IRC. 773

GEOLOGICAL SURVEY CIRCULAR 773

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Description of Triassic(?) basalt and Upper Cretaceous to Pleistocene sediments recovered from 514 meters of test coring

1978

United States Department of the Interior
CECIL D. ANDRUS, *Secretary*

Geological Survey
W. A. Radlinski, *Acting Director*

Library of Congress catalog-card No. 78-600008

Free on application to Branch of Distribution, U.S. Geological Survey
1200 South Eads Street, Arlington, Va. 22202

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Stratigraphic Test Well, Nantucket Island, Massachusetts

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ABSTRACT

The U.S. Geological Survey, in cooperation with the Massachusetts Water Resources Commission and the Nantucket Conservation Foundation, continuously cored 514 m of sediment and volcanic rock in a stratigraphic and water-quality test.

Stratified sediments were divided texturally into three zones: the upper zone (0–128 m) contains mostly coarse sand and gravel; the middle zone (128–349 m) contains mostly silty clay and a few beds of sand and silt; and the lower zone (349–457 m) contains soft, unconsolidated, clayey sand. Below the lower zone, a saprolite, composed mostly of clay, grades abruptly downward at 470 m into partially altered basalt that extends to the bottom of the hole at 514 m.

Fossils are sparse throughout the cores, but Pleistocene, Eocene, and Upper Cretaceous assemblages were identified. On the basis of limited foraminifer and ostracode assemblages, Pleistocene deposits are inferred to extend to a depth of about 85 m. A Lower Eocene section 25 m thick is defined on the basis of palynomorph and dinoflagellate assemblages. (However, samples from a water well drilled in 1933, 10 km to the north, contain Pliocene and Miocene, early Eocene, and Paleocene foraminifers.) Upper Cretaceous beds, inferred to extend from 128 to 349 m, are identified mostly on the basis of pollen and spores. The oldest datable fossiliferous sample at 345 m is early-to-middle Cenomanian in age.

Samples found below 345 m are barren of indigenous fossils and are assigned an Albian Age on the basis of electric log correlations. Paleontologic evidence suggests that the Pleistocene section was deposited under nearshore marine conditions, the Tertiary section under open-shelf marine conditions, and most of the Upper Cretaceous section under nonmarine conditions.

The unstratified clay that makes up the saprolite was probably formed by subaerial weathering of basalt similar to that which underlies the saprolite. Chemical evidence suggests that the basalt was probably deposited as a series of flows. The oldest K-Ar date obtained in the basalt was 183±8 m.y. (Early Jurassic); however, because of alteration, this probably represents a minimum age.

Lignites and coal in the Upper Cretaceous section are of low rank and, on the basis of their thermal immaturity, have probably never been buried deeply; thus, local generation of petroleum hydrocarbons in this shoreward area of the continental margin is unlikely.

Freshwater or low-salinity brackish water was found in sediments far below the depth predicted by the Ghyben-Herzberg principle. These interstitial waters are probably relict ground water emplaced during times of low sea level during the Pleistocene.

INTRODUCTION

PURPOSE

In 1975, the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Water Resources Commission, planned to drill a 122-m hole near the geographic center of Nantucket Island to assess the total thickness of freshwater in the sediments. Calculations based on the Ghyben-Herzberg principle predicted a zone of freshwater 120–150 m thick (Kohout and others, 1977). This principle is the theory of hydrostatic equilibrium between freshwater and more dense seawater in a coastal aquifer; it states that for each meter of ground-water elevation above sea level, the freshwater lens will depress the saltwater interface about 40 m below sea level. The USGS later proposed to deepen the test to about 500 m, the approximate depth of a prominent acoustic reflector (Oldale, 1969), which was assumed to be basement. The primary objective of the additional drilling was to obtain new stratigraphic information near the shoreward margin of the Georges Bank basin. Seismic reflection and refraction surveys by oil companies and by the USGS have been carried out for several years in the region of Georges Bank, where leasing of tracts and exploratory drilling are imminent.

The nearest pre-Pleistocene sedimentary strata exposed on land are Tertiary and Cretaceous clay and sand that crop out at Gay Head, Martha's Vineyard (fig. 1). However,

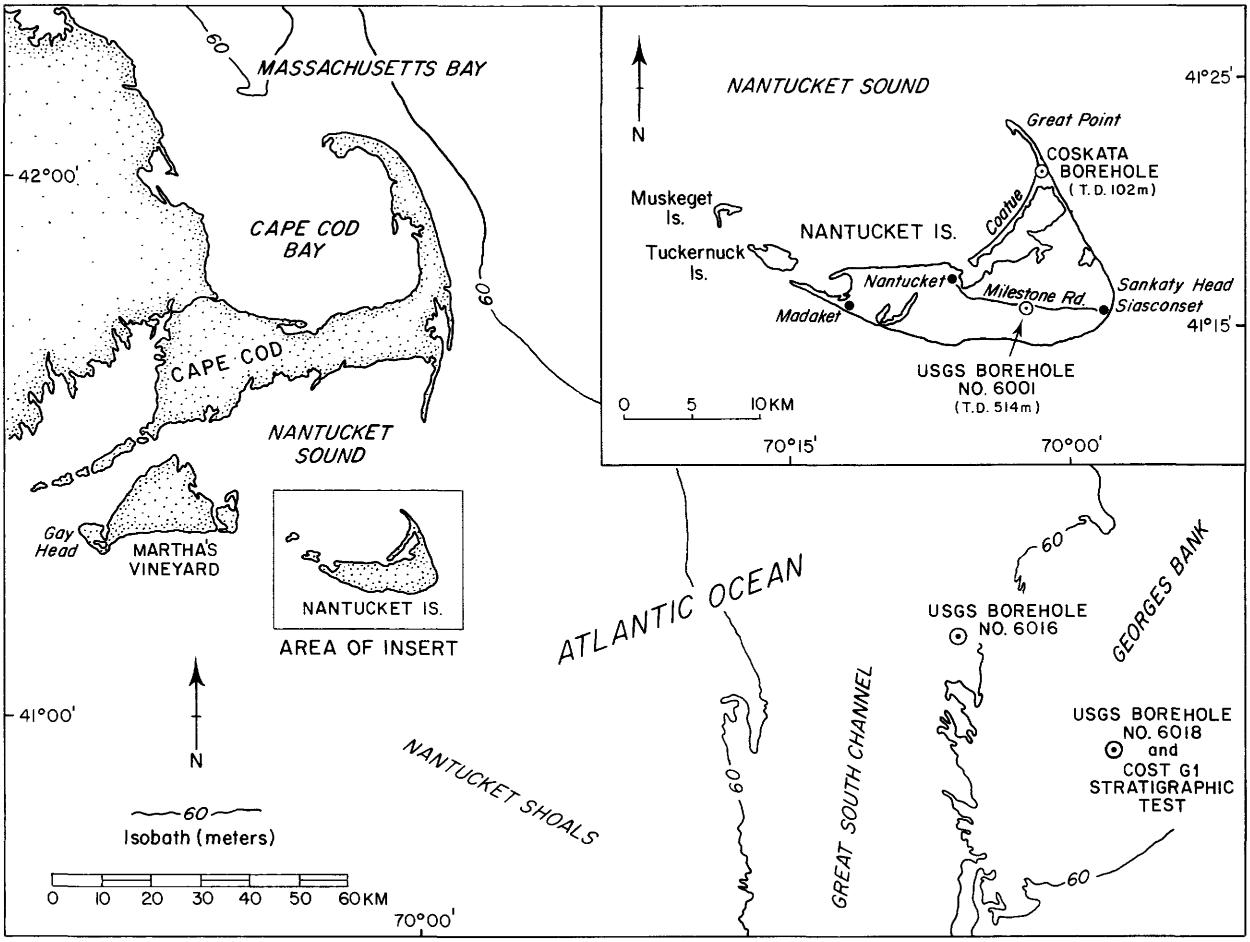

FIGURE 1.—Index map of Nantucket Island and surrounding area showing location of Nantucket stratigraphic test well (USGS borehole No. 6001) and other boreholes in the region. T.D. shows total depth of some of the boreholes.

they are dislocated and highly folded and faulted, apparently from loading or "bulldozing" by glacial ice (Kaye, 1964), and they do not provide a clear picture of the stratigraphy. The Nantucket test-well site is located farther seaward from Martha's Vineyard, and it provided an opportunity to gain data where sediments are thicker, closer to the basin center, and presumably less affected by ice movements. Furthermore, penetrating the sedimentary section and identifying basement would be useful in the interpretation of geophysical data collected to assess the resource potential of the area.

SETTING

Nantucket Island is about 25 km long, as much as 10 km wide, and lies 40 km south of the coast of Cape Cod, Mass., on the eastern Continental Shelf of the United States. It has a maximum elevation of only 33 m (Folger Hill), and encompasses a total area of 132 km^2.

Exposed surficial sediments are mostly glacial sand, gravel, and some clay (Richards, 1962; Woodworth, 1934). These deposits are part of the Ronkonkoma-Vineyard-Nantucket moraine and its outwash plain that extends eastward to form part of Georges Bank (Pratt and Schlee, 1969). Controversy has surrounded the age of shelly deposits underlying the sand and gravel at Sankaty Head (fig. 1), but most evidence available suggests that they are also of Pleistocene age (Richards, 1962; Gustavson, 1976).

The well site (borehole 6001) is at lat 41°15′54.9″ N. and long 70°02′16.72″ W. near the geographic center of the island on land owned by the Nantucket Conservation Foundation, which, because of its interest in island water resource evaluation, kindly granted the USGS permission to drill. The site was conveniently located 60 m from Milestone Road, the main highway between Nantucket and Siasconset (fig. 1), in a long linear depression known as Madequecham Valley that was probably eroded by a proglacial melt-water stream. Ground surface elevation at the site is 10.9 m above mean sea level.

PREVIOUS WORK

Discussions concerning sediments of Nantucket date back to Desor (1849) who suggested that fossils exposed at the base of cliffs at Sankaty Head were Tertiary in age. In subsequent work, this conclusion was hotly contested and a Pleistocene age for them was established (Merrill, 1896; Cushman, 1906; Richards, 1962); thus, most work on the geology of the island has concerned its glacial evolution (Shaler, 1889; Woodworth, 1934). However, extensive study of Tertiary and Cretaceous exposures on Martha's Vineyard at Gay Head, contiguous shores, and in pits located inland laid the basis for conjecture concerning the subsurface stratigraphy of Nantucket (Woodworth, 1934; Kaye, 1964, 1972).

Fourteen deep boreholes drilled on lower Cape Cod penetrated as much as 137 m of glacial clastic deposits and 172 m of bedrock composed of schist and granite (Koteff and Cotton, 1962; Oldale, 1976). Sediments of Tertiary age (Eocene) were recovered in three holes drilled near Provincetown, at the northern tip of Cape Cod (Zeigler and others, 1960). A hole has recently been drilled on Martha's Vineyard to a total depth of 262.2 m; the core contains a condensed but similar stratigraphic section to that penetrated on Nantucket (Raymond E. Hall, USGS, written commun., 1977).

On Nantucket, a water well was drilled in 1933 using a manually operated cable-tool rig at Coskata, about 10 km north of USGS borehole No. 6001 (fig. 1). No freshwater was recovered, but the hole penetrated 44 m of sand and gravel overlying 58 m of silt and clay. Cuttings from the hole were assembled in 1936 by Walter Barrett, then a Nantucket High School student, and examined for microfossil content with the help of J. A. Cushman. On the basis of Foraminifera that he discovered in the fine-textured sediments, he assigned them a Tertiary age. This work, remarkable for a high school student, remained unpublished until now. The Coskata samples, which had been saved by Mr. Barrett, provided for us a Tertiary section that is mostly absent in the USGS borehole.

Geophysical investgiations of the island to our knowledge have been sparse. Weston Geophysical Co. conducted a refraction seismic and resistivity survey in 1966 (Massachusetts Water Resources Commission, written commun.). One refraction line was long enough to reach a high velocity (5.7 km/s) refractor at −509 m near the western end of the island. A shorter line laid out along Milestone Road revealed two refracting horizons less than 46 m deep close to the location of the USGS hole. Oldale (1969) shot several refraction lines along the beaches, but none was long enough to reach refractors with velocities in excess of 2.8 km/s. He did, however, compile all available data in the Cape Cod, Martha's Vineyard, and Nantucket area to construct a depth-to-basement map. Though he had only the one site from Weston's unreversed line at which higher velocity material was penetrated, his prediction of basement depth at the USGS borehole of −500 m was within a few meters of the depth at which basalt was penetrated.

A deep CDP (common depth point) seismic line (No. 5) was shot by the research vessel *Gulf Seal*, operated by Digicon Geophysical, Inc., for the USGS Outer Continental Shelf Resource Assessment Program, 20 km west of Nantucket (Grow and Schlee, 1976). There, sediments overlying basement thicken from less than 1 km nearshore to 8 km offshore beneath the Continental Slope. Figure 2 shows the processed record and our interpretation of seismic line No. 5. West of Nantucket, the line appears to cross several subsurfurce basins that may be down-faulted. These have been interpreted on the basis of previous work to be Triassic or Jurassic grabens (Grow and Schlee, 1976, map 2; Ballard and Uchupi, 1975; Ballard and Sorensen, 1968; Uchupi and Emery, 1967; Uchupi, 1968).

On the basis of magnetic data, Nantucket

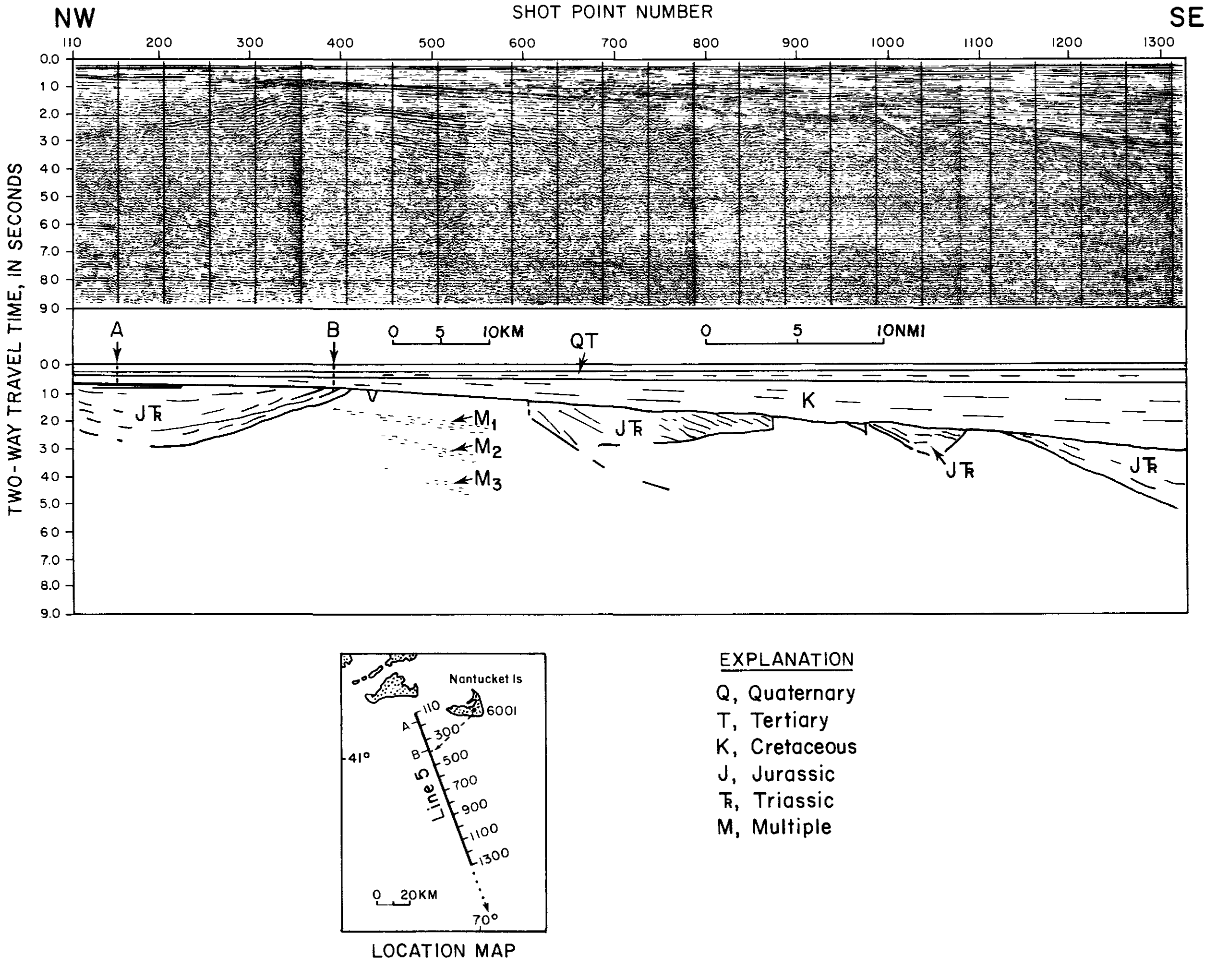

FIGURE 2.—Cross section of part of Continental Shelf showing processed record and interpretation of USGS seismic line No. 5 (CDP) south and west of Nantucket. M_1, M_2, and M_3 are interpreted as multiples of reflector at base of Cretaceous. The geologic setting of borehole 6001 may be represented by location B on the profile (near shot point 400) with respect to its position relative to the inferred Triassic-Jurassic basin. The basalt found in borehole 6001 may be represented by the strong reflector at a reflection time of about 0.7 seconds (between shot points 110 and 230 below location A), because this reflector occurs in the area of seismic line No. 5 at a depth below sea level similar to the depth of the basalt in the borehole.

lies close to the northern end of a northeast-trending basement ridge that is bordered on the northwest by a parallel broad basin that underlies Nantucket Sound and extends southwestward under the Continental Shelf (Klitgord and Behrendt, 1977).

ACKNOWLEDGMENTS

F. A. Kohout [1] and M. H. Bothner set up the equipment and conducted on-site determinations of tests of salinity and pH of interstitial water squeezed from the cores recovered from the borehole. E. G. A. Weed described and sampled cores during virtually the entire period of the drilling operations, managed the logs of the data obtained, and aided in training and supervising the technicians who assisted from time to time in processing cores. E. C. Rhodehamel participated in on-site operations during the drilling of the saprolite and basalt in the lower part of the borehole and during the final logging of the well. He also interpreted the logs and provided tentative correlations of these with other wells of the Atlantic Coastal Plain.

[1] All persons mentioned in these acknowledgments are from the USGS unless an affiliation is otherwise indicated.

J. A. Commeau made partial chemical analyses of the core materials by X-ray fluorescence. L. J. Poppe prepared X-ray diffraction patterns and made qualitative mineralogic analyses of the cores.

S. A. Wood assisted in part of the on-site work with the cores and also assembled and proofed some tabular material and parts of the text and assembled information from some of the references.

E. H. Walker participated in the early on-site salinity determinations and provided advice on local ground-water conditions on Nantucket.

W. S. Barrett of Nantucket, Mass., gave important assistance in arrangements with local groups and contractors on Nantucket, lent advice and counsel on local conditions, and provided history, samples, and original paleontologic analyses from the well drilled in 1933 at Coskata.

The following assisted in the work of describing, sampling, photographing, and packing cores at various times during the coring of the well: Susan Wieber, Rebecca Belastock, Charles O'Hara, Ellen Davie, Raymond Hall, Robert Commeau, John Schlee, James Robb, W. M. Ferrebee, Lyle McGinnis, Anna Sundberg, Christina Schoen, John Dunlavey, David Delaney, Patricia Forrestel, Stanley Locker, and Paul Cousins.

John Baker and Michael Frimpter supervised the original arrangements for the water resources test well and lent advice and counsel during later stages of the program. David Delaney aided extensively in the interstitial water chemistry studies during the drilling operations.

James Lentowski, executive secretary of the Nantucket Conservation Foundation, arranged for the clearing of the site prior to the drilling and for the restoration of the site after completion of the project.

The late Austin Tyrer, local water-well drilling contractor, drilled freshwater supply wells for the program and rendered assistance in numerous logistic problems that arose during the operations.

Larry J. Nutter ran electric logs (self-potential and resistivity) of the upper 125 m of the well.

H. Peyton Herman supervised the crew of the U.S. Army Corps of Engineers, who ably conducted the drilling and coring operations despite severe winter conditions. Janet R. Moller of Falmouth, Mass., drafted most of the illustrations for this paper.

METHODS

The U.S. Army Corps of Engineers began drilling on November 9, 1975, with a Failing[2] 2000 rotary rig. Our objective was to core the entire hole to provide as much stratigraphic information as possible. Several methods, including split-spoon coring, punch or driven barrel coring, as well as rotary coring, were used to improve recovery in the upper unconsolidated glacial sands and gravels. Nevertheless, recovery was poor (10.3 percent) throughout the upper 120 m of section until casing (24.5 cm or $9\frac{5}{8}$ in. I.D.) was set at 125 m. From that point on, best recovery (45.5 percent) was obtained in clay-rich sediments using a core barrel 15.2 cm (6 in.) I.D. by 6.1 m (20 ft) long, designed by the Corps of Engineers. Where hard rock was penetrated, a conventional petroleum core barrel with a diamond rock-coring bit (Hycalog 9.1 m (30 ft) long; 6.35 cm ($2\frac{1}{2}$ in.) I.D.) was used and obtained 73 percent recovery.

Immediately after recovery, cores were described, photographed, and sampled for textural, hydrocarbon, mineralogic, paleontologic, and water analyses. Squeezing for pore water analysis was carried out immediately by a hydraulic press (Manheim, 1966) and salinity values obtained using an Endeco type 102 refractometer. Some microscopic examination of the samples was carried out on the well site.

In the laboratory, samples were examined for microfossils, including Foraminifera, nannofossils, pollen, and spores. At places where lithologic changes were seen or at one depth in each core, mineral content was assessed by L. J. Poppe, using a Norelco X-ray diffractometer equipped with a graphite curved-crystal monochromator and a proportional counter alined to record copper Kα radiation ($\lambda = 1.5418$ Å). Textural analyses were carried out with a Rapid Sediment Analyzer (Schlee, 1966) and a Coulter Counter Model TAII by Sally Wood, Peter Johnson, and Wayne M. Ferrebee. Hydrocarbons were assessed by Robert Miller, David

[2] Trade names in this publication are used for descriptive purposes only, and do not constitute endorsement by the U.S. Geological Survey.

Schultz, and George Claypool of the USGS by soxhlet extractions and gas chromatography. Two potassium-argon ages were determined by R.F. Marvin, H. H. Mehnert, Kinyoto Futa, and Violet Merritt. Potassium content was determined using an Instrument Laboratories Flame Photometer with a lithium internal standard. Permeability and porosity measurements were carried out by Core Lab., Inc. Chemical compositions were obtained by Judith A. Commeau, using a Diano XRF 8000 automated X-ray fluorescence analyzer. Sample preparation was by the methods of Rose, Adler, and Flanagan (1963). Carbon-14 date W–3542 was measured in the laboratory of the USGS by Meyer Rubin.

RESULTS

STRATIGRAPHY

GENERAL LITHOLOGY

To a depth[3] of 457 m, the borehole penetrated unconsolidated and semiconsolidated sedimentary clastic detritus that ranges in texture from clay (<0.004 mm) to cobbles (128 mm). Below 457 m, a saprolite, composed mostly of clay, grades abruptly at about 470 m into partially weathered or altered basalt that extends to the bottom of the hole at 514 m.

The sedimentary section can be divided into three lithologic zones. The upper zone, from the surface to 128 m, is dominated by coarse sand and gravel and a few thin beds of clay and silt; the middle zone, from 128 to 349 m, is composed mostly of silty clay showing increasing consolidation as the depth increases, interbedded with a few clayey, silty, sandy beds (3–12 m thick) and indurated siltstone beds as much as 30 cm thick. The lower zone, from 349 to 457 m, contains soft, unconsolidated, water-saturated, clayey sand interrupted by clay layers 3 to 6 m thick.

The lithology of the section from the borehole is shown in columnar section in figure 3.

UPPER ZONE

Lithology.—In the upper zone (0–128 m), sands range in texture from medium to very coarse grained and range in color from light tans, grays, and olives to bright green. Pea-size (<1 cm) gravel is most common but coarse gravel and cobbles apparently are scattered

[3] All depths are from ground level (10.9 m above sea level).

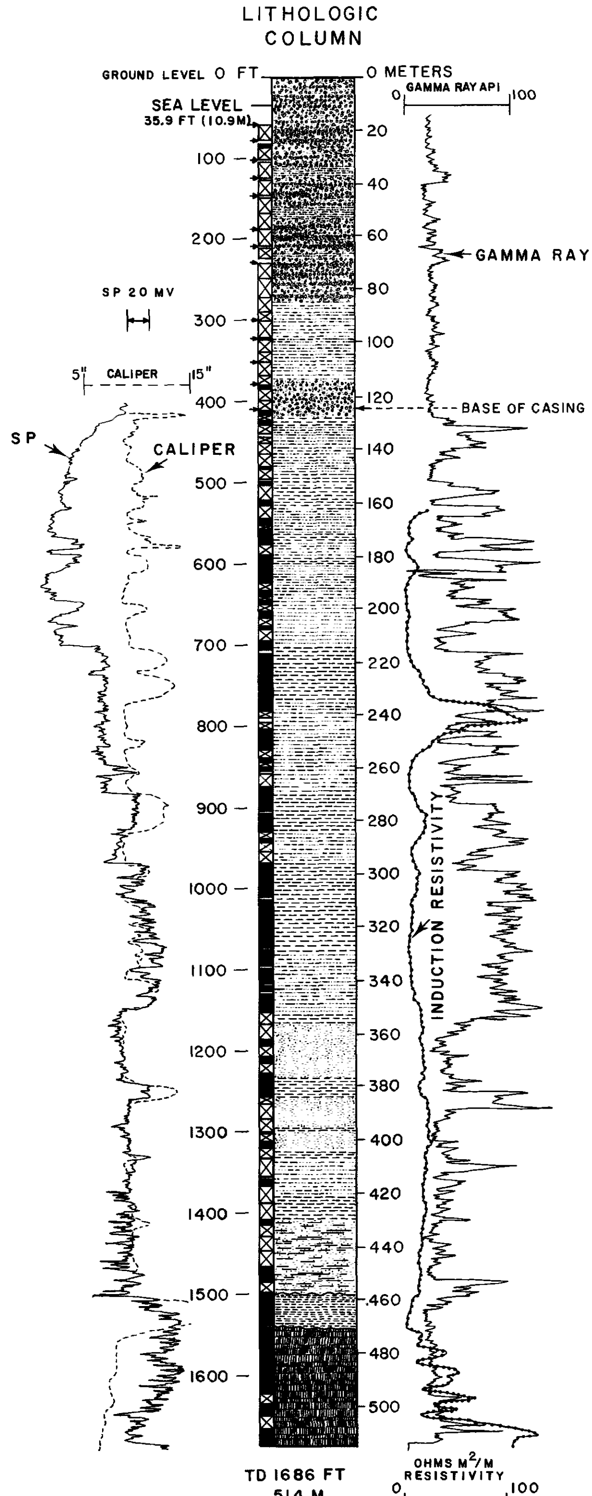

FIGURE 3.—Columnar section of borehole 6001 showing lithology, core recovery (solid black, left side of column; small arrows indicate driven cores), self potential (SP), caliper, induction resistivity, and gamma ray logs. See figure 7 for explanation of lithologic symbols.

throughout the section, especially between 60 and 80 m. Two thin zones cored at 35 and 63 m contain a mixture of gravel, sand, silt, and clay, and may be glacial tills or weathered soil zones. Shell fragments, as much as 7 cm across, form layers that are most common between 38 and 61 m. Greensand having a matrix of silt and clay-size glauconite was first found at 91 m and, though recovery was poor, appears to dominate at least to 107 m and perhaps as deep as 126 m.

Mineralogy.—Dominant clay minerals in the upper 120 m of the section are illite and minor kaolinite; chlorite and dioctahedral vermiculite are also common in several intervals. Smectite, which was observed in several samples from this zone, is probably contamination from the drilling mud because it shows extremely sharp and well ordered X-ray diffraction peaks, quite unlike the mixed-layered assemblages usually found in such detrital sediments. The coarse fraction comprises mainly quartz and plagioclase feldspar. Calcite and aragonite are present in strata containing shells.

MIDDLE ZONE

Lithology.—The middle zone (128–349 m) contains mostly variegated clay and fewer interbeds of light-gray sand. The dense, compact, and silty clay ranges in color from white to red, yellow, brown, purple, olive gray, and black; in many places, it is mottled in combinations of these colors. The black and dark-gray layers contain abundant lignite and many leaf imprints; at least one interval contains lignite/subbituminous coal at 328 m (described below). Particles of lignite are also scattered throughout most of this middle zone. Interbedded sands are commonly gray to brown, highly micaceous, kaolinitic, and contain abundant lignite. Very fine to medium-grained sand is most abundant, but coarse to very coarse material is present. Sand is more common than clay from about 128 to 213 m, whereas clay tends to be more common below 213 m. The sediments are more indurated toward the base of the zone at 349 m; some layers are hard cemented siltstone.

Mineralogy.—Clay minerals are the most common constituents of this zone. Of these, kaolinite is most abundant accompanied by minor amounts of illite and smectite; chlorite is absent. Minor amounts of mixed layer smectite-illite are found toward the base of the zone. Quartz, rare amounts of plagioclase feldspar, goethite, gibbsite, hematite, siderite, and occasionally anatase constitute the main non-clay fraction. The mineralogy of this interval is thus characteristic of a heavily weathered and leached soil, probably formed under tropical, humid conditions.

Coal.—A bed of lignite/subbituminous coal at least 20 cm thick was found at 328 m. When the core was first recovered, freshly exposed surfaces were dark brown but turned black within seconds after exposure to the air. Analyses by George E. Claypool, USGS, showed that it is a relatively pure coal containing 58.8 percent organic carbon. Soxhlet extraction yielded 2.68 percent bitumen. Of this, 0.14 percent is composed of saturated hydrocarbon, 0.18 percent is nominal aromatic hydrocarbon material, and the balance of 2.36 percent is nonhydrocarbon extractable organic matter. Its total hydrocarbon concentration of 3,181 ppm and a hydrocarbon-to-organic carbon ratio of 0.54 are typical of low-rank coals. The saturated-to-aromatic hydrocarbon ratio of 0.76 is much higher than typical humic coals, suggesting a higher content of waxy tissues in this coal. Thermal analysis/pyrolysis showed only 12.2 percent of the organic carbon recoverable as pyrolytic volatiles. This relatively small amount indicates that the organic matter of the coal would be a relatively inefficient generator of petroleum hydrocarbons.

Gas chromatography of the products of pyrolysis showed that, although the coal is capable of generating light (C_{10}–C_{25}) paraffin hydrocarbons, it is thermally immature and has not done so. The temperature of maximum pyrolysis yield (450°C) indicates a low-temperature history, or lignite/subbituminous rank (G. E. Claypool, written commun., 1975). These results indicate that sediments in this part of the shoreward edge of the Atlantic continental margin sediment wedge have never been buried deeply enough to generate mature petroleum hydrocarbons. Thus, unless migration has taken place, any accumulations of petroleum hydrocarbons probably occur far seaward of the Nantucket site in areas where source sediments have been buried much more deeply than those at Nantucket.

LOWER ZONE

Lithology.—In the lower zone (349–457 m), sandy sediments are predominant; they are unconsolidated and mostly light gray or occasionally tan, and contain rare pebbles (<1 cm) and layers of yellowish clay. The sand is fine to very coarse grained and has an abundant matrix of clay that is mostly kaolinite. The cores recovered were usually soft and watery. Interbedded clay horizons, a few meters to 10 m thick, are light gray, red, and yellow, commonly mottled, very sandy, silty, and micaceous.

Mineralogy.—The abundant sand in the lower zone contains mostly quartz and minor plagioclase feldspar. Clay minerals are mainly kaolinite, lesser amounts of illite, and rare smectite. Neither chlorite nor vermiculite was observed.

In summary, the upper 128 m zone of sediments is almost entirely sand and gravel, the middle 221-m zone is mostly clay and silt, and the lower 108 m zone is mostly sand.

SAPROLITE AND BASALT

Lithology.—At 457 m, the stratified sands and clays are in contact with an unbedded maroon clay containing many rounded blebs and veins of white clay. The white structures closely resemble those in the veined amygdaloidal basalt that underlies the clay zone. We concluded that the maroon and white clay is a saprolite derived by weathering-in-place of igneous rock having similar structure. At about 470 m, the clay grades into hard partially weathered or altered basalt that is maroon to brown and aphanitic to finely crystalline; the basalt is veined with calcite and has vesicles filled with zeolite or saponite. Toward the bottom of the hole at 514 m, the basalt is bluish gray and contains many amygdules and veins consisting of red, white, and green zeolites, saponite, and calcite.

Two samples of the basalt were dated by the K-Ar methods. A sample from 485.7 m gave an age of 183 ± 8 m.y. (Early Jurassic); the other sample taken at 513.8 m, was dated at 164 ± 3 m.y. (Middle Jurassic). Because the basalt in both samples was partially altered, however, these probably represent minimum ages, and the basalt may well be at least Triassic in age.

The types of clay and other alteration minerals in the basalt are not the result of weathering processes as is the kaolinite of the saprolite zone. Alteration within the basalt itself probably took place as a result of hydrothermal processes early in the history of the rock, and thus the ages obtained may not be as much in error as the existence of alteration might otherwise suggest. The saprolite, however, is probably the result of later subaerial weathering.

Chemistry.—Chemical analyses (table 1) for SiO_2, Al_2O_3, Fe_2O_3, MnO_2, MgO, CaO, Na_2O, K_2O, TiO_2, and P_2O_5 and modal mineralogical analyses by X-ray diffraction were made for samples taken from the cores at 1- to 3-m intervals. Fluctuations in abundances (fig. 4) of some elements (expressed as oxides) appear to reflect mainly the extent of weathering and leaching. For example, the saprolite zone from about 470 m to 457 m shows upward decreasing concentrations of MgO, SiO_2, P_2O_5, CaO, and Na_2O and increasing concentrations of Al_2O_3, Fe_2O_3, and TiO_2. The first five elements thus have been removed, apparently as deep weathering has proceeded with time, and the last three have concurrently increased as part of residual, refractory mineral constituents. The K_2O and MnO_2 contents show only slight decreasing trends in this interval.

Below 470 m, variations are more complex. Several samples in which MgO content and the ratio of SiO_2/Al_2O_3 are large correlate with the occurrence of the mineral saponite. Saponite (not to be confused with the term "saprolite" above) is a magnesium-rich smectite (montmorillonite group minerals) having relatively low aluminum content. Its idealized structural formula (Ross and Hendricks, 1945) is:

$$\begin{array}{c} \qquad\quad Na_{0.33} \\ \qquad\quad \uparrow \\ Mg_3 \{Si_{3.67}\, Al_{0.33}\}\, O_{10}\{OH_2\} \end{array}$$

The chemical composition for sample 6001–120–5 (55–58 cm) gives the following calculated structural formula:

$$\begin{array}{c} \qquad\qquad\qquad \{Na_{0.53}\, K_{0.01}\, \frac{Ca_{0.10}}{2}\} \\ \qquad\qquad\quad \uparrow \\ \{Mg_{2.49}\, Fe_{0.20}\, Al_{0.10}\}\, \{Si_{3.37}\, Al_{0.63}\}\, O_{10}\, \{OH_2\} \end{array}$$

TABLE 1.—*Partial chemical and X-ray modal analyses of volcanic rock and saprolite*

[Chemical analyses by J. A. Commeau; X-ray diffraction analyses by L. J. Poppe and J. C. Hathaway]

Sample No.[1]	6001–116–1 (15 cm)	6001–116–2 (10 cm)	6001–116–2 (60 cm)	6001–116–2 (90 cm)	6001–116–3 (107 cm)	6001–116–4 (25–50 cm)
Depth (m)	456.5	457.5	458.0	458.3	459.6	460.0
Material	Gray sedimentary clay.	Maroon clay with white blebs.	Maroon clay with white blebs.	Maroon clay with white blebs.	Dark red clay.	Yellow blebs.
Partial chemical analyses for major oxides in weight percent from X-ray fluorescence						
SiO_2	38.51		26.80		19.37	33.01
Al_2O_3	27.45		18.41		28.53	21.27
Fe_2O_3	2.21		27.30		24.89	13.34
MnO_2	.03		.11		.12	.05
MgO	.96		.83		.78	.46
CaO	.11		.13		.12	.14
Na_2O	.37		.50		.58	—
K_2O	.00		.00		.005	.02
TiO_2	3.18		2.91		3.06	.85
P_2O_5	.00		.04		.05	.06
Partial total	72.82		77.03		77.505	69.20
Estimated modes from X-ray diffraction						
Kaolinite	99	75	72	75	75	87
Smectite (montmorillonite group other than saponite)	—	—	—	—	—	—
Saponite	—	—	—	—	—	—
Mixed layered smectite-chlorite	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—
Illite	—	—	—	—	—	—
Talc	—	—	—	—	—	—
Heulandite	—	—	—	—	—	—
Stilbite	—	—	—	—	—	—
Analcime	—	—	—	—	—	—
Prehnite	—	—	—	—	—	—
Potassium feldspar	—	—	—	—	—	—
Plagioclass feldspar	—	—	—	—	—	—
Calcite	Tr.	—	—	—	—	—
Hematite	—	25	28	25	25	13
Other			Quartz tr.			Quartz tr.

Sample No.[1]	6001–116–4 (90 cm)	6001–116–5 (40 cm)	6001–116–6 (20 cm)	6001–117–1 (50 cm)	6001–117–2 (55 cm)	6001–117–3 (55 cm)
Depth (m)	460.5	461.2	462.0	462.7	464.0	465.2
Material	Maroon clay with white blebs.	Maroon clay with white blebs.	Maroon clay with white blebs.	Maroon clay with white blebs.	Dark-maroon clay with green amygdules	Maroon clay with white amygdules
Partial chemical analyses for major oxides in weight percent from X-ray fluorescence						
SiO_2			31.37	34.54		43.64
Al_2O_3			23.31	20.09		14.87
Fe_2O_3			20.36	23.04		15.76
MnO_2			.11	.11		.05
MgO			.00	.33		1.98
CaO			.17	.53		1.13
Na_2O			.49	.98		1.68
K_2O			.16	.77		.89
TiO_2			2.96	3.14		2.67
P_2O_5			.19	.21		.35
Partial total			79.12	83.74		83.02
Estimated modes from X-ray diffraction						
Kaolinite	70	90	79	75	30	15
Smectite (Montmorillonite					55	69
group other than saponite)	—	—	—	—	—	—
Saponite	—	—	—	—	—	—
Mixed layered smectite-chlorite	—	—	—	—	—	—

TABLE 1.—*Partial chemical and X-ray modal analyses of volcanic rock and saprolite*—Continued

Estimated modes from X-ray diffraction						
Chlorite	—	—	—	—	—	—
Illite	—	—	—	—	—	—
Talc	—	—	—	—	—	—
Heulandite	—	—	—	—	—	—
Stilbite	—	—	—	—	—	—
Analcime	—	—	—	—	—	—
Prehnite	—	—	—	—	—	—
Potassium feldspar	—	—	—	Tr.	—	—
Plagioclase feldspar	—	—	—	Tr.	—	—
Calcite	—	—	—	—	—	—
Hematite	20	10	21	25	10	16
Other	Quartz tr.	Quartz tr.				

Sample No.[1]	6001–117–4 (25 cm)	6001–118–1 (3–5 cm)	6001–118–3 (47–49 cm)	6001–118–3 (109–110 cm)	6001–118–3 (110–111 cm)	6001–119–1 (1–2 cm)
Depth (m)	465.4	465.5	467.8	468.4	468.5	469.4
Material	Maroon clay with white amygdules	Red clay	Amygdules	Red clay	Veins and amygdules.	Red basalt
Partial chemical analyses for major oxides in weight percent from X-ray fluorescence						
SiO_2		42.30	46.73	47.53	54.29	40.96
Al_2O_3		17.79	14.74	15.77	16.83	15.70
Fe_2O_3		15.88	8.75	16.77	5.83	14.42
MnO_2		.05	.05	.05	.04	.06
MgO		2.04	2.05	1.10	3.77	.16
CaO		1.24	.82	1.40	.78	4.82
Na_2O		1.48	—	3.32	2.04	3.64
K_2O		.16	.34	1.18	.42	.95
TiO_2		1.96	.82	2.45	.69	2.09
P_2O_5		.40	.08	.31	.06	.27
Partial total		83.30	74.38	89.88	84.75	83.07
Estimated modes from X-ray diffraction						
Kaolinite	15	20	—	—	—	—
Smectite (montmorillonite group other than saponite)	69	65	90	53	90	20
Saponite	—	—	—	—	—	—
Mixed layered smectite-chlorite	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—
Illite	—	—	—	—	—	—
Talc	—	—	—	—	—	—
Heulandite	—	—	—	—	—	—
Stilbite	—	—	—	—	—	—
Analcime	—	—	—	—	—	—
Prehnite	—	—	—	—	—	—
Potassium feldspar	Tr.	—	—	—	—	—
Plagioclase feldspar	—	—	—	30	Tr.	70
Calcite	—	—		—	—	Tr.?
Hematite	15	15	8	17	6	15
Other	Quartz 1		Unidentified mineral.		Unidentified mineral.	

Sample No.[1]	6001–120–1 (4–6 cm)[2]	6001–120–1 (95–96 cm)[2]	6001–120–4 (48–49 cm)	6001–120–4 (66–69 cm)	6001–120–5 (44–46 cm)	6001–120–5 (55–58 cm)
Depth (m)	472.7	473.6	476.5	476.7	477.6	477.8
Material	Maroon basalt	Basalt with green amygdules	White calcite vein	White calcite vein	Red vein	Yellow vein
Partial chemical analyses for major oxides in weight percent from X-ray fluorescence						
SiO_2	39.94	38.93	1.54	18.84	37.62	45.55
Al_2O_3	12.40	12.37	.37	4.74	8.65	8.45
Fe_2O_3	11.51	11.78	.46	1.05	6.01	3.61
MnO_2	.17	.16	.70	.59	.33	.00
MgO	5.14	4.51	4.71	4.48	12.61	22.61
CaO	7.63	6.23	46.89	33.93	7.62	1.29

TABLE 1.—*Partial chemical and X-ray modal analyses of volcanic rock and saprolite*—Continued

Partial chemical analyses for major oxides in weight percent from X-ray fluorescence						
Na_2O	4.68	2.80	3.08	2.65	2.51	3.26
K_2O	.54	1.04	.00	.56	.49	.11
TiO_2	1.55	1.51	.00	.00	.01	.00
P_2O_5	.19	.18	.13	.07	.00	.00
Partial total	83.75	79.51	57.88	66.91	75.85	84.88
Estimated modes from X-ray diffraction						
Kaolinite	—	—	—	—	—	—
Smectite)montmorillonite group other than saponite)	[2] 20	[2] 68	—	[3] 10	[3] 62	[3] 100
Saponite	—	—	—	—	—	—
Mixed layered smectite-chlorite	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—
Illite	—	—	—	—	—	—
Talc	—	—	—	—	—	—
Heulandite	—	—	Tr.	20	20	—
Stilbite	—	—	—	—	—	—
Analcime	—	—	—	—	—	—
Prehnite	—	—	—	—	—	—
Potassium feldspar	—	Tr.	—	—	—	—
Plagioclase feldspar	60	4	—	2	—	—
Calcite	8	15	99	53	11	—
Hematite	12	12	—	—	6	—
Other						

Sample No.[1]	6001–120–5 (64–66 cm)	6001–120–5 (73–75 cm)	6001–121–1 (22 cm)	[5] 6001–121–1 (30–31 cm)	[6] 6001–121–1 (30–31 cm)	6001–121–7 (27–29 cm)
Depth (m)	477.9	478.0	479.4	479.5	479.5	485.3
Material	Maroon basalt	White crumbly vein	White vein	Greenish amygdules	Maroon basalt	Green vein
Partial chemical analyses for major oxides in weight percent from X-ray fluorescence						
SiO_2	41.34	46.27	6.59	50.44	43.12	38.80
Al_2O_3	12.85	10.32	1.53	15.58	13.99	7.34
Fe_2O_3	13.28	1.51	1.41	4.63	14.21	10.09
MnO_2	.15	.23	.95	.07	.13	.08
MgO	10.80	12.39	5.32	7.01	6.95	19.45
CaO	5.72	5.14	42.57	.91	1.59	1.89
Na_2O	3.12	2.32	2.65	2.18	3.30	—
K_2O	1.04	.23	.22	.40	.63	.08
TiO_2	1.77	.01	.06	.18	2.07	.65
P_2O_5	.24	.00	.12	.00	.25	.05
Partial total	90.31	78.42	61.42	81.40	86.24	78.43
Estimated modes from X-ray diffraction						
Kaolinite	—	—	—	—	—	—
Smectite (montmorillonite group other than saponite)	[3] 30	80	—	80	33	10
Saponite	—	—	—	15	22	80
Mixed layered smectite-chlorite	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—
Illite	—	—	—	—	—	—
Talc	—	10	—	—	—	—
Heulandite	—	—	10	—	—	—
Stilbite	—	—	—	—	—	10
Analcime	—	—	—	—	—	—
Prehnite	—	—	—	—	—	—
Potassium feldspar	—	—	—	—	—	—
Plagioclase feldspar	42	—	—	—	28	Tr.
Calcite	10	10	[4] 90	2	2	—
Hematite	13	—	—	3	15	—
Other						

TABLE 1.—*Partial chemical and X-ray modal analyses of volcanic rock and saprolite*—Continued

Sample No.[1]	6001–121–7 (64–70 cm)	6001–121–7 (67–70 cm)	6001–122–1 (35–37 cm)	6001–122–2 (90–95 cm)	6001–123–1 (24–26 cm)	6001–123–2 (13–15 cm)
Depth (m)	485.7	485.7	487.1	488.9	489.4	491.3
Material	Maroon basalt	Maroon basalt	Maroon basalt	Green amygdules	Gray basalt with green amygdules	Gray basalt
Partial chemical analyses for major oxides in weight percent from X-ray fluorescence						
SiO_2		41.19	40.58	38.06	38.61	41.91
Al_2O_3		14.08	11.77	6.98	10.38	11.96
Fe_2O_3		13.18	14.38	10.91	10.73	11.56
MnO_2		.11	.12	.06	.10	.16
MgO		6.87	11.41	23.66	9.40	7.59
CaO		8.92	6.68	.96	6.50	3.31
Na_2O		3.45	2.66	2.87	2.79	4.14
K_2O		.62	.51	.01	.37	1.14
TiO_2		1.68	1.70	.20	1.41	1.84
P_2O_5		.23	.22	.01	.16	.24
Partial total		90.33	90.03	83.72	80.45	83.85
Estimated modes from X-ray diffraction						
Kaolinite	—	—	—	—	—	—
Smectite (montmorillonite group other than saponite)	—	10	—	—	—	20
Saponite	20	10	20	89	30	—
Mixed layered smectite-chlorite	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—
Illite	—	—	—	—	—	—
Talc	—	—	—	—	—	—
Heulandite	—	—	—	—	—	—
Stilbite	—	—	—	—	—	—
Analcime	—	—	—	—	—	—
Prehnite	—	—	—	—	—	—
Potassium feldspar	—	—	—	—	—	—
Plagioclase feldspar	67	67	65	—	59	68
Calcite	—	—	—	—	—	—
Hematite	13	13	15	11	11	12
Other						

Sample No.[1]	6001–123–4 (13–15 cm)	6001–124–1 (73 cm)	6001–124–3 (55–58 cm)	6001–124–3 (74–76 cm)	6001–124–3 (112–114 cm)	6001–124–4 (50 cm)
Depth (m)	495.4	498.8	503.0	503.2	503.5	505.4
Material	Maroon basalt with amygdules	Maroon basalt	Red basalt	Orange vein	Red basalt	Red "rotten" rock
Partial chemical analyses for major oxides in weight percent from X-ray fluorescence						
SiO_2	44.46	46.08	46.21	55.66	38.89	39.34
Al_2O_3	13.67	13.82	14.99	19.09	14.99	15.17
Fe_2O_3	12.92	11.77	10.50	9.40	13.85	10.98
MnO_2	.14	.18	.11	.54	.15	.20
MgO	4.45	8.34	4.35	3.61	5.88	16.32
CaO	4.37	5.04	1.74	2.73	1.85	5.73
Na_2O	5.86	4.86	5.68	4.33	1.49	1.73
K_2O	1.91	1.17	1.20	1.73	3.12	.55
TiO_2	2.50	1.70	1.29	1.42	1.40	.64
P_2O_5	.33	.22	.11	.23	.10	.13
Partial total	90.61	93.18	86.18	98.74	81.72	90.79
Estimated modes from X-ray diffraction						
Kaolinite	—	—	—	—	—	—
Smectite (montmorillonite group other than saponite)	20	18	—	16	—	—
Saponite	—	—	22	—	—	—
Mixed layered smectite-chlorite	—	—	—	—	30	30
Chlorite	—	—	—	—	—	—
Illite	—	—	Tr.	5	7	—
Talc	—	—	—	—	—	—

TABLE 1.—*Partial chemical and X-ray modal analyses of volcanic rock and saprolite*—Continued

Estimated modes from X-ray diffraction—Continued						
Heulandite	—	—	—	—	—	—
Stilbite	—	—	—	—	—	—
Analcime	32	—	—	—	—	—
Prehnite	—	—	—	—	—	—
Potassium feldspar	—	—	—	—	10	5
Plagioclase feldspar	35	70	66	70	39	54
Calcite	—	—	—	—	—	—
Hematite	13	12	11	9	14	11
Other						

Sample No.[1]	6001–124–4 (80 cm)	6001–125–1 (0–1 cm)	6001–126–1 (1–2 cm)	6001–126–2 (18–20 cm)	6001–126–2 (20–22 cm)	6001–126–5 (23–24 cm)
Depth (m)	505.7	507.2	508.4	509.6	509.6	512.9
Material	Maroon basalt	Maroon basalt	Maroon basalt	Gray basalt	Maroon basalt with white crystals	Maroon basalt
Partial chemical analyses of major oxides in weight percent from X-ray fluorescence—Continued						
SiO_2	43.50	43.74	46.91	49.12	38.67	41.60
Al_2O_3	12.68	11.73	13.62	16.50	19.42	12.92
Fe_2O_3	11.84	11.63	12.10	12.83	7.42	11.78
MnO_2	.16	.15	.15	.13	.07	.15
MgO	6.43	6.33	6.64	6.60	4.48	7.00
CaO	5.05	5.13	5.87	9.67	20.35	6.37
Na_2O	5.57	5.80	—	4.85	1.13	5.63
K_2O	.88	.75	.87	.37	.36	.90
TiO_2	1.76	1.78	2.15	1.71	.82	1.74
P_2O_5	.21	.20	.21	.24	.15	.22
Partial total	88.08	87.24	88.52	102.02	93.47	88.31
Estimated modes from X-ray diffraction—Continued						
Kaolinite	—	—	—	—	—	—
Smectite (montmorillonite group other than saponite)	—	—	—	—	—	—
Saponite	—	—	—	—	—	—
Mixed layered smectite-chlorite	15	15	15	10	—	—
Chlorite	—	—	—	—	10	5
Illite	—	—	—	—	—	tr
Talc	—	—	—	—	—	—
Heulandite	—	—	—	—	—	—
Stilbite	—	—	—	—	—	—
Analcime	—	20	tr	—	—	55
Prehnite	—	—	—	15	80	—
Potassium feldspar	—	—	tr	tr	—	20
Plagioclase feldspar	73	53	72	62	—	20
Calcite	—	—	—	—	tr	—
Hematite	12	12	12	13	8	—
Other						

Sample No.[1]	6001–126–5 (85–88 cm)	6001–126–5 (105–107 cm)	6001–126–5 (110–114 cm)
Depth (m)	513.6	513.8	513.9
Material	Red basalt with white crystals	Basalt	Gray basalt
Partial chemical analyses for major oxides in weight percent from X-ray fluorescence			
SiO_2	28.20		48.56
Al_2O_3	11.65		16.34
Fe_2O_3	8.87		12.63
MnO_2	.19		.15
MgO	6.87		6.84
CaO	21.31		9.33
Na_2O	1.63		4.20
K_2O	.08		.89
TiO_2	.36		1.97
P_2O_5	.10		.27
Partial total	79.26		101.18

TABLE 1.—*Partial chemical and X-ray modal analyses of volcanic rock and saprolite*—Continued

	Estimated modes from X-ray diffraction		
Kaolinite	—	—	—
Smectite (montmorillonite group other than saponite)	—	—	10
Saponite	—	20	—
Mixed layered smectite-chlorite	20	—	—
Chlorite	—	—	—
Illite	Tr.	—	—
Talc	—	—	—
Heulandite	—	—	—
Stilbite	—	—	—
Analcime	—	—	—
Prehnite	10	—	—
Potassium feldspar	8	—	—
Plagioclase feldspar	15	69	77
Calcite	35	—	—
Hematite	9	11	13
Other			

[1] Sample number is composed of four parts. First 4 digits gives hole number; next 3 digits, core number; last single digit, section number; measurement in parenthesis shows position of sample within section and equals centimeters below top position of that section.

[2] Mineral expands to 17 Å with ethylene glycol, but fails to collapse with heat treatments as does normal smectite. Intensity relationships preclude chlorite layers.

[3] As [2] above, but no collapse, even at 750° C.

[4] Magnesium calcite (about 18 percent $MgCO_3$).

[5] Amygdules.

[6] Host basalt.

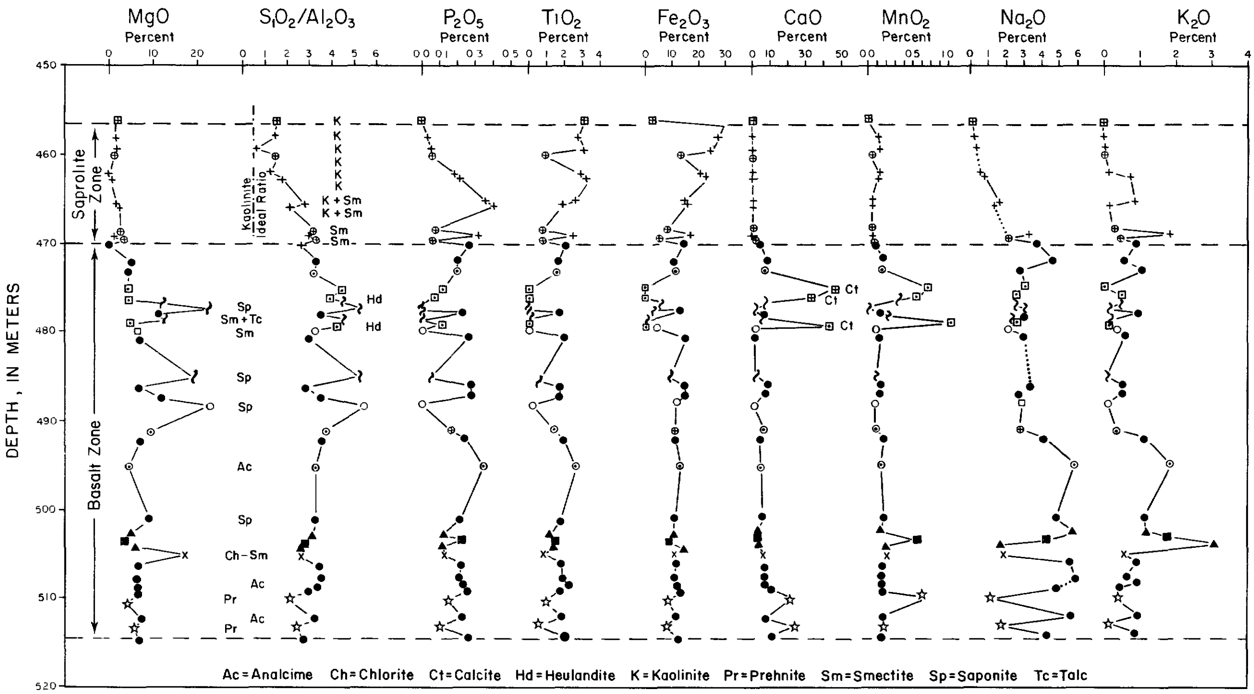

FIGURE 4.—Diagram showing variation of chemical elements and minerals as depth increases in the basalt and saprolite zones of borehole 6001. See figure 5 for explanation of symbols, which depict type of sample or rock.

These values are within the range of saponite composition shown by Ross and Hendricks (1945), and Grim (1968).

As shown in figures 4 and 5, TiO_2 and P_2O_5 tend to fluctuate together, except in the upper saprolitic zone, where TiO_2 increases upward and P_2O_5 decreases.

Manganese content (fig. 6) generally shows increases where CaO content is large.

Many of the samples were selected to assess the composition of vein and amygdaloidal minerals. Immediately below the saprolite, most veins are either calcite or saponite, whereas many amygdules are filled by zeolites. As the

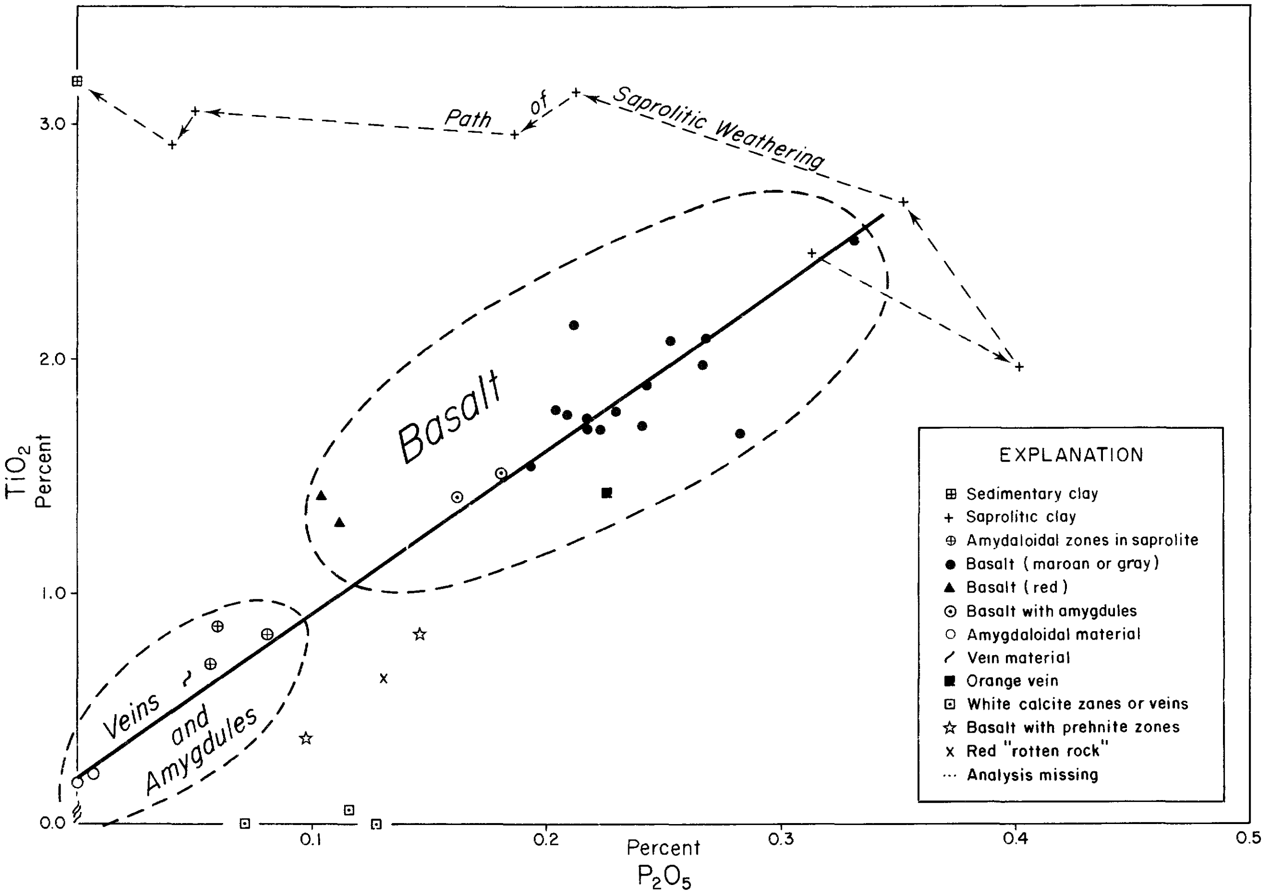

FIGURE 5.—Diagram showing variation of TiO_2 and P_2O_5 in the basalt and saprolite zones of borehole 6001.

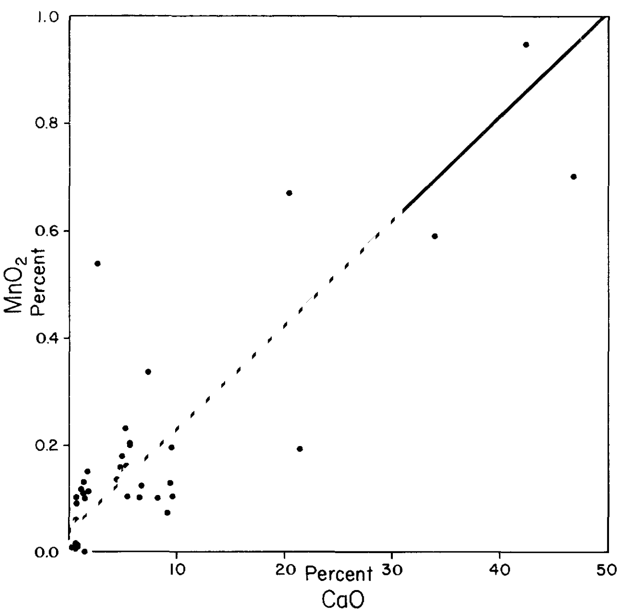

FIGURE 6.—Diagram showing variation of MnO_2 and CaO in the basalt and saprolite zones of borehole 6001.

depth increases, heulandite and stilbite are succeeded by analcime and prehnite.

PALEONTOLOGY

COSKATA WELL

PLEISTOCENE

In the upper 44 m of sand and gravel, benthic and pelagic foraminifers of Pleistocene age are identical to those recovered in borehole 6001 and are indicative of deposition in a nearshore shelf environment similar to that present today in the New England region.

PLIOCENE OR MIOCENE

In silty clay from 46 to 55 m, a Pliocene or Miocene assemblage contains a sparse foraminiferal fauna. A few planktic specimens appear to be *Neogloboquadrina pseudopachyderma* (Cita, Primoli Silva, and Rossi). Benthic forms include *Cibicidoides floridanus* (Cushman), *Bulimina marginata* (d'Orbigny), *Oridorsalis umbonatus* (Reuss), and *Florilus grateloupi* (d'Orbigny), probably all deposited in a mid-shelf environment.

Eocene

In silty clay from 55 to 75 m, early Eocene foraminiferal faunas contain numerous benthic forms and small planktic specimens, most of which belong to indeterminate species. Those species that are recognizable and diagnostic are *Acarinina broedermanni* (Cushman and Bermudez), *Morozovella* cf. *M. trichotrocha* (Loeblich and Tappan), *Guembelitria* cf. *G. columbiana* (Howe), *Bulimina pseudocacumenata* Olsson, *Turrilina robertsi* (Howe and Roberts), *Pseudohastigerina micra* (Cole), *Alabamina wilcoxensis* Toulmin, *Gyroidinoides octocameratus* (Cushman and Hanna). This assemblage was probably deposited in outer continental shelf conditions.

Paleocene

In silty clay of Paleocene age from 75 to 102 m, foraminiferal assemblages contain many species common to the Aquia Formation of Maryland and the Vincentown Formation of New Jersey. The planktic and benthic species are diverse and include *Acarinina tribulosa* (Loeblich and Tappan), *A. aquiensis* (Loeblich and Tappan), *A. pentacamerata* (Subbotina), *A. strabocella* (Loeblich and Tappan), *A. esnaensis* (Leroy), *Morozovella aequa* (Cushman and Renz), *Subbotina triloculinoides* (Plummer), *Pseudohastigerina micra* (Cole), *Alabamina midwayensis* (?) Brotzen, *Trifarina wilcoxensis* (Cushman and Ponton), *Gyroidinoides octocameratus* (Cushman and Hanna), *Turrilina robertsi* (Howe and Roberts), and *Anomalinoides midwayensis* (Plummer). This assemblage contains more planktic specimens and more deep water benthic specimens than younger sediments in the hole, but probably still reflects outer shelf conditions during deposition.

BOREHOLE 6001

Fossils are scarce in the core, but Pleistocene, Eocene, and Upper Cretaceous assemblages have been identified; they include benthic foraminifers, ostracodes, dinoflagellates, and, especially, spores and pollen (sporomorphs). Pleistocene samples contain only ostracodes and foraminifers; Eocene samples yield dinoflagellates and sporomorphs; and Upper Cretaceous beds contain sporomorphs, rare agglutinated benthic foraminifers, and a few casts of mollusks.

Pleistocene

The Pleistocene microfossil assemblages are limited to the medium to coarse quartz sands in the interval from 38 m to 45 m. The total Pleistocene section is inferred to extend to 85 m depth. Twenty-one species of benthic foraminifers are represented, but specimens are rare. The predominant forms are *Elphidium orbiculare* (H. B. Brady), *Elphidium clavatum* (Cushman), *Cibicidoides lobatulus* (Walker and Jacob), *Glabratella wrightii* (H. B. Brady), *Buccella inusitata* Andersen, and *Buccella frigida* (Cushman). Modern representatives of these species inhabit the shallow waters adjacent to Nantucket Island, and the Pleistocene sediments containing them presumably were deposited under similar conditions.

A small but well-presrved ostracode assemblage was recovered from a depth of 45 m. The sample contains abundant molluscan fragments, and 19 species of ostracodes:

Baffinicythere emarginata (Sars); *Bensonocythere americana* Hazel; *B.* sp. A of Valentine (1971); *B.* sp. B of Valentine (1971); *B.* sp. D of Valentine (1971); *B.* sp.; *Cytheridea* sp. A of Valentine (1971); *Cytherura* sp.; *Finmarchinella angulata* (Sars); *F. finmarchica* (Sars); *Hemicythere villosa* (Sars); *Hemicytherura clathrata* (Sars); *Leptocythere angusta* Blake; *Loxoconcha* aff. *L. granulata* Sars of Valentine (1971); *Microcytherura choctawhatcheenis* (Puri); *Muellerina canadensis* (Brady); *M.* aff. *M. lienenklausi* (Ulrich and Bassler) of Hazel (1970) and of Valentine (1971); *Sclerochilus* sp. C of Valentine (1971); and *Xestoleberis* sp.

All the ostracode species range throughout the Holocene and Pleistocene, and a few also range into the Pliocene. The modern geographic distribution of 15 of these species is known (Hazel, 1970, 1971; Valentine, 1971).

Hazel (1970) established the presence of an ostracode faunal province boundary at Cape Cod that delineates the cold temperate Nova Scotian faunal province to the north from the mild temperate Virginian province to the south. The boundary is found somewhat to the north of Nantucket Island. The fossil ostracode assemblage from the Nantucket well is composed (with two exceptions) of two groups of species: those that now range from the Arctic or sub-Arctic to the Nova Scotian-Virginian province boundary or into the Virginian province; and species that are restricted to the Virginian and Nova Scotian provinces. Typical southern forms are absent.

The fossil ostracode assemblage, though less diverse, resembles the modern Cape Cod assemblage, and therefore confirms the inference from the foraminifers that the marine climate at the time of deposition approximated the present mild to cold temperature climate offshore from Nantucket Island. Deposition took place during a period of raised sea level in the Pleistocene, possibly during the Sangamon Interglaciation, or perhaps marking an interval of glacial retreat during the Wisconsin Glaciation. A radiocarbon date based on marine fossils of >40,000 years B.P. at 57.3 m does not confirm this interpretation but at least does not invalidate it.

Pleistocene deposits also are found in the sea cliffs at Sankaty Head on Nantucket (Cushman, 1904; Wilson, 1905). In a recent study, Gustavson (1976) reevaluated the age and paleoenvironmental interpretation of the molluscan assemblages from this locality as follows: The ranges of living representatives of species from the lower Sankaty beds overlap in the area off Nantucket; the fossil assemblage may in part represent the transition from a Sangamonian to a Wisconsinan climatic regime; and, the upper Sankaty beds contain a cold-water molluscan assemblage of probable Wisconsinan Age. Paleontological correlation of the Sankaty beds with the Pleistocene of the Nantucket borehole is not possible at this time.

Eocene

Samples from the greensand collected between 91 m and 98 m yielded sporomorph and dinoflagellate assemblages. The dinoflagellates are sparse but well preserved, and include *Wetzeliella symmetrica* Weiler, *W. articulata* Eisenack, *W.* sp., *Pentadinium sp., Cordosphaeridium fibrospinosum* Darcy and Williams, and *Membranosphaera maestrichtica* Samoilovitch. All these forms have been recorded from lower Tertiary sedimentary rocks and the assemblage is considered to be of Eocene age (Fred May, written commun., 1976).

The palynomorphs of the greensand include a single specimen of the Paleocene to basal middle Eocene genus *Thomsonipollis*, among an assemblage of reworked Cenomanian species and modern contaminants. Cenomanian forms include *Peromonolites allenensis* Brenner, *Tricolporopollenites triangulus* Groot, Penny and Groot, *Ajatipollis* cf. *A. tetraedralis* (Bolkhovitina) Krutzsch, *Cyathidites minor* Couper, *Cicatricosisporites hallei* Delcourt and Sprumont, and *Retitricolpites minutus* Pierce. Modern forms are *Quercus* sp., *Pinus* sp., *Alnus* sp., *Corya* sp., *Myrica* sp., and members of the familes Chenopodiaceae and Ericaceae.

Upper Cretaceous

Upper Cretaceous beds were identified by their spore and pollen assemblages, which can be correlated with those of the New Jersey Coastal Plain formations.

Abundant palynomorphs of latest Campanian Age are the youngest Cretaceous forms identified. They were found in the black clay that marks the top of the middle lithologic zone at 128.8 m and are equivalent to the flora of the basal part of the Navesink Formation or Mount Laurel Sand in New Jersey. Diagnostic species include *Holkopollenites* sp. C, *Casuarinidites* sp., and *Betulaceoipollenites* sp. At 133.9 m the presence of *Brevitricolporites* sp. B, *Proteacidites* sp. D, and *Triatriopollenites* sp. B. indicate correlation with the Wenonah Formation (upper Campanian). Beds equivalent to the Wenonah and Marshalltown Formations are present at 136.6 m as indicated by the presence of *Holkopollenites* sp. C and *Tricolporites* sp. W.

Lower Campanian equivalents of the Englishtown Formation or Woodbury Clay were found at 141.5 m. Diagnostic forms are *Osculapollis aequalis* Tschudy and *Brevitricolporites* sp. A. The presence of *Chomotriletes* spp., *Complexiopollis abditus* Tschudy, and *Retitricolpites* sp.

A at 173.2 m suggest an age no younger than that of the Englishtown Formation, but its age is otherwise not definite.

The highest occurrence of Magothy equivalents (Santonian or possibly lower Campanian) was found at 174.2 m, as shown by the presence of *Trudopollis* sp. A, *Choanopollenites* cf. C. *transitus* Tschudy, and cf. *Holkopollenites* sp. A. The occurrnce of *Complexiopollis abditus* Tschudy and *C.* sp. B at 211.6 m also indicates a Magothy age.

Equivalents of the Woodbridge Clay Member of the middle Raritan Formation (middle Cenomanian) were found from 259.2 m to 338.0 m. Characteristic fossils are *Ajatipollis* cf. A. *tetraedralis* (Bolkhovitina) Krutzsch, *Atlantopollis* spp. and *Complexiopollis* spp.

Thin intervals of marginal marine strata were also observed in the Woodbridge equivalents at 309.9 m, 319.7 m, and 321.1 m. Each sample contains a distinct assemblage of fragile, agglutinated benthic foraminifers of the genera *Trochammina* and *Ammobaculites*, accompanied by abundant plant fragments and fish teeth. These beds may represent the equivalent of the subsurface Bass River Formation of Petters (1976) in New Jersey, which was deposited in a continental shelf environment during the major Cenomanian transgression.

The oldest datable fossiliferous sample (depth 345 m) contains *Ajatipollis* cf. *A. tetraedralis* (Bolkhovitina) Krutzsch, *Tricolpollenites parvulus* Groot and Penny, *Retitricolpites georgensis* Brenner, *R. vulgaris* Pierce, and *Tricolporoidites* spp., which sugegst equivalence to the lower or middle part of the Raritan Formation (lower to middle Cenomanian). Samples collected below this point are barren of all indigenous fossils.

POROSITY AND PERMEABILITY

Fourteen undisturbed sand samples were analyzed using conventional petroleum industry techniques for porosity and permeability. All were taken from the Upper Cretaceous section between 137 and 307 m. Samples of sand between 350 and 457 m were too unconsolidated to obtained undisturbed samples suitable for analyses.

Porosity was high and averaged 30 percent for all samples and varied from 24.5 to 35.9 percent with no obvious trend. Horizontal permeability in 12 samples (2 were unsuitable for analysis) averaged 162 mD (millidarcys) and varied widely from 10 to 780 mD (table 2).

DISCUSSION

REGIONAL STRATIGRAPHY

We have attempted in figure 7 to correlate biostratigraphic and lithostratigraphic units defined in borehole 6001 and the Coskata borehole in Nantucket southwest to Long Island and New Jersey where the stratigraphic relationships, though controversial, have been

TABLE 2.—*Porosity and permeability analyses*

[Analysts: Core Laboratories, Inc., Dallas, Tex.]

Sample No.[1]	Description	Depth (m)	Helium porosity (percent)	[2] Horizontal permeability to air (mD)
6001–45–1 (15–25 cm)	Gray sand	136.6	26.9	10
6001–50–1 (28–36 cm)	----do----	159.4	32.9	431
6001–58–3 (105 cm)	----do----	185.1	29.1	25
6001–59–1 (70–80 cm)	----do----	188.3	28.5	780
6001–60–1 (77–87 cm)	----do----	192.6	32.8	(3)
6001–61–1 (68–74 cm)	----do----	195.9	24.5	(3)
6001–63–1 (37 cm)	----do----	206.1	32.1	111
6001–67–1 (84–94 cm)	White sand	222.3	35.9	74
6001–69–2 (100–113 cm)	Gray sand	233.9	24.9	15
6001–71–1 (90–95 cm)	White sand	244.3	34.7	42
6001–72–1 (70–80 cm)	Gray sand	247.2	26.3	162
6001–73–1 (73–85 cm)	----do----	254.7	29.8	254
6001–82–1 (85–95 cm)	Laminated silt	286.0	32.1	22
6001–87–1 (46–49 cm)	Gray sand	306.7	31.6	15

[1] Sample number is composed of four parts. First four digits give hole number; next two digits, core number; last single digit, section number; measurement in parenthesis shows position of sample within section and equals centimeters below top position of that section.
[2] mD = millidarcys.
[3] Sample unsuitable for permeability measurement.

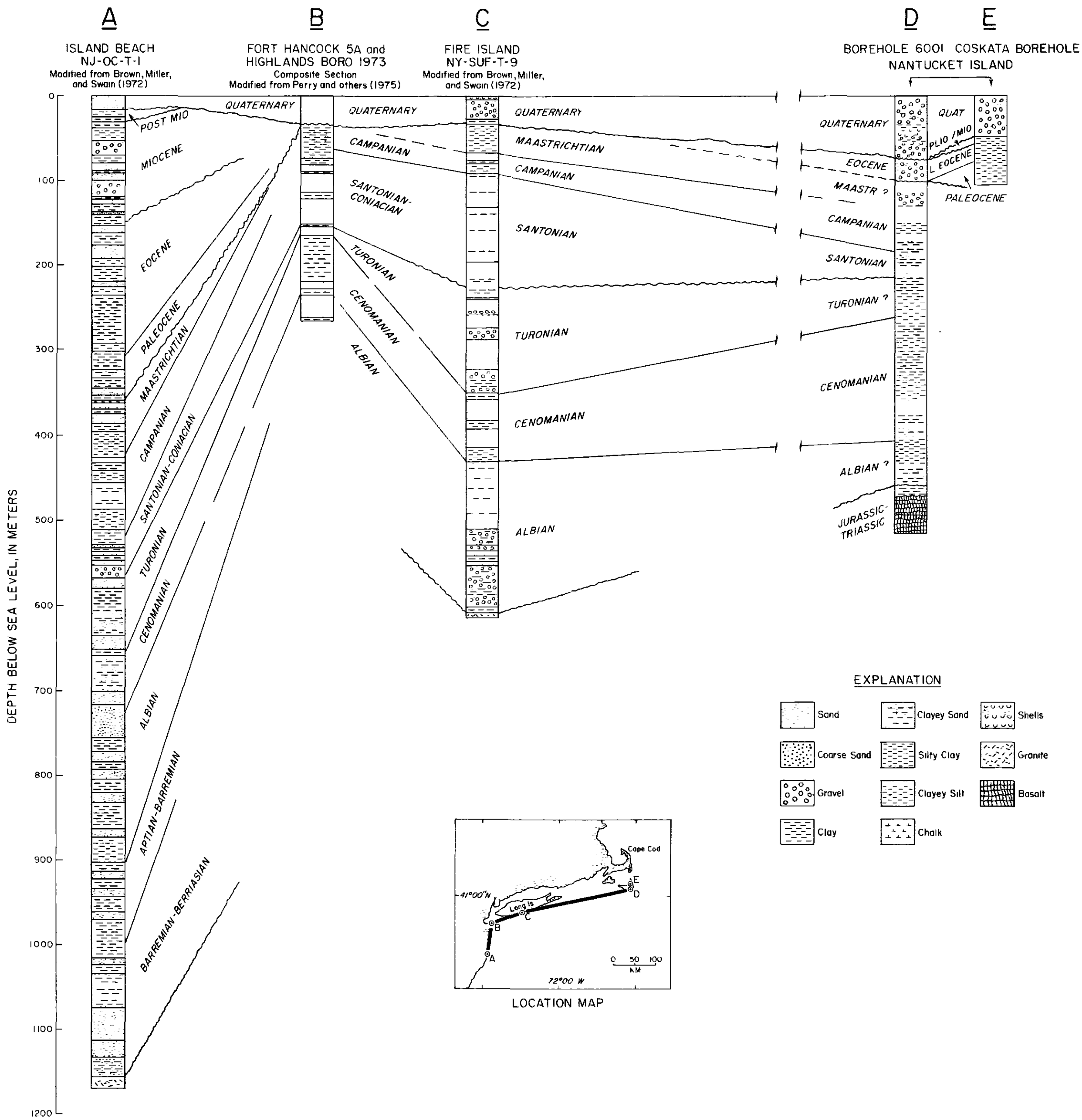

FIGURE 7.—Stratigraphic sections showing regional correlation of the Nantucket boreholes (6001 and Coskata) with other holes drilled in the Atlantic Coastal Plain to the west and south. Assignment of Cretaceous stages follows Sohl and Mello (1970).

worked out in considerable detail. We used microfossils, megascopic lithologic analysis, and borehole geophysical logs. Lithostratigraphic boundaries were established by Brown, Miller, and Swain (1972) in the Fire Island (Suffolk County, T–9) and Island Beach (Ocean County, T–1) boreholes (they used microfossils to date some boundaries); Petters (1976) and Poag (herein) modified the age boundaries by analyzing foraminiferal faunas. Lithostratigraphic boundaries were assigned by Perry and others (1975) in the Fort Hancock 5A well. Most sedimentary materials of Cretaceous age and younger in the northern part of the Atlantic

Coastal Plain are unconsolidated or at most, semi-consolidated. Therefore, they are called sediments rather than sedimentary rocks in this discussion.

The Pleistocene section in borehole 6001 is about twice as thick as that in the other wells, which is not surprising because it is much closer to Pleistocene terminal moraines than the Island Beach well or Fort Hancock well. The Pleistocene section thins from 85 m in borehole 6001 to 44 m in the Coskata borehole. The Coskata borehole lies north of the axis of the moraine. Probably the thicker section at borehole 6001 is in part due to erosion of underlying Tertiary sediments and subsequent filling by glacial outwash debris.

Tertiary sediments are thin or absent in both the Fort Hancock and Fire Island wells. At Island Beach, a 340-m section comprises Miocene, Eocene, and Paleocene sediments. Neither Pliocene nor Oligocene materials were identified. At Nantucket, the Tertiary boundaries are not well defined. An early Eocene fauna was identified between 91 m and 98 m in borehole 6001; on the basis of these fossils and lithology, we have assigned a Tertiary age to about 25 m of the section. In the nearby Coskata borehole, lower Eocene of approximately equal thickness was identified on the basis of a sparse planktic foraminifer assemblage. This is overlain by a thin (10 m) Pliocene or Miocene section (that was apparently eroded at the site of the Nantucket borehole), and underlain by almost 30 m of Paleocene sediment. Our failure to find the Paleocene section only 10 km away in borehole 6001 may be due to the poor sample recovery in this interval.

The Upper Cretaceous section down to the top of the Albian is similar in thickness (300–400 m) in the Island Beach, Fire Island, and Nantucket boreholes. Only at Fort Hancock is the section significantly thinner (about 200 m thick). This appears to be due mostly to erosion of the Maastrichtian section at the top of the Upper Cretaceous strata and to a reduced thickness of Turonian sediment.

In detail, the Maastrichtian sediments are thickest (60 m) in the Island Beach well and thin to almost 35 m in the Fire Island well. They were not identified at Nantucket but may be present in a nonfossiliferous facies. Campanian sediments are about 90 m thick at Island Beach, thin to 25 m at Fort Hancock and Fire Island, and thicken to a maximum of 80 m at Nantucket. In contrast, Santonian and Coniacian sediments are thin at both Island Beach (~50 m) and borehole 6001 (~30 m) and are thicker at Fort Hancock (85 m) and Fire Island (~125 m). Turonian strata are 90 to 125 m thick at Island Beach and Fire Island, but are only about 10 m thick at Fort Hancock. About 50 m of Turonian sediments are present at Nantucket, but the lower boundary is not well defined. Cenomanian sediments are almost 75 m thick in the three southern holes, but double that at Nantucket. Upper and lower boundaries of the Cenomanian at Nantucket, however, are only partly controlled by fossiliferous samples. Only the Island Beach well contains an Albian section definitely underlain, apparently conformably, by Lower Cretaceous sediments.

Lithologic variations along the section appear to reflect mainly the changing relative percentages of sand and clay in the Cretaceous sediments. Upper Quaternary sediments are mainly sand and gravel, whereas Tertiary deposits contain more silt and clay. The Upper Cretaceous sediments in the Island Beach well, Fort Hancock well, and Nantucket borehole 6001 contain more sand and clay at the top and become clayey toward the middle of the section. Sand again becomes more prevalent during early Cenomanian and Albian time. The Fire Island well, however, appears to have much coarser clastic sediments throughout the entire Upper Cretaceous section than the other three. Thus, the sedimentary facies vary mainly in texture—finer detritus more common at Island Beach and Nantucket, but coarser detritus more common at Fire Island.

A paleoenvironmental evaluation of the fauna and flora in the sediments of the wells revealed that during late Tertiary and Quaternary time, at all locations, sediments were deposited in nonmarine to marginal marine conditions (fig. 8). During the early Tertiary, however, sediments were accumulating in a middle to outer shelf environment in all areas. Despite the similarity in facies along the line of section, the environment of deposition during Late Cre-

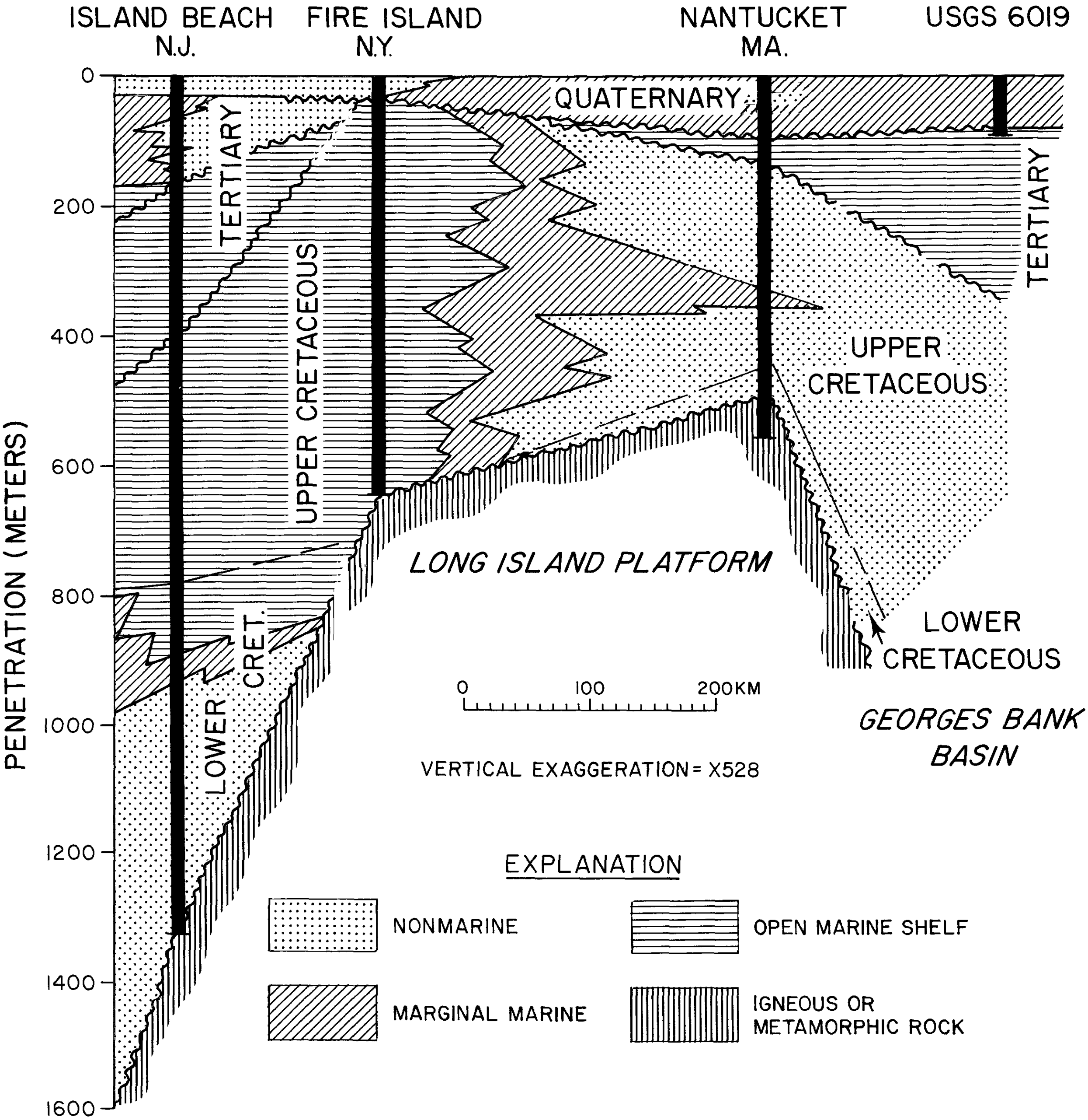

FIGURE 8.—Section from New Jersey to Georges Bank along the inner edge of the Continental Shelf showing the environment of deposition of the sediments. See figure 7 for location of wells; USGS borehole 6019 is located and described in Hathaway and others (1976). The interval labeled Quaternary in the Nantucket boreholes contains thin beds of Miocene or Pliocene age which were deposited in marginal marine conditions. Depositional environments shown are based on interpretation of paleontologic evidence.

taceous time at Nantucket was significantly different from that at Island Beach and Fire Island. Both the Island Beach and Fire Island wells contain a Late Cretaceous fauna characteristic of a shelf environment, whereas at Nantucket a nonmarine sporomorph assemblage is dominant. The only marine interval detected in the Upper Cretaceous sediments at Nantucket was a marginal marine assemblage of agglutinated foraminifers deposited during the Cenomanian. This apparently reflects the global Cenomanian marine transgression, of which

Petters (1976) also found evidence in the Island Beach well (represented by his Bass River Formation).

The Fort Hancock well apparently bottomed in Albian sediments; the Fire Island well bottomed in crystalline basement; and the Nantucket borehole 6001 bottomed in Jurassic or Triassic volcanic rocks overlain by barren sediments inferred to be Albian on the basis of tenuous correlations of electric logs.

In summary, Upper Cretaceous sediments are apparently uniform in thickness along strike between Island Beach, N.J., and Nantucket. Only at Fort Hancock is the section significantly thinner, but within the time stratigraphic stages, the thickness of sediments does vary significantly, possibly indicating changes in sediment supply with time. However, paleontologic and well control are insufficient to rule out the presence of unconformities or faults that also could affect observed thicknesses. Northeast of the Island Beach well, where Lower Cretaceous sediments were not positively identified, the updip limit of Lower Cretaceous sediments apparently lies seaward of the line of section.

REGIONAL STRUCTURE

Recently acquired shipboard gravity and aeromagnetic data on the Atlantic continental margin have been mapped by Grow and others (1976 and by Klitgord and Behrendt, 1977). The shipboard gravity coverage in waters surrounding Cape Cod, Martha's Vineyard, and Nantucket is sparse; however, an ocean bottom seismic survey of Cape Cod Bay (Bothner, 1977) provided additional coverage north of Cape Cod. Together, these data reveal a large (> +30 mGal (milligals)) linear positive gravity anomaly elongated north-northeast that passes through the eastern part of Martha's Vineyard and crosses Cape Cod just east of the Cape Cod Canal (fig. 9). A similar linear feature of approximately the same magnitude (> +30 mGals) lies to the southeast, and, though control is absent, its axis appears to pass through the site of the Nantucket borehole 6001. The positive feature passing through Martha's Vineyard has been modeled as a large mafic body intruded into crystalline basement that probably is buried on Cape Cod and under Cape Cod Bay only by Pleistocene glacial drift (Bothner, 1977). Because of sparse control in the area of the anomaly that passes through Nantucket, no modeling has been done. However, the basalt cored from 457 to 514 m beneath Nantucket may account for the equally large anomaly there. Thus, the gravity data depicts two linear positive anomalies that may be caused by basalt intruded into crystalline basement beneath Cape Code and Nantucket.

The aeromagnetic survey of the area is based on a 3.2 × 32 km line spacing and hence the coverage is excellent. A northeast grain is evident that is roughly parallel to the trend of the two positive gravity anomalies. The magnetic trend is characterized by an area of low magnetic gradients that extends between eastern Martha's Vineyard and western Nantucket. This is flanked on the southeast and northwest by higher gradients and closely spaced anomalies. A possible interpretation of this contrast is that the magnetic basement lies closer to the surface on the northwest and southeast than in the area between the islands where it is more deeply buried by sediments (Klitgord and Behrendt, 1977). Conceivably, the basalt found in the Nantucket borehole is responsible for the higher gradients at Nantucket, and a similar body or bodies of mafic rocks are responsible for the higher gradients to the northwest under Cape Cod and Martha's Vineyard.

Several seismic profiles have been run on the Continental Shelf, both north and west of Nantucket. The nearest profile to the west (USGS seismic line No. 5, CDP) has been interpreted by Grow and Schlee (1976); the nearest profile to the north is an unpublished single channel survey conducted by the USGS in 1972. Our reinterpretation of the multichannel profile is shown in figure 2. We believe that the deeper high-angle reflectors are rocks of Jurassic and Triassic age that fill possibly faulted basins similar to those mapped under the Continental Shelf in the Gulf of Maine and beneath Georges Bank basin (Uchupi, 1970; Weed and others, 1974; Oldale and others, 1974; Ballard and Uchupi, 1975; Schlee and others, 1976; Schlee and others, 1977), and off Canada (King and MacLean, 1975). Though borehole 6001 cannot be projected precisely into these profiles, its location probably lies close to the southeastern margin of an extension under

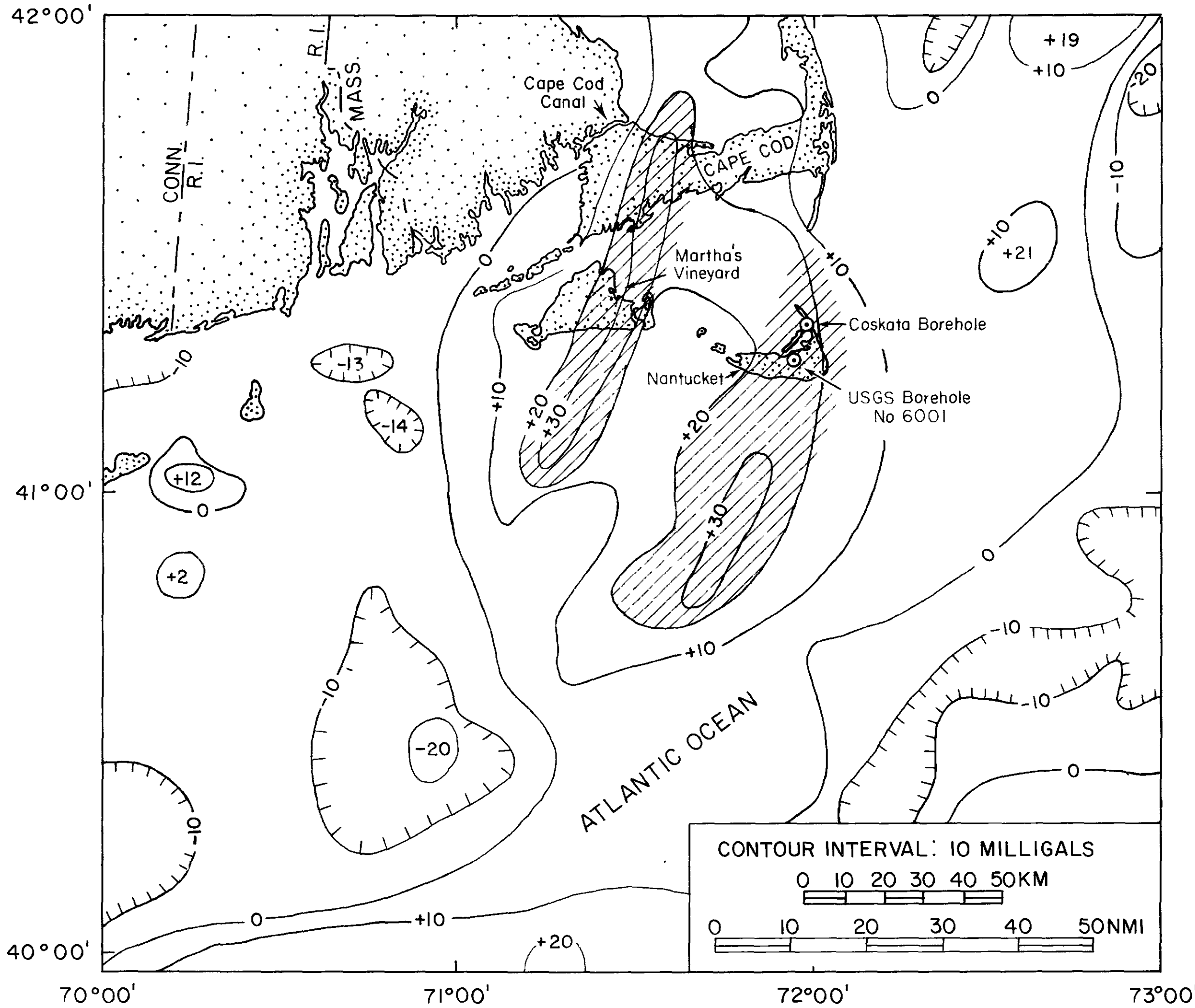

FIGURE 9.—Gravity data in the Nantucket region. Two elongated positive anomalies (shaded) pass through the Martha's Vineyard and Nantucket areas, respectively (modified from Grow and others, 1976).

Nantucket Island of the basin shown in the cross section (fig. 2).

The Jurassic or Triassic basalt penetrated may have been injected along a zone of crustal weakness associated with flexure or fracture of the basin margin and extruded as flows. The strong reflector at the northwest end of the profile shown in figure 2 may represent such flows. Thus, partly on the basis of the information from the borehole, we suggest that the geophysical data may best be explained by a Jurassic and Triassic basin or graben, with a northeast-trending axis, that lies between Nantucket and Martha's Vineyard.

A single channel seismic profile north of Nantucket (fig. 10) shows steeply dipping and folded reflectors, which we interpret as part of the Jurassic and Triassic basin that projects north of Martha's Vineyard and Nantucket. We interpret a displacement of these reflectors and the overlying flat reflectors as evidence of a late fault that cuts both the Jurassic and Triassic basin and presumed Cretaceous sediments; the fault may be as young as Tertiary, but probably does not cut Pleistocene deposits.

HYDROLOGY

The water table at borehole 6001 lies at about 3.7 m above sea level or 7.3 m below the top of the hole. To a depth of 158 m, pore water salinity was less than 1 ppt (parts per thousand). From 158 to 192 m, it increased irregularly to 29 ppt; this interval probably repre-

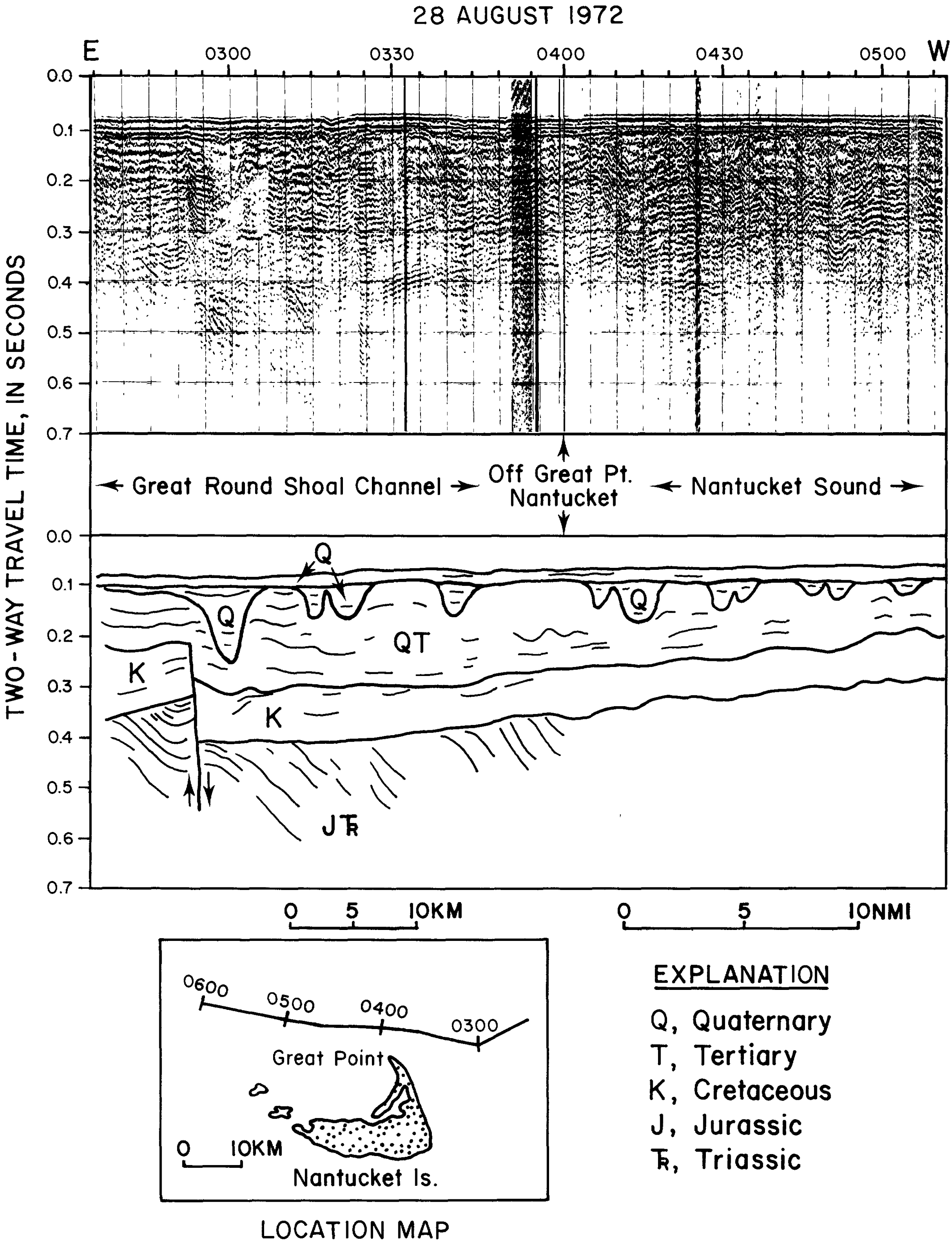

FIGURE 10.—Single channel seismic reflection profile (R/V *F. V. Hunt*, USGS, Leg III, August 28, 1972, 0230–0510 hours), east to west through Great Round Shoal Channel and Nantucket Sound (looking south), showing stratigraphic interpretation. We believe that the fault at 0252 cuts both Jurassic-Triassic and Cretaceous sediments. Sediment filling stream channels is interpreted as Pleistocene in age.

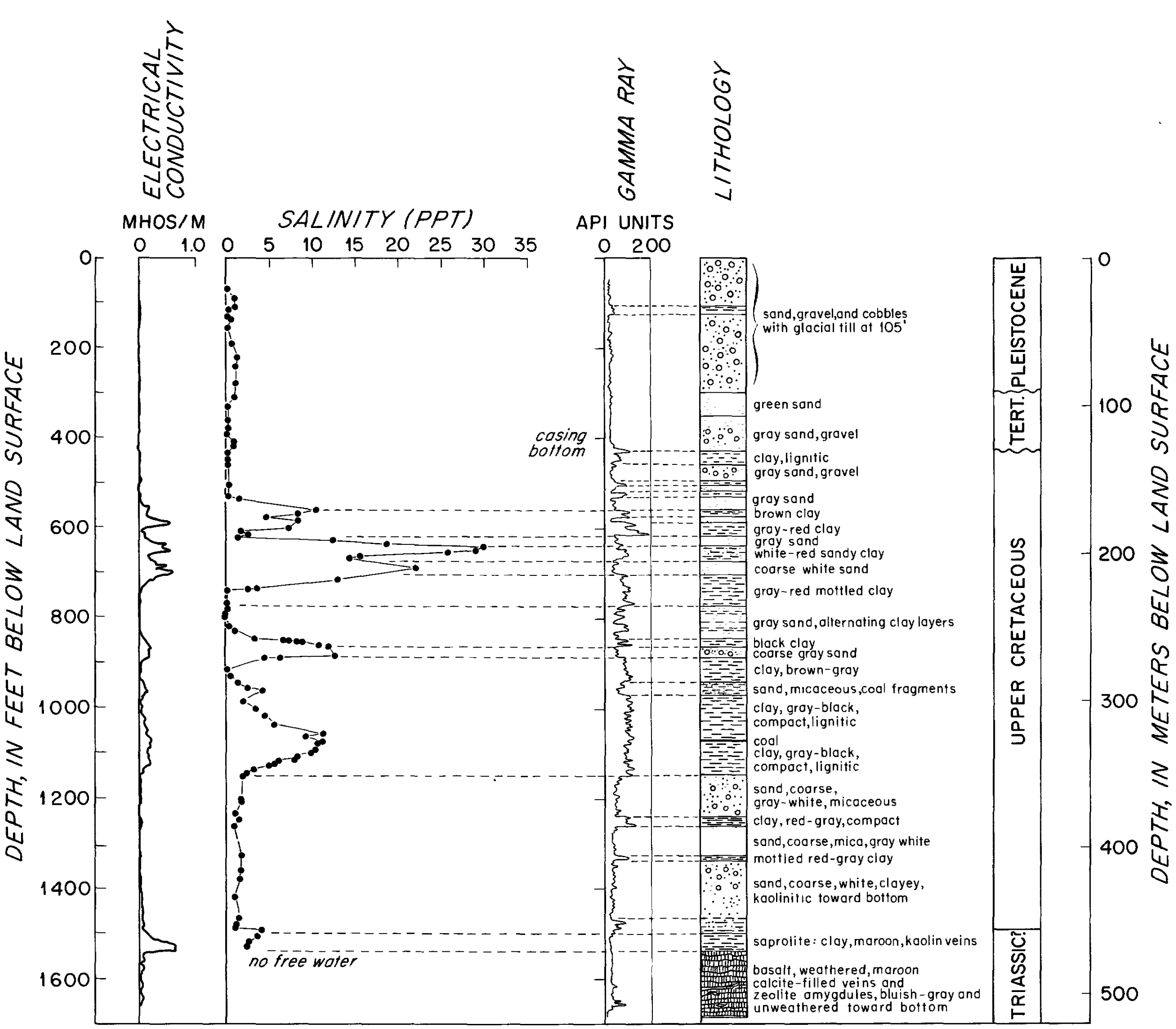

FIGURE 11.—Graph comparing salinity of interstitial water with electrical conductivity and lithology in borehole 6001. (Modified from Kohout and others, 1977.)

sents the zone of diffusion to saltwater and is not smooth because the lithology through the zone comprises interbedded lenses of permeable sands and low permeability clay. The freshwater and the transition zones thus represent a thick freshwater lens beneath Nantucket that only sligtly exceeds that predicted (Kohout and others, 1977) by the Ghyben-Herzberg principle, which is the theory of hydrostatic equilibrium between freshwater and more dense seawater in a coastal aquifer. However, below the lens, pore water salinity, instead of increasing to 33 ppt (that of seawater surrounding Nantucket), decreased again to less than 0.5 ppt between 220 and 250 m; it was even less than 0.1 ppt at 241 m. These and other thin freshwater zones probably are aquifers separated from the upper water table by low permeability clay horizons. In addition, the sandy section between 350 and 457 m appears to be a separate aquifer with slightly higher salinity of 2 to 3 ppt.

The similarity of the thickness of the freshwater lens to that predicted by the Ghyben-Herzberg relation indicates that the lens is approximately in hydrodynamic equilibrum with present sea level. However, the deeper zones bearing freshwater are anomalous. It is unlikely that they are connate waters. They may have been recharged from Cape Cod or Martha's Vineyard, but good recharge areas are not obvious and may be revealed only by additional drilling. As a third possibility, they may be residual from the time of last glacial advance when sea level was more than 120 m lower than at present (Milliman and Emery, 1968).

The zones of freshwater occurrence are shown in figure 11. These are discussed in detail in Kohout and others (1977).

SUMMARY

The 514-m deep borehole at Nantucket has provided the following hydrologic and geologic information.

1. A thick (150 m) freshwater lens overlies saltwater in approximately the relationship predicted by the Ghyben-Herzberg theory. However, beneath the lens are several zones that contain anomalously low salinity water (less than 2 ‰) that may be due to recharge, or may be relict from glacial time. The lowermost zone is more than 100 m thick and extends to the top of the saprolite zone found near the bottom of the borehole.
2. Pleistocene sediments on Nantucket are about 85 m thick and comprise mostly coarse clastic deposits. A radiocarbon date on marine fossils of Pleistocene age indicated that the deposits at a depth of 57.3 m are older than 40,000 years.
3. Marine fossils and glauconite indicate that the thin (~25 m) section of Tertiary sediment (Eocene) drilled was deposited under continental shelf conditions. Ten kilometers to the northeast, however, Miocene and Pliocene, lower Eocene, and Paleocene marine sediments total 60 m thick in a water well drilled at Coskata in 1933.
4. Upper Cretaceous sediments are largely nonmarine, even where fossiliferous. They appear to have been deposited in fluvial to deltaic environments that occasionally gave way to lagoonal or lacustrine conditions. Palynomorphs in semiconsolidated clay (240 m thick) and thin interbeds of sand define deposits of late Campanian to Cenomanian Age; the underlying unconsolidated sand (~100 m thick) and thin interbeds of clay are barren but may be of Albian Age on the basis of electric log correlations.

   Lignite and coal in the Upper Cretaceous are of low rank and are thermally immature. These sediments were probably never deeply buried; thus, generation of petroleum hydrocarbons in this vicinity or similar shoreward parts of the continental margin sediment wedge is unlikely.
5. A saprolite zone, 13 m thick, consisting mostly of kaolinite, overlies 44 m of partially altered basalt of Jurassic or Triassic age. Geochemical data and amygdaloidal structure suggest that the basalt was deposited as a series of flows, and that the upper surface was deeply weathered under tropical or humid conditions. The hole bottomed in the basalt.
6. The depth of the basalt and sound velocities logged in it agree well with those calculated for a prominent acoustic refractor that was detected previously under Nantucket. The well thus established the identity of the refractor and showed that the basalt is not correlative with the older crystalline (acoustic) basement under Cape Cod.
7. The presence of Mesozoic basalt under Nantucket, coupled with previously acquired gravity, magnetic, and seismic data, suggest that the borehole is close to the southeastern flank of a buried Jurassic and Triassic basin or graben that trends northeast. Its axis lies between the islands of Nantucket and Martha's Vineyard.

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