the existence of the offshore fresh-water lens, whose extent was not even guessed at by early workers concerned about saline encroachment (*71*).

Origin of fresh ground water beneath the continental shelf. Two modes of origin of fresh water in offshore strata may be considered: (i) submarine discharge from extensions of mainland aquifers (*66, 72, 73*) and (ii) remnants of fresh ground water that infiltrated and became trapped in shelf sediments during the Pleistocene glacial maximum, when land extended far seaward of the present coastline. The crossing of lithologic and stratigraphic boundaries by the isochlors and the extent of low-salinity water far offshore of New Jersey and Massachusetts suggest that in the Northern and Middle Atlantic segments, relict Pleistocene waters are responsible for the observed phenomena. This is in agreement with the inferred origin of anomalously deep fresh waters found by pore fluid extraction in drill cores from Nantucket Island (*70*). Since the last flooding of the continental shelf about 8000 years ago (*74–76*), the ground-water reservoir would require more than 30,000 years to reach a new equilibrium (*77*).

In the southern Atlantic margin, the situation is complicated by the relatively high permeability of cavernous limestone in the Floridan aquifer and by the breaching of the overlying confining beds by submarine springs and submarine sinkholes—the latter being inactive sites of former submarine springs now converted to points of salt-water intrusion (*67, 70, 73, 78, 79*). In certain areas, such as Savannah, Georgia (*80*), and the coastal areas south of Saint Augustine (*81*) and near the Tampa–Saint Petersburg area in Florida, the saline water in the aquifer appears to be in hydrodynamic equilibrium with the present level of the sea.

Increased salinity and buried evaporite relationships. Drill sites on or near the shelf edge characteristically show only a slight or no significant decrease in interstitial chlorinity with depth, with values fluctuating close to the mean for seawater (19 g/kg). At the two southernmost sites, 6002 and 6004 (Fig. 1c), salinity and chlorinity increase with depth to 40.7 and 23.7 g/kg, respectively—well beyond maximum contemporary or Pleistocene seawater values. Similar increases were observed earlier in three holes on the continental slope and Blake Plateau off Florida to South Carolina (*60*), and more recently for a slope site off New Jersey (*82*). Such increases in pore-water salinity are normally associated with the presence of buried (often deeply buried) evaporitic strata, as confirmed in many areas by study of cores from DSDP sites (*56, 83*). These increases have been attributed (*56*) to molecular diffusion of salt upward in response to concentration gradients, and the presence of evaporitic strata beneath the Atlantic continental margin has been inferred from COST well, geophysical, and other evidence (*7, 84*). The increasing chlorinity gradient of Fig. 1c strongly supports the inference of ancient evaporitic strata at depth.

Sediment, water, and organic matter interactions. Two further types of pore-water anomalies were found in the AMCOR test holes. At sites 6002 and 6004, significant alkalinity and H_2S anomalies are correlated with phosphate-enriched organic matter in Miocene and Oligocene rocks (Fig. 6). Alkalinity can be produced by a bacterially mediated sulfate-reduction process (*85*), which is normally followed by biogenic methane formation (*86*), shown schematically by

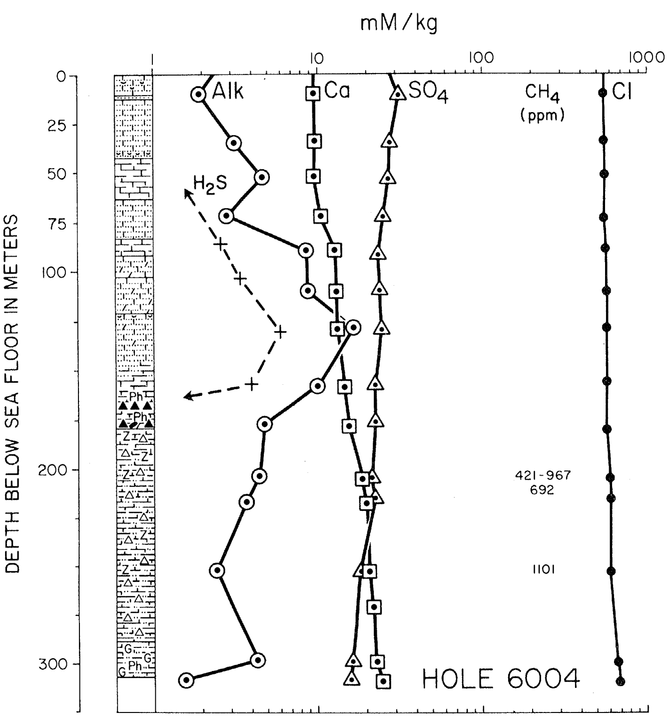
$$2CH_2O + SO_4^{2-} = 2HCO_3^- + H_2S \quad (1)$$

To sustain bacterial production of H_2S and alkalinity, breakdown of organic matter must have been a continuous process since middle Tertiary time, when the phosphate-rich strata were laid down—that is, about 20 million years ago. Also, to sustain this process beyond the point where the sulfate originally buried with the sediments was exhausted, it appears that sulfate must be supplied by downward diffusion from overlying seawater or by lateral hydraulic flow and hydrodynamic dispersion (*65, 68, 69, 77*).

Simple steady-state calculations based on electrical resistivity measurements of the present drill core sediments (*1*) and relationships linking these to diffusional properties (*87, 88*) indicate a downward flux of 2 g of sulfate per square centimeter per 10^6 years. This is equivalent to a yearly organic matter consumption of about 1.4×10^{-6} g/cm^2, using the molecular ratios of organic matter and sulfate given by Eq. 1. If this flux took place through a 50-m-thick section of rock at a depth of 200 m below the sea floor since early Miocene time (22 million years), a minimum of about 0.03 percent organic carbon, expressed in terms of dry sediment, would have been consumed. Also, we must consider the possibility that methane gas, observed below the phosphate-rich horizons (*1, 50*), moved upward and participated in bacterially mediated reactions with downward or laterally diffusing sulfate.

A more extreme alkalinity anomaly is found in hole 6013 (Fig. 7), where values of 86 milliequivalents per kilogram (total alkalinity) approach the highest found in any marine interstitial waters. We believe alkalinity to be due largely to the bicarbonate ion. The steep sulfate gradient below 20 m suggests that the zone of most active reaction is in the region 20 to 40 m below the sea floor. The entire section is Pleistocene. The high alkalinity cannot be due to attack on carbonates because calcium is depleted in the interstitial waters, which have ammonia concentrations as high as 27 millimoles per kilogram. The high gas content in the sediments and the relatively constant proportions of straight-chain aliphatic hydrocarbons in the range C_1 to C_6 (*50*) suggest that migration of hydrocarbon gas may be taking place and may contribute to sulfate reduction at site 6013.

Sediment organic matter and sulfate interactions. The interactions of sediment organic matter with sulfate of seawater origin have resulted in an unusual sulfate distribution in the Pleistocene and younger sediments of hole 6019. Whereas concentrations decreasing with depth were observed at most locations,



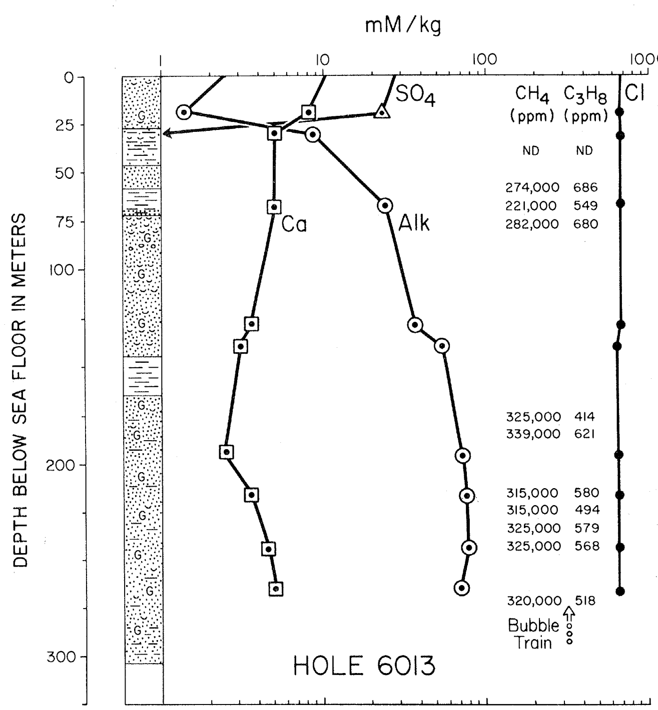


Fig. 6 (left). Variation of hydrogen sulfide, alkalinity (quantity of HCl needed to titrate a sample to pH 4.5), calcium, sulfate, methane, and chlorinity with depth and lithology at site 6004. See Fig. 2 for explanation of lithologic symbols. Fig. 7 (right). Variation of alkalinity, calcium, sulfate, methane, propane, and chlorinity with depth and lithology at site 6013. See Fig. 2 for explanation of lithologic symbols.

in core 6019 the sulfate levels in the upper 29 m of sediment are less than 0.2 g/kg, but below 30 m sulfate increases with depth to a value of about 1.7 g/kg in the deepest sediment recovered (Fig. 8).

The strong depletion of sulfate in the upper 29 m is undoubtedly due to vigorous reduction, because the sediment in this interval contains 1 to 2 percent organic carbon and abundant H_2S and biogenic methane. The exceptionally high alkalinity values, as much as 60 meq/liter, suggest that sulfate of seawater origin is diffusing into the sediment and reacting with organic matter to produce H_2S and HCO_3^-. The reaction is apparently vigorous enough to limit sulfate concentrations to near zero in samples above 30 m. The small values measured may, in fact, be due to sulfide oxidation during sampling and storage.

Below 29 m, the shape of the sulfate profile suggests that the organic-rich section is consuming the sulfate that diffuses upward from deeper sediments which have lower concentrations of organic carbon and no observed H_2S or methane. A simple time-dependent diffusion model (*89*) was used to calculate the diffusion coefficient required to account for the observed sulfate profile below 29 m by vertical diffusion. From carbon-14 data (*90*), an age of 8000 years is estimated for the 29-m interface. If the upper organic-rich sediments rapidly depleted the sulfate available in original pore waters so that diffusive gradients were formed soon after this sediment began to accumulate, an apparent diffusion coefficient can be chosen on the basis of the best fit between calculated and observed sulfate concentrations at various depths. The diffusion coefficient obtained in this way is 3.25×10^{-6} cm²/sec. The solid line in Fig. 8 represents the best-fit distribution of sulfate, using this diffusion coefficient and the age of 8000 years for the base of the organic-rich unit.

The calculated apparent diffusion coefficient is greater than might be expected, as it is only slightly less than the value of 4×10^{-6} cm²/sec obtained experimentally for surficial sediments that are highly unconsolidated (*91*) or in free solution (*92*). This suggests that processes in addition to vertical diffusion, such as migration of methane bubbles, may be balancing the upward flux of sulfate from deeper sediments.

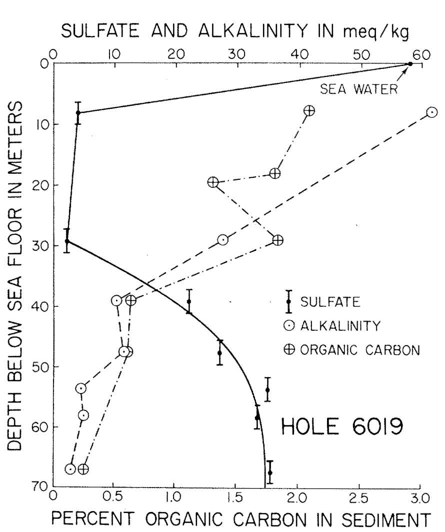
Geotechnical Engineering Studies

Geotechnical engineering studies of AMCOR sediments were designed to provide basic information on identification, strength, compressibility, and response to dynamic loading. These properties are important for the assessment of geologic hazards and the quantitative analysis of offshore geologic processes.

The identification tests included measurements of size distribution, mineralogy, plasticity (liquid and plastic limits), bulk density, and grain specific gravity. A tremendous variety of materials was found, although from an engineering standpoint these sediments were not particularly unusual, with a few notable exceptions, and in many cases were similar to the terrestrial sediments of the adjacent coastal plain.

Soil plasticity classification of the fine-grained silts and clays (Fig. 9) indicates that most of the sediments fall within the range of normal coastal plain sediments of the eastern United States. Most of the sediments collected during AMCOR and tested for engineering properties were of Pleistocene or Holocene age. Sediments older than Pleistocene are clearly a separate group in Fig. 9. In addition to having consistently higher plasticity than most AMCOR sediments, the Tertiary sediments generally have higher stability and lower compressibility than would be expected. These unusual characteristics are undoubtedly related to the difference in geologic origin of the Tertiary materials, most of which were sampled from the southern part of the study area. The Tertiary sediments have a significantly larger amount of biogenic material than the more recent sediments, which are primarily composed of mineral detritus, and this difference is reflected in their engineering properties (*93*). Materials of this type frequently have properties resulting from some natural cementation between particles, bonded or cemented sediments tending to be structurally rigid, stronger, and less compressible than similar noncemented materials (*94*).

For evaluating the stability of the natural sea floor or of man-made structures supported on the sea floor, the most important engineering property is the sediment strength or shearing resistance. This property can be measured, described, and used in a variety of ways. One approach is to treat the sediment, or soil (*95*), as a simple engineering material whose measured shearing resistance can be applied directly to the actual stability problem. This is generally called a "total



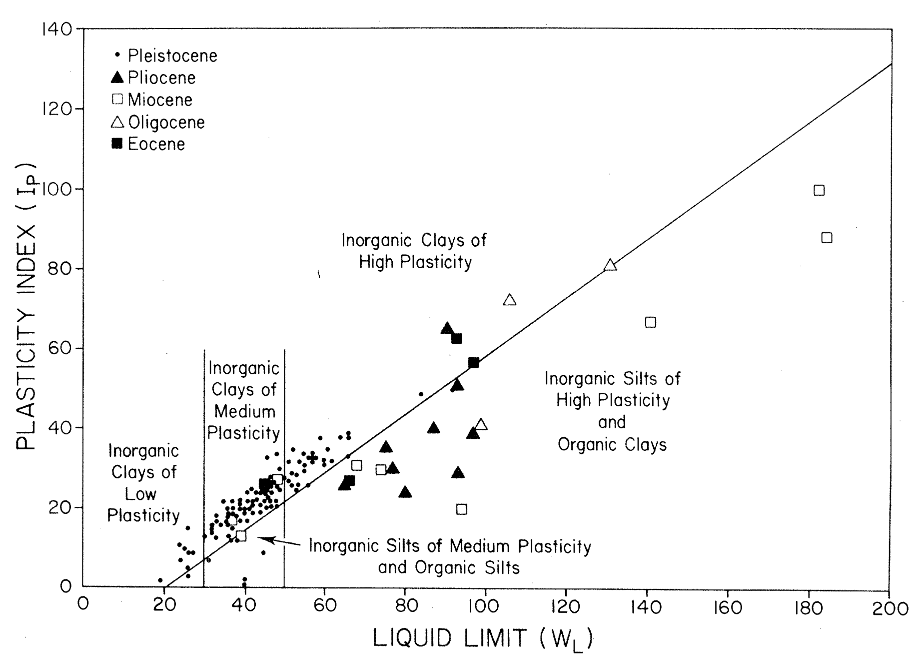


Fig. 8 (left). Variation of sulfate, alkalinity, and organic carbon with depth at site 6019. Fig. 9 (right). Site plasticity classifications for AMCOR samples.

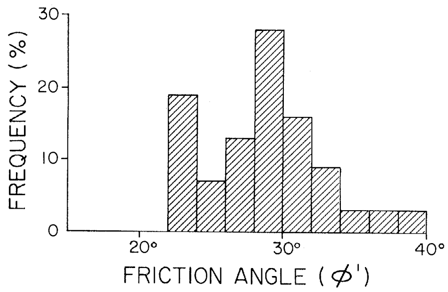


Fig. 10. Distribution of effective stress friction angle in AMCOR samples.

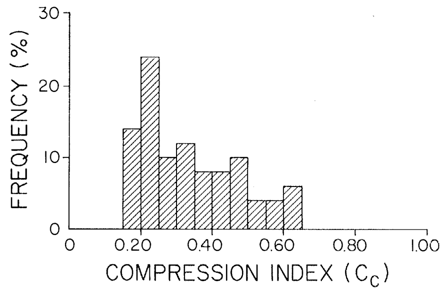


Fig. 11. Compressibility characteristics of AMCOR samples.

stress" approach. Alternative "effective stress" methods recognize that the strength behavior of natural soils and rocks is much more complicated and that the pressure in fluids within sediments, the pore fluid pressure, controls the shearing resistance. In effective stress methods, pore fluid pressures are either measured or predicted and are then used in conjunction with effective stress strength parameters—the effective stress friction angle (ϕ') and the cohesion intercept (c')—to predict the appropriate shearing resistance for the sediment in situ.

Measurements of undrained shearing resistance were made on AMCOR sediments at the time they were brought on board ship. The emphasis in strength testing, however, was to evaluate the effective stress strength properties. For most of the sediments tested, c' was negligible or zero and effective stress strength predictions could be based on the single parameter ϕ'. This observation is consistent with the normally consolidated stress history of most AMCOR sediments. For approximately 10 percent of the clay sediments tested, the strength envelope defined a significant cohesion intercept, and in most of these cases the materials were also overconsolidated to some extent. The distribution of ϕ' (Fig. 10) is what one might expect for onshore sediments from the eastern United States, confirming the general conclusion based on sediment classification.

Consolidation and compression testing of AMCOR sediments was complicated by sample disturbance. Nevertheless, the data obtained support some general conclusions. Most of the silt and clay sediments were essentially normally consolidated, in the sense that their preconsolidation stress was equal to the existing state of effective stress in situ. Some specimens were overconsolidated, indicating a history of greater stress, but there was no consistent correlation of the overconsolidated specimens with either spatial or temporal factors. None of the sediments tested showed the characteristics of underconsolidation that are common in other marine areas such as the Mississippi River Delta (*96*). Underconsolidation can be caused by such factors as cyclic loading, free gas in the sediments, and abnormal fluid pressures (*97*) but is usually due to rapid sedimentation (*98*). All the AMCOR drilling was done in areas where the sediments were relatively old or sedimentation rates were low; thus the absence of underconsolidated sediments is not surprising.

The compressibility characteristics of sediments tested in this program are summarized in Fig. 11. As with the other properties, the range and distribution are not unusual. The correlation between the compression index, C_c, and the liquid limit was good for all the sediments tested, except for the Tertiary sediments discussed previously, which were less compressible than would be expected.

Extensive deposits of loose sand and silt were found throughout the Atlantic margin area. These deposits are clearly susceptible to liquefaction and similar strength reduction. This problem is particularly acute in the upper 10 to 20 m of sediment, although many deposits of this type are not vulnerable because they have been densified, apparently by past wave action. The effects of wave action would apply at least to the top 10 to 20 m of sediment in water depths less than about 50 m.

Some silt and clay sediments are susceptible to undrained cyclic loading, which results in strength reductions of as much as two-thirds. Only four of the AMCOR cores have been tested for dynamic behavior, however, so a general conclusion is premature. Because of their depth below sea level and below the water-sediment interface, silt and clay sediments are susceptible to cyclic loading mainly through interaction between the sediments and man-made structures or earthquakes. Direct loading of submarine sediments by surface water waves should not be a major problem, certainly not on the order of the problem in the Gulf of Mexico (*99*).

References and Notes

1. J. C. Hathaway *et al.*, *U.S. Geol. Surv. Open File Rep. 76-844* (1976).
2. Because several scientific disciplines are involved, the authors of each section are listed here. C. W. Poag and P. C. Valentine prepared the section on stratigraphy; C. W. Poag, paleoecology; R. E. Miller, D. M. Schultz, and M. H. Bothner, preliminary organic geochemistry; F. A. Kohout, F. T. Manheim, and M. H. Bothner, hydrogeology and water chemistry; and D. A. Sangrey, geotechnical engineering studies.
3. Abundant, well-preserved micro- and nannofossil assemblages include the foraminifers *Globotruncana contusa* (Cushman), *G. elevata* (Brotzen), *G. gansseri* Bolli, and *Bolivinoides giganteus* Hiltermann and Koch.
4. A. J. Zupan and W. H. Abbott, in (*1*), appendix B.
5. The rich well-preserved micro- and nannofossil assemblage includes the foraminifers *Acarinina pusilla* (Bolli), *Morozovella conicotruncata* (Subbotina), *Planorotalites compressus* (Plummer), *P. pseudomenardii* (Bolli), and *Subbotina triloculinoides* (Plummer).
6. Among the foraminifers, only small benthic forms are present, including *Lenticulina midwayensis* (Plummer), *Bulimina pseudocacumenata* Olsson, *Spirobolivina emmendorferi* (Jennings), and *Bulimina referata* Jennings.
7. C. W. Poag, *Annu. Rev. Earth Planet. Sci.* **6**, 251 (1978).
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9. The upper 65 m contains abundant calcareous nannofossils and planktic foraminifers, among which are *Hantkenina alabamensis* Cushman, *Turborotalia cerroazulensis* (Cole), *T. increbescens* (Bandy), and *Cassigerinella eocenica* Cordey. The lower 45 m contains only sparse planktic forms and is characterized by abundant cheilostome bryozoans and larger benthic foraminifers, such as *Pseudophragmina (P.) bainbridgensis* (Vaughan), *P. (P.) floridana* (Cushman), *Nummulites ("Operculinoides") willcoxi* Heilprin, and *Lepidocyclina (L.) ocalana* Cushman.
10. R. Enright, in *Geology of Selected Areas in New Jersey and Eastern Pennsylvania and Guidebook of Excursions*, S. Sabitsky, Ed. (Rutgers Univ. Press, Rutgers, N.J., 1969), p. 14.
11. A sparse benthic foraminiferal fauna includes primarily *Alabamina wilcoxensis* Toulmin, *Turrilina* sp., *Pararotalia* sp., and *Gyroidina* sp. The only planktic representative is *Chiloguembelina* sp.
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13. Early Eocene planktic foraminifers include *Acarinina quetra* (Bolli), *A. senni* (Beckmann), and *Subbotina frontosa* (Subbotina). Typical middle Eocene forms are *Truncorotaloides rohri* Bronnimann and Bermudez, *Cibicidina westi* (Howe), and *Alabamina wilcoxensis* Toulmin.
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16. Early Oligocene species include *Turborotalia ampliapertura* (Bolli), *Globigerina sellii* (Borsetti), *G. angiporoides* (Hornibrook), and *G. gortanii* (Borsetti). Upper Oligocene assemblages include *Globigerina angulisuturalis* Bolli, *G. anguliofficinalis* Blow, *G. ciperoensis* Bolli, and members of the *G. ouachitaensis* plexus.
17. This interval bears atypical specimens of *Turborotalia kugleri* (Bolli), *Catapsydrax dissimilis* (Cushman and Bermudez), and *Globigerina angulisuturalis* Bolli, mixed with a few middle Miocene species such as *Turborotalia peripheroronda* (Blow and Banner).
18. W. H. Abbott, personal communication.
19. Among these are *Globigerinatella insueta* Cushman and Stainforth and *Globigerinoides sicanus* de Stephani.
20. Forms such as *Orbulina suturalis* Bronnimann, *O. universa* d'Orbigny, *Clavatorella bermudezi* (Bolli), *Turborotalia peripheroronda* (Blow and Banner), and *Globorotalia archaeomenardii* Bolli are present.
21. The most frequently encountered forms are *Bulimina elongata* d'Orbigny, *Florilus mediocostatus* (Cushman), and *Lenticulina spinosa* (Cushman).
22. *Lenticulina spinosa* (Cushman) and *Florilus mediocostatus* (Cushman) are the most con-

spicuous forms; a few planktic species include *Globigerinoides extremus* Bolli and Bermudez and *Turborotalia* cf. *T. siakensis* (LeRoy).
23. *Globorotalia miocenica* Palmer, *G. multicamerata* Cushman and Jarvis, and *Globoquadrina altispira* (Cushman and Jarvis).
24. *Globigerina riveroae* Bolli and Bermudez, *Neogloboquadrina acostaensis* (Blow), *N. dutertrei* (d'Orbigny), and *Sphaeroidinella dehiscens* (Parker and Jones).
25. Frequent *Buliminella elegantissima* (d'Orbigny) and *Cassidulina* sp.
26. *Globigerina decoraperta* Takayanagi and Saito, *Neogloboquadrina pseudopima* Blow, *N. pseudopachyderma* (Cita, Primoli Silva, and Rossi), and *Bulimina elongata* d'Orbigny.
27. H. J. Knebel and E. Spiker, *Bull. Am. Assoc. Pet. Geol.* **61**, 861 (1977).
28. Characterized by *Elphidium* sp.
29. Diagnostic species include *Globorotalia tosaensis* Takayanagi and Saito at the base and *G. truncatulinoides* (d'Orbigny), *G. cultrata* (d'Orbigny), *Turborotalia inflata* (d'Orbigny), and pink *Giobigerinoides ruber* (d'Orbigny) in the upper part.
30. Prominent foraminifers include *Elphidium clavatum* (Cushman), *Brizalina* sp., *Nonionella* sp., *Amphistegina gibbosa* d'Orbigny, *Neogloboquadrina dutertrei* (d'Orbigny), *N. pseudopachyderma* (Cita, Primoli Silva, and Rossi), *Turborotalia inflata* (d'Orbigny), *Globorotalia truncatulinoides* (d'Orbigny), and *Globigerinoides ruber* (d'Orbigny).
31. The few benthic foraminifers recovered are mainly *Elphidium clavatum* (Cushman), *Buccella inusitata* Andersen, *Nonionella* sp., and miliolids.
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33. Dark gray silty and sandy clays contain an assemblage of *Elphidium clavatum* (Cushman), *Cibicides lobatulus* (Walker and Jacob), *Globobulimina auriculata* (Bailey), *Neogloboquadrina dutertrei* (d'Orbigny), and *Turborotalia inflata* (d'Orbigny).
34. The upper 73 m contains the typical *Elphidium clavatum*-dominated fauna. The second prominent assemblage contains *E. clavatum* (Cushman) plus *Globobulimina auriculata* (Bailey), *Nonionella atlantica* Cushman, and *Cassidulina* sp., with frequent diatoms. The third assemblage includes *Melonis barleeanus* (Williamson), *G. auriculata* (Bailey), *Cassidulina laevigata* d'Orbigny, *Glandulina* sp., and *Fursenkoina* sp.
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36. There *Sigmoilopsis schlumbergeri* (Silvestri) and *Osangularia cultur* (Parker and Jones) join the *Globobulimina-Bulimina-Melonis* association.
37. *Elphidium clavatum* characterizes the sandy intervals; the clayey beds contain more *Cibicides lobatulus* (Walker and Jacob) and *Cassidulina* spp.
38. The predominant foraminifer is *Globobulimina auriculata* (Bailey); *Brizalina subaenariensis* (Cushman), *Nonionella atlantica* Cushman, and *Trochammina* sp. are also present, but in low numbers.
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$$\frac{\partial A}{\partial t} = D \frac{\partial^2 A}{\partial Z}$$

where A is the concentration of sulfate, t is time, D is the diffusion coefficient of sulfate in interstitial water, and Z is the depth in sediment below the organic-rich horizon, which extends to an estimated 29 m. This is analogous to diffusion of an element toward an absorbing barrier [G. T. Csanady, *Turbulent Diffusion in the Environment* (Reidel, Dordrecht, 1973)].
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109. The Atlantic Margin Coring Project was planned in consultation with the state geological surveys of the Atlantic coastal states and was carried out by a team of more than 40 scientists and technicians of the U.S. Geological Survey (USGS) and state geological surveys, who served alternating tours of duty aboard the drilling vessel *Glomar Conception*. Shipboard staff (affiliation USGS unless otherwise indicated) included chief scientists J. C. Hathaway and J. S. Schlee; paleontologists C. W. Poag, P. C. Valentine, C. D. Smith, and R. E. Hall; sedimentologists E. G. A. Weed, P. M. Hanshaw, W. H. Abbott (South Carolina Division of Geology), P. F. Huddlestun (Georgia Department of Natural Resources), J. H. Talley (Delaware Geological Survey), P. B. Dahlgren (New Jersey Bureau of Geology and Topography), W. B. Rogers (New York Geological Survey), B. W. Nelson (Maine Geological Survey), N. S. Hardin, M. J. Carnavalle, H. J. Knebel, P. A. Scholle, and J. C. Behrendt; water chemists F. T. Manheim, F. A. Kohout, J. M. Weigle, R. Schoen, and M. H. Bothner; organic chemists D. M. Schultz, D. D. Brandon, and R. E. Miller; geotechnical specialists A. F. Richards, R. M. Coad, and Michael Perlow (all from Lehigh University); chief technician R. F. Commeau; core technicians L. J. Poppe, P. L. Forrestel, J. M. Dunlavey, A. C. Sundberg, P. W. Cousins, M. H. Winsor, B. Tausey, R. J. Fabro, and S. J. Purdy; and secretaries K. M. Seitsinger, J. L. Gelinas, and S. C. Merchant. Geophysicists J. M. Robb and R. E. Sylwester and electronics technicians K. F. Parolski, W. L. Jaworski, and D. W. Kinney worked aboard the supply boat, motor vessel *L'Olonnois*, making geophysical surveys of each site before drilling and determining the navigational coordinates. J. C. Hathaway, project chief, was chief scientist for the first 4 weeks and the last 3 weeks of the cruise and J. S. Schlee for the intervening 3 weeks. Figures in this article were drafted by J. R. Moller, except for Fig. 3, which is by L. Sylwester. Publication has been authorized by the director, U.S. Geological Survey.