1. ISLAND BEACH SITE REPORT[1]

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Chief Scientist: Miller
Operations: Queen
Lithostratigraphy: Browning, Goss, Liu, Sugarman, Van Fossen
Biostratigraphy:
Foraminifers: Browning, Liu
Nannofossils: Aubry (Cenozoic), Bukry (Mesozoic)
Diatoms: Burckle
Sr-isotopic stratigraphy: Sugarman

SUMMARY

The Island Beach borehole was the first site drilled as part of the New Jersey coastal plain drilling project, Leg 150X. Located directly updip of the proposed offshore shelf sites (MAT1–3) and the *Ewing* multichannel seismic (MCS) grid, this site focused on lower Miocene–Oligocene ("Icehouse"), middle–upper Eocene ("Doubthouse"), and Paleocene–lower Eocene ("Greenhouse") sequences.

The upper Pleistocene–Holocene Cape May Formation at Island Beach records a generally deepening upward succession of fluvial, bay–estuarine–inner neritic, to nearshore facies that represents at least the Holocene transgression and perhaps additional sea-level cycles. Recovery of the 427-ft Miocene Kirkwood Formation was excellent, and the facies represent diverse fluvial, nearshore, and inner neritic (including prodelta) environments. Diatoms indicate correlation of the Kirkwood Formation at Island Beach primarily to East Coast Diatom Zone (ECDZ) 2 and older (lowermost middle to lower Miocene), whereas Sr-isotope stratigraphy dates the lowermost Kirkwood sequence recovered here as 21.8 Ma (early Miocene). Other biostratigraphic and isotopic correlations are lacking for the Kirkwood Formation at Island Beach because of shallow-water and nonmarine facies; however, the lithostratigraphic subdivisions of the Kirkwood Formation can be correlated to the Atlantic City borehole where they are dated using Sr-isotopic stratigraphy. These correlations allow the evauation of facies changes in at least four Miocene sequences tied to a time stratigraphic framework.

Although the well-recovered Paleogene succession at Island Beach contains most nannofossil (NP3, NP5, NP6, NP9 through NP22, NP24–NP25), and planktonic foraminifer (P1c through P21a) zones, the section contains at least 10 disconformities. A 196-ft Oligocene section has unconformities at its top (505 ft, hiatus from 24.3 to 21.8 Ma based on Sr-isotope stratigraphy), middle (?602 ft, Zones P20–P21a), and base (697 and 701 ft; lowermost Oligocene Zones NP22 and NP21, respectively).

The Eocene section contains several unconformities that have been well dated using magnetobiostratigraphy only at one other borehole in the New Jersey coastal plain (ACGS#4, Mays Landing). Excellent recovery, well preserved and diverse microfossils, good well logs, and preliminary magnetostratigraphy shows that the Eocene section at Island Beach will provide one of the best dated records of these "Doubthouse" and "Greenhouse" sequences. A 78-ft thick upper Eocene (and ?upper–middle Eocene) middle neritic (30–100 m paleodepth) section contains one or more disconformities at its base (the interval between 767 and 779 ft). The middle Eocene Shark River Formation (83 ft) is middle–outer neritic (30–200 m paleodepth) and may be broken into two sequences by a probable unconformity at 800 ft and a distinct disconformity at its base (862 ft; at the lower/middle Eocene boundary). The thick (213 ft) uppermost Paleocene–lower Eocene Manasquan Formation provides an apparently continuous record of deeper water (primarily outer neritic; 100–200 m paleodepth) deposition across the Paleocene/Eocene through to the lower/middle Eocene boundary although further studies are needed to evaluate a possible break near the Paleocene/Eocene boundary (i.e., Zone P6b is missing). Preliminary magnetostratigraphic studies of this unit reveal polarity zones that can be calibrated to the Geomagnetic Polarity Time Scale (GPTS), whereas the Paleocene/Eocene boundary section contains sufficient foraminifers for oxygen and carbon isotopic studies. A time-transgressive diagenetic porcellanite and porcellanitic clay (= Horizon A^c) occurs in the upper lower Eocene at Island Beach.

The upper Paleocene Vincentown Formation contains remarkable, apparently cyclic laminations of clays and silts deposited in lower shoreface environments. It represents at least one depositional sequence with a glauconite shell bed at its base (1160–1163 ft; Zone NP5); this represents a "condensed section" (glauconite sand) overlain by a Highstand Systems Tract. A possible sequence boundary occurs in the middle Paleocene (1148 ft between Zones NP6 and NP8). A lower Paleocene sequence is represented by the downdip equivalent of the Hornerstown Formation; it records laminated silts (Zones NP3 and P1c) of a Highstand System Tract that are not preserved updip. The Cretaceous/Paleogene contact was not recovered. The Maastrichtian glauconite sandy clay to clayey sands are assigned to the undifferentiated Red Bank–Navesink formations.

Drilling at Island Beach fulfilled expectations. The excellent recovery, well-developed facies, good Paleogene biostratigraphy, Sr-isotope stratigraphy, and potential for magnetostratigraphic studies provides the material needed to date Cenozoic sequences and to evaluate facies changes within sequences. Highlights include: (1) a dateable record of the late Pleistocene to Holocene sea-level change; (2) lithostratigraphic correlations of the Miocene section with the well-dated Atlantic City section; (3) relatively thick and dateable Oligocene and upper–middle Eocene sections; and (4) a well developed Paleocene/Eocene boundary and lower Eocene section.

BACKGROUND AND OBJECTIVES

This chapter and the following Atlantic City site chapter are site reports for the first two continuously cored and logged boreholes

[1] Miller, K.G., et al., 1994. *Proc. ODP, Init. Repts.,* 150X: College Station, TX (Ocean Drilling Program).
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drilled onshore as part of the New Jersey Sea-level Transect. The geological background and scientific justification for the transect are given in Chapter 2 (Mountain, Miller, Blum, et al., 1994). The transect is an integration of ODP offshore, supplementary nearshore, and onshore drilling. The transect is intended to document the response of passive continental margin sedimentation to glacioeustatic changes during the late Oligocene to Miocene "Icehouse world" (Miller et al., 1991b) and to document the ages of Eocene and older "Doubthouse" sequences.

The onshore drilling program was sponsored by the National Science Foundation, Earth Science Division, Continental Dynamics Program and the Ocean Science Division, Ocean Drilling Program. Onshore drilling is a collaborative effort among Rutgers University, Lamont-Doherty Earth Observatory, the U.S. Geological Survey, and the New Jersey State Geological Survey. PCOM endorsed the onshore drilling as an ODP-related activity (Leg 150X). As noted in Chapter 2 (Mountain, Miller, Blum, et al., 1994), determining relative sea level and evaluating eustatic changes requires the integration of studies from nearshore to deep-sea environments. The goal of onshore drilling is to recover updip counterparts of the sequences drilled by Leg 150 slope-rise and future shelf drilling. In addition, the onshore boreholes provide continuous coring of "Doubthouse" sequences (Paleocene–Eocene).

Previous studies have shown that coastal plain sections can be correlated to the GPTS by integrating magnetostratigraphic, biostratigraphic, and Sr-isotope studies (e.g., Miller et al., 1990, 1993). Boreholes are less subject to weathering than outcrops, and problems of low remanence encountered in coastal plain magnetostratigraphic studies can be minimized by analyzing large samples. Initial studies of the Miocene of the mid-Atlantic coastal plain indicate that the subsurface record is suitable for integrated magneto-, bio-, and Sr-isotope studies. However, previous studies lack the material needed to conduct these studies, particularly from downdip locations that can be tied into the offshore transect. The most complete records previously obtained are from the continuously cored ACGS#4 (Owens et al., 1988; Miller et al., 1990) and Belleplain boreholes (Sugarman et al., 1993). These updip boreholes are stratigraphically less complete than downdip boreholes, and the shallower water updip sections are less suitable for magnetostratigraphic studies. The onshore drill sites in this project were selected to be as close to the present day beach as possible to make use of offshore seismic ties and to take advantage of the thicker downdip sections. The downdip boreholes yielded more pelagic microfossils, better biostratigraphy, and more complete sections than updip boreholes. The deeper water nature of these sediments also provides a better chance to obtain a reliable magnetochronology.

The onshore boreholes are located along the coast in a northeast-southwest direction (i.e., approximately along strike). This along-strike component to the dip transect from Island Beach to the Leg 150 sites was designed to sample different parts of the Miocene and older sections. Paleodepths increase and Oligocene–Miocene sediments thicken not only downdip but also along the coast toward the south, reflecting the influence of the Salisbury Embayment (Owens and Gohn, 1985). Because of regional tectonic differences, onshore boreholes to the south will sample progressively younger Miocene strata, and boreholes to the north will sample progressively older Paleogene strata (see isopach maps in Sugarman et al., 1993).

The first onshore borehole in the onshore project was drilled in March–May 1993 at Island Beach, New Jersey. The rotary-sampled water test well near Island Beach penetrated the top of the Eocene at approximately 225 m (739 ft; Olsson et al., 1980); our objective was to reach the top of the Cretaceous (1200 ft; 400 m) to document the Paleogene and Neogene depositional histories. Island Beach is immediately updip from the offshore boreholes (proposed Sites MAT1–9, ODP Sites 902–906). The closest approach feasible for an oceanographic vessel is 6.5 nmi (Exxon Line 6), MCS line Ew1003 comes within 12 nmi of this location (Fig. 1). Although shoals prevent a closer approach with a large vessel, high-resolution Geopulse™ (e.g., Ashley et al., 1991) or sparker data obtained from small craft can be used to bridge this gap at a later date.

OPERATIONS

Drilling began 24 March 1993 at Coast Guard Station 112, Island Beach State Park, NJ (39°48′10″N, 74°05′37″W; elevation 12 ft; Barnegat Light, NJ 7.5′ quadrangle), approximately 2.5 mi north of Barnegat Inlet. Drilling operations were superintended by Don Queen, U.S. Geological Survey; drillers were Gene Cobbs, Todd Heibel, Dave Mason, and Mike Hoffmann. Water, electricity, and garage space for core description were provided by park superintendent William Vibbert.

The first core was obtained on 25 March 1993. Coring proceeded to 58 ft below surface using the Christensen 94-mm (HQ) system, with a 4¼- to 2½-in. hole diameter and a 2½-in. core diameter. Six-inch PVC casing was set and grouted at 57 ft, to be extracted at completion. Coring continued on 26 March using the Christensen 94-mm system. Coring runs were generally 5 ft for the upper 450 ft (Table 1). For unconsolidated sands, an extended shoe was used to contact the sediment 0.75 in. in front of the bit. Core recovery was excellent (Table 1) in unconsolidated sands and stiff clays. From 23 to 453 ft, recovery averaged 87% with a median of 96% (Fig. 2 and Table 1). Intervals of poor to moderate recovery (20%–50%) were restricted to only three 5-ft coring runs between 7 and 453 ft (38–43 ft, 122–127 ft, and 358–363 ft). We expected to penetrate thick unconsolidated sands (the "800-foot sands") and set casing at 400 ft in clays predicted from gamma-ray logs obtained from water wells on Island Beach. This level was attained on 31 March; however, the clay layers were interbedded with sands. Drilling continued until tighter clays were penetrated on 1 April (443–453 ft).

Rods were pulled on 2 April and the hole reamed to 146 ft. Reaming continued on 3 April; odd conditions developed in the hole from 210 to 290 ft, with drilling mud continuing to run 5 min after the pump was shut down. The hole was reamed to 451 ft on 4 April, and the rods were pulled to set casing.

John Curran of the New Jersey Geological Survey (NJGS) attempted a gamma-ray log of the hole on 5 April; the sonde would not penetrate below 80 ft. Casing was set from 9 to 80 ft; casing would not penetrate below 80 ft because of clay swelling. The hole was redrilled to 146 ft. The NJGS obtained a gamma-ray log of the Island Beach hole from land surface to 140 ft on 5 April; the hole could not be logged below because of clay swelling. The hole was drilled to 280 ft, a level below the last clay. Four-inch PVC casing was set to 454 ft on 6–7 April using the rig to pump casing into place. Because of the tight fit of the casing in the hole, we did not grout the casing in place.

Coring resumed on 7 April at 453 ft with a Christensen CNWL (NQ) system, 3.162-in. hole diameter, and 1.875-in. (1⅞ in.) core diameter with rock shoe (1.67 in. with extended shoe). Recovery averaged 85% from 453 to 507 ft. The first greensand was penetrated on 8 April in the lower Kirkwood Formation (477–484 ft). Continuous, partially lithified glauconite sands were penetrated at 505.5 ft on 8 April. Alternations of hard (indurated), "gummy" muddy sands with softer sands proved difficult to recover, and drilling slowed on 9–10 April. Recovery rates dropped to a mean of 68% for the interval of 505.5 to 568 ft. Drilling continued slowly with moderate recovery on 11 April (58% recovery between 568 and 608 ft) and 12 April (45% recovery between 608 and 658 ft). High feed pressures (Table 2) were needed to penetrate the indurated greensands. Because of the high down pressure, an oil seal was broken on 10 April and a water line ruptured on 11 April. We reset the blowout to 800 psi and changed the oil in the right angle drive. On 12 April, the shoe was mangled; we cut and sharpened a new shoe. On 13 April, core recovery returned to 100%. The sediments were as "gummy" but less indurated than above and the new shoe allowed them to be cut.

Coring continued slowly on 14 and 15 April (40 and 45 ft per day, respectively) so as to recover critical lower Oligocene–middle Eocene contacts. Recovery was remarkable, and often exceeded 100% due to clay expansion. In particular, two runs between 769 and 784 ft recovered 16 ft of core; depth at 784 ft was verified and depths within this

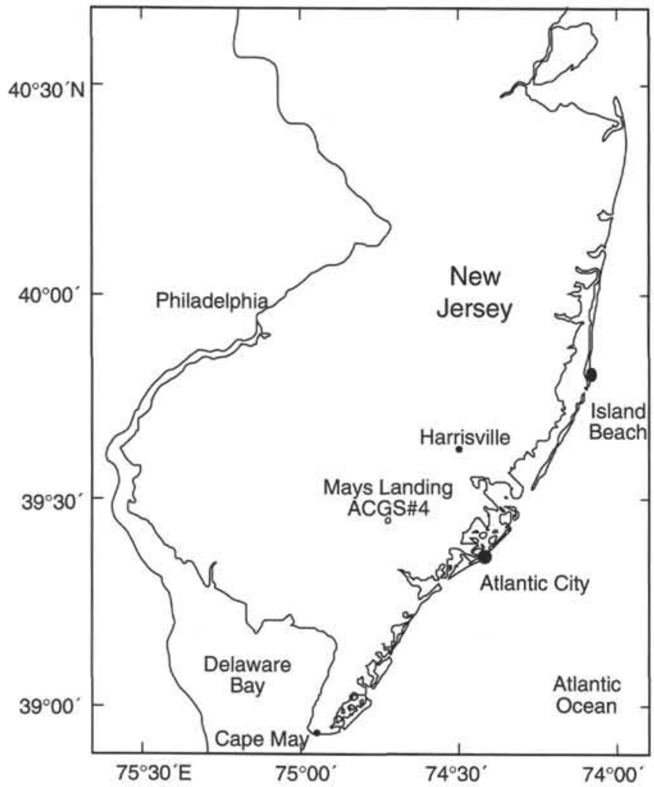

Figure 1. Location map showing boreholes drilled in 1993 (large closed circles), proposed boreholes (small closed circles), and the ACGS#4 borehole (Owens et al., 1988).

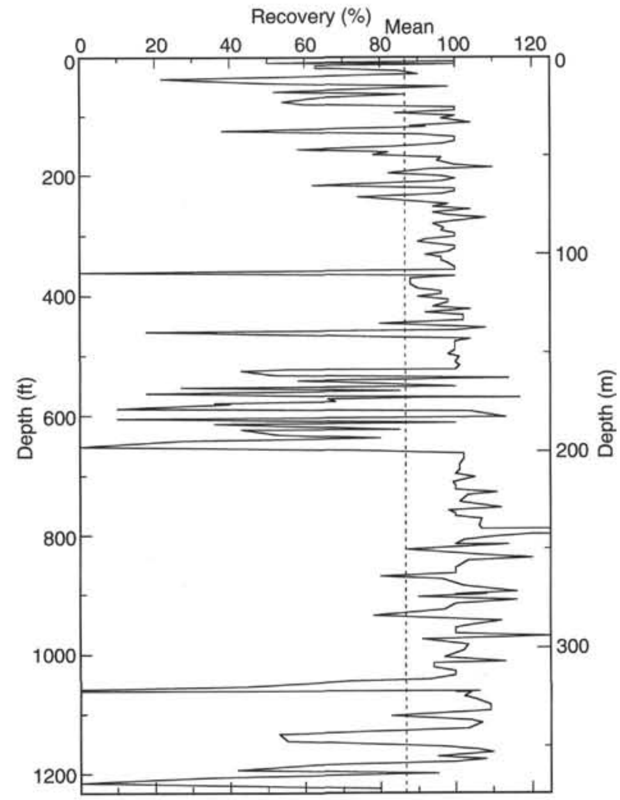

Figure 2. Recovery in each core vs. depth, Island Beach borehole.

core and subsequent cores with greater than 100% recovery must be adjusted for clay expansion.

Recovery began to exceed 110% (Table 1) on 15 and 16 April, and we considered explanations other than clay expansion for these cores. The interval from 789 to 794 ft recovered 8.3 ft of solid section. It is impossible to explain this 160% recovery by expansion alone. The depths at 784 ft and 794 ft were verified. Because recovery from 784 to 789 ft was 107%, there is no room to fit 8 ft into the 5 ft interval between 789 and 794 ft. Sedimentary structures appear in situ; the core is solid, and it shows clear drilling marks. Thus, the excess section is not attributable to caving or slumping downhole. One solution is that we double cored this interval. The drill pipe was raised by ~5 ft in between runs and rotated during lowering to the base of the hole. Therefore, it is possible that double coring occurred, and subsequent log data support this (see below). No other instances of double coring were noted.

It is also possible that some of the intervals with greater than 100% recovery were caused by stretching of plastic clays. From 810.5 to 819 ft, recovery was 10 ft (117%); however, this section was stretched as indicated by core thinning and high downpressures needed to recover core (Table 2). The core was as thin as 1.5 in.; with the extended shoe the expected width is 1.67 in. Thus, recovery of 1.5-in. core can explain 124% core recovery. On 17 April, we had 120% recovery in a 5-ft run (834–839 ft). Otherwise, our recovery on 17–18 April was 90%–100% between 829 and 889 ft.

Drilling slowed on 19 April as alternating layers of very indurated rock (calcareous porcellanite) and softer clay were penetrated. Only 20 ft was drilled, with 20.4 ft of recovery. We switched from the medium to the rock shoe at 904 ft on 19 April. On 20 April, we were still drilling alternations of porcellanite and clay, although the interval was generally harder than immediately above. We improved penetration to 50 ft (recovery 47.3 ft) on 20 April by making 10 ft runs in this generally harder material and using the rock shoe. Drilling on 21–22 April was slowed because of mechanical difficulties (clogged carburetor; clogged fuel filters; replaced wireline with 3500 ft); only 19 ft was drilled (20.4 ft recovered) on 21 April and 27 ft was drilled on 22 April (27.25 ft recovered).

Drilling continued to be slow on 23–26 April because of various mechanical difficulties. Problems developed on 23 April. The core barrel would become blocked at about 7 ft into a 10-ft run. The need to run high pressures (up to 800 psi) caused problems with the beam pump. We ended 23 April at 1028 ft with good recovery (98% from 1005 to 1028 ft). On 24 April, we ran 7 ft, recovered 8 ft, making up for a foot left in the hole on the 23 April. After a 3-ft run with 100% recovery, we recovered only 6 ft from 1038 to 1048 ft. We ran from 1048 to 1053 ft and from 1053 to 1054 ft with no recovery, although there was core in the bottom of the shoe. We were able to pump the hole. On 25 April, we determined that the missing 4 ft of core had broken off and lodged inside of the core barrel. As a result of the lodged core, we drilled 5 ft with the inner barrel not properly locked in; this core also lodged in the core barrel, blocking it. We confirmed that cores were lodged in the barrel by going back inside with the inner barrel and recovering 2.2 ft of core without any run, just by hammering down with the inner barrel; this interval was from the 1038- to 1048-ft run. The rest of the day was spent trying to recover the core inside the barrel. We pulled 20 ft of rod, put the beam pump into fourth gear, and increased pressure to 1000 psi; this blew the core in the barrel down into hole. On 26 April, we replaced the 20 ft of rods, ran from 1055 to 1057 ft, and recovered 2.5 ft of material that came from the 1048- to 1053-ft interval, but none from 1055 to 1057 ft. The motor kept cutting out; we rebuilt the carburetor. We tried a 1 ft run with no recovery, but determined that core had gone into the shoe. To capture the core, we changed to a short shoe out the barrel, ran from 1058 to 1063 ft, and recovered 8 ft of solid core that included material from 1055 to 1058 ft. Despite these setbacks, we only lost less than 8 ft in the interval between 1038 and 1058 ft (Table 1; 62% recovery).

Table 1. Core description, Island Beach borehole, Leg 150X.

Core	Interval (ft)	Recovery (%)	Description	Color	Formation
1	7–8	1.0 ft (100%)	Pebbly, medium-coarse quartz sands, pebbles up to 3 mm in diameter, subrounded, heavy minerals throughout.	5Y 6/1, gray	Cape May Formation
2	8–11	1.6 ft (53.3%)	Pebbly, medium-coarse quartz sands, pebbles up to 3 mm in diameter, subrounded to subangular, heavy minerals throughout.	5Y 6/1, gray	
3	11–14	3.0 ft (100%)	Pebbly, medium-coarse quartz sands, subrounded to subangular pebbles, well sorted.	5Y 6/1, gray	
4	14–18	2.6 ft (65%)	Pebbly, medium-coarse quartz sands, subangular to subrounded pebbles, micaceous and with heavy minerals.	5Y 6/1, gray	
5	18–23	3.1 ft (62.5%)	Pebbly, medium-coarse quartz sands, pebbles up to 3 mm in diameter, slightly coarser upward, heavy minerals throughout.	5Y 6/1, gray	
6	23–28	4.3 ft (85%)	Pebbly, medium-coarse sands, mostly quartz, well sorted and rounded, finer below 24.9 ft, peat layer at 24.65 ft.	5Y 6/1, black; 10YR 6/1, gray	
7	28–33	4.5 ft (90%)	Pebbly, medium to coarse quartz sands, well sorted and rounded, no bedding; 2–3 mm pebbles in upper 1.8 ft; heavy minerals throughout.	5Y 4/1, dark gray	
8	33–38	2.9 ft (58%)	Uniform pebbly medium to coarse quartz sands, pebbles to 18 mm; no bedding; shell fragments, pebbles at bottom.	5Y 6/1, gray	
9	38–43	1.1 ft (22%)	Well-rounded, coarse to very coarse sand with subrounded pebbles to to 7 mm; no bedding, two shells (*Anomia*? and *Pecten*?).	5Y 6/1, gray	
10	43–48	2.5 ft (50%)	Sandy shelly mud with quartz pebbles (2–5 mm), *Pecten?*, *Anomia?*, gastropods; H_2S odor; uniform bedding.	5Y 4/1–5Y 4/2, dark gray	
11	48–53	4.9 ft (98%)	Bioturbated sandy mud at top 1 ft grading to muddy medium sand from 49 to 50 ft and coarse sand from 50 to 51 ft; pebbly shell bed at 50.5–51.0 ft; at 51.0 ft, there is a distinct bioturbated surface with sticky mud below in lower 4 ft; H_2S odor.	5Y 5/1–5Y 3/1, gray to very dark gray	
12	53–58	3.7 ft (74%)	Sticky mud at top, grades to sandy mud with shells.	5Y 5/1–5Y 4/1, gray to dark gray	
13	58–63	2.6 ft (52%)	Alternating layers of medium-coarse clean sands and pebbly medium sands, with shells and mud matrix.	5Y 4/1, dark gray	
14	63–68	4.3 ft (86%)	Mud-sandy mud, with quartz pebbles up to 10 mm.	5Y 3/1, very dark gray	
15	68–73	3.2 ft (64%)	Coarse sand with quartz pebbles; 70.4–70.7 ft clay with H_2S odor.	5Y 4/1, dark gray	
16	73–78	2.7 ft (54%)	Pebble conglomerate with coarse sand matrix and subrounded quartz and chert pebbles up to 15 mm.	5Y 5/1, gray	
			-------------Lithologic contact 78 ft (below is the Kirkwood Formation)-------------		
17	78–83	3.0 ft (60%)	Homogeneous clay, with silty layers.	2.5Y 5/0–2.5Y 6/0, gray	Kirkwood Formation
18	83–88	5.4 ft (108%)	Homogeneous clay, some layers with pebbles up to 5 mm.	5Y 6/1–5Y 5/1, gray	
19	88–93	5.3 ft (106%)	Alternating homogeneous clay, silty clay, and muddy sands.	5Y 6/1, gray	
20	93–98	4.2 ft (84%)	From 93.0 to 96.4 ft: coarse sands with lignite at 95.2 ft and peat at 96.3 ft; from 96.4 to 97.2 ft: sandy clay and hard clay beds.	5Y 5/1, gray	
21	98–103	5.0 ft (100%)	Hard clay with silts; some dark and light banding.	5Y 3/1, very dark gray	
22	103–108	4.8 ft (96%)	Slightly silty clay with sand from 106.0 to 106.1 ft; lignite from 105.3 to 105.4 ft.	5Y 3/1–5Y 2.5/1, very dark gray to black	
23	108–113	5.2 ft (104%)	Hard clay with lignites at 109 and 112.5 ft.	5Y 3/1, very dark gray	
24	113–117	3.5 ft (87.5%)	Very homogeneous, featureless, hard clay.	5Y 3/1, very dark gray	
25	117–122 ft	4.6 ft (92%)	Mottled hard clay.	5Y 4/1–5Y 3/2, dark gray to dark olive gray	
26	122–127.5	2.1 ft (38%)	Homogeneous, featureless, hard clay.	5Y 4/1, dark gray	
27	127.5–132.5	4.5 ft (90%)	Homogeneous hard clay with peat layers.	5Y 4/1, dark gray	
28	132.5–135	2.5 ft (100%)	Homogeneous hard clay with silty clay at 134.25–134.35 ft.	5Y 4/1, dark gray	
29	135–139	4.0 ft (100%)	Homogeneous hard clay.	5Y 3/1, very dark gray	
30	139–143	4.0 ft (100%)	Homogeneous hard clay; when fresh, color is very dark grayish brown (10YR 3/2).	5Y 3/1, very dark gray	
31	143–148	4.8 ft (96%)	Homogeneous hard clay.	5Y 3/1, very dark gray	
32	148–153	4.2 ft (84%)	From 148.0 to 151.9 ft: homogeneous hard clay; from 151.9 to 152.2 ft: homogeneous silty-sandy clay containing pebbles.	5Y 3/1–10YR 3/2, very dark gray–grayish brown	
33	153–158	2.9 ft (58%)	Chocolate dark clay; lithologic contact not recovered.	5Y 3/1–10YR 3/2	
34	158–163	4.1 ft (82%)	Lithologic change; muddy medium sands containing granules.	5Y 4/1–5Y 3/2, dark gray to dark olive gray	
35	163–168	3.9 ft (78%)	Medium-coarse sands grading down to poorly sorted coarse sand.	5Y 4/1–5Y 3/2, dark gray to dark olive gray	
36	168–173	4.8 ft (96%)	Micaceous silty sand from 168.0 to 169.5 ft, changing to poorly sorted, very coarse sand below.	5Y 4/1–5Y 5/1, very dark to dark gray	
37	173–178	4.75 ft (95.5%)	Very fine to fine sands grading to clayey silt, with occasional low-angle cross beds below 175 ft.	5Y 4/1–5Y 3/1, very dark to dark gray	
38	178–183	5.0 ft (100%)	Laminated, micaceous silt and very fine sands.	10YR 3/1–5Y 4/1, very dark gray	
39	183–185	2.2 ft (110%)	Fine-medium sands grading down to medium to very coarse pebbly pebbly sands below 183.5 ft.	5Y 6/2, light olive gray	
40	185–188	2.8 ft (93.3%)	Medium to very coarse sand with subrounded granules.	5Y 5/1, gray	
41	188–193	4.5 ft (90%)	Pebbly (up to 5 mm), very coarse sand.	5Y 6/1–5Y 5/1 gray	
42	193–198	4.1 ft (82%)	Pebbly (up to 5 mm), very coarse sand.	5Y 5/1–5Y 4/1, gray	
43	198–203	4.8 ft (96%)	Pebbly (up to 5 mm), very coarse sand and gravel.	5Y 5/1, gray	
44	203–208	5.0 ft (100%)	Pebbly coarse sand with four medium-fine sand layers.	5Y 3/1, very dark gray	
45	208–213	4.8 ft (96%)	Pebbly, very coarse sand.	5Y 5/1–5Y 4/1, gray	
46	213–218	3.1 ft (62%)	Pebbly, very coarse sand.	5Y 5/1–5Y 4/1, gray	
47	218–223	5.0 ft (100%)	Medium quartz sand.	5Y 5/1, gray	
48	223–228	5.0 ft (100%)	Medium sand grading down to coarse sand.	5Y 5/1–5Y 4/1, gray	
49	228–233	4.8 ft (96%)	Silty, sandy clay above 229.4 ft; medium to coarse sand below.	5Y 4/1, dark gray	
50	233–238	3.7 ft (74%)	Medium to very coarse sand; pebbles up to 3 mm.	5Y 3/1–5Y 4/1, dark to very dark gray	
51	238–243	4.2 ft (84%)	Well-rounded coarse to medium sand, with dark minerals.	5Y 4/1–5Y 3/2, dark gray to dark olive gray	
52	243–248	4.9 ft (98%)	Coarse sand in top 1 ft, medium quartz sand alternating with black clay layers below.	5Y 2.5/1–5Y 3/1, black to dark gray	
53	248–253	4.7 ft (94%)	Black clay on top grading down to fine-medium clayey sand.	5Y 3/1, very dark gray	
54	253–258	5.2 ft (104%)	Medium sand 253.0–256.5 ft, with hard dark clay below.	5Y 4/1, dark gray	
55	258–263	4.7 ft (94%)	Hard clay with subangular to angular coarse sand from 259 to 261 ft.	5Y 5/1, gray	
56	263–267	3.9 ft (97.5%)	Hard clay with coarse sand from 263.3 to 263.8 ft.	5Y 3/1, very dark gray	
57	267–272	5.4 ft (108%)	Dark hard clay with fine sand from 270.2 to 270.8 ft and lignite between 271.1 and 271.3 ft.	5Y 2.5/1, black	

Table 1. (continued)

Core	Interval (ft)	Recovery (%)	Description	Color	Formation
58	272–277.4	5.4 ft (100%)	Dark hard clay with a small amount of sand.	5Y 2.5/1–5Y 3/1, black to very dark gray	Kirkwood Formation
59	277.4–282.8	5.0 ft (92.5%)	Dark clay and fine sand alterations above 278.7 ft, muddy fine sand below.	5Y 3/1–5Y 4/1, very dark to dark gray	
60	282.8–288	5.2 ft (97%)	Fine sand, grading to medium-fine sand in 286.2–288 ft.	5Y 3/1–5Y 4/1, dark gray	
61	288–293	4.8 ft (96%)	Fine-medium sand with one pebbly sand layer (289.8–290 ft), a lignite layer (290–290.7 ft), and a coarse sand layer (290.7–291.1 ft).	5Y 3/1, very dark gray	
62	293–298	5.0 ft (100%)	Muddy fine-medium sand.	5Y 4/1, dark gray	
63	298–303	5.0 ft (100%)	Alternations of medium-coarse sand and hard sandy clay; lignite bed containing pyrite from 299.6 to 300.9 ft and pyrite.	5Y 2.5/2, dark gray	
64	303–308	4.6 ft (92%)	Hard sandy clay on top with coarse quartz sand and muddy medium sand below.	5Y 5/1–5Y 4/1, black	
65	308–313	4.5 ft (90%)	Coarse to pebbly very coarse quartz sand, subangular.	5Y 3/1, very dark gray	
66	313–318	5.0 ft (100%)	Medium coarse sand, sandy clay, and clayey fine sand.	5Y 5/1–5Y 4/1, gray to dark gray	
67	318–323	5.0 ft (100%)	Fine-medium and clayey fine sand; one thin clay layer.	5Y 3/1, very dark gray	
68	323–328	4.9 ft (98%)	Medium-coarse sands with lignite at 323.6–323.7 ft.	5Y 3/1, very dark gray	
69	328–333	4.6 ft (98%)	Medium and coarse quartz sand.	5Y 3/1, very dark gray	
70	333–338	4.8 ft (96%)	Coarse quartz sand with bands of heavy minerals.	5Y 6/1, gray	
71	338–343	4.8 ft (96%)	Medium to coarse sand above, with very coarse sand below.	5Y 5/1–5Y 4/1, dark gray	
72	343–348	4.9 ft (98%)	Medium to very coarse sand interbedded with silty medium sand.	5Y 3/1, very dark gray	
73	348–353	5.0 ft (100%)	Medium to coarse sand on top grading to very coarse sand; peat at 350.3 and 350.8 ft; silty medium sand at base.	5Y 3/1, very dark gray	
74	353–358	5.0 ft (100%)	Two cycles of muddy medium sand grading down to coarse to very coarse sand.	5Y 3/1–5Y 3/2, very dark gray to dark olive gray	
75	358–363	0.0 ft (0%)	Possibly coarse–very coarse sand.		
76	363–368	5.0 ft (100%)	Silty fine-medium sand with coarse sand beds; thin carbonaceous beds; sand becomes micaceous at base.	5Y 4/1, dark gray	
77	368–373	4.4 ft (88%)	Coarse sand and medium sand with a hard clay layer (371.9–372.4 ft), and two lignite horizons (at 368.9 and 369.7 ft).	5Y 5/1–5Y 4/1, gray to dark gray	
78	373–378	4.4 ft (88%)	From 373 to 375.9 ft: silty fine to medium sand with lignite plugs and some cross bedding; from 375.9 to 377.4 ft: medium to very coarse sand, some pebbles.	5Y 5/1–5Y 3/1, gray to very dark gray	
79	378–383	4.5 ft (90%)	Coarse and very coarse sand with subrounded quartz pebbles.	5Y 4/1–5Y 3/1, dark gray to very dark gray	
80	383–388	4.5 ft (90%)	Medium-coarse sand with pebbles.	5Y 2.5/2, black	
81	388–393	4.8 ft (96%)	Silty fine-medium uniform sand with peat beds.	5Y 5/1, gray	
82	393–398	4.8 ft (96%)	Silty medium uniform sand.	5Y 5/1, gray	
83	398–403	4.5 ft (90%)	Fine-medium uniform sand.	5Y 6/1–5Y 5/1, gray	
84	403–408	4.9 ft (98%)	Massive, micaceous, medium to fine sand, with wood chunks at 407.6–407.9 ft.	5Y 5/1–5Y 6/1, gray	
85	408–413	4.8 ft (96%)	Muddy medium sand, fining upward.	5Y 4/1–5Y 3/2, dark gray	
86	413–418	4.7 ft (94%)	Muddy medium to fine sand, with an organic rich clay in middle.	5Y 2.5/2, black	
87	418–423	5.2 ft (104%)	Muddy fine–very fine sand, with lignite at top.	5Y 5/1, gray	
88	423–428	4.6 ft (92%)	Bioturbated muddy fine sand.	5Y 3/1, very dark gray	
89	428–433	5.2 ft (104%)	Uniform fine sand, with lignite fragments.	5Y 4/1, dark gray	
90	433–438	5.1 ft (102%)	Uniform silty fine sand, more micaceous at bottom.	5Y 3/1, very dark gray	
91	438–443	5.1 ft (102%)	Fine sandy silt in top 2.7 ft, medium-coarse sand below.	5Y 4/1, dark gray	
92	443–448	4.0 ft (80%)	Stiff uniform silty clay, pebbles near base.	5Y 2.5/2–5Y 3/2, black to dark olive gray	
93	448–453	5.3 ft (106%)	Stiff, laminated, silty clay with 2-mm lignite layer in upper part.	5Y 4/1–5Y 4/2, dark gray	
94	453–457	4.0 ft (100%)	Uniform hard silty clay.	5Y 4/1, dark gray	
95	457–467	1.8 ft (18%)	Fine, laminated, clayey silt.	5Y 4/1, dark gray	
96	467–472	5.2 ft (104%)	Silty, very fine sand in upper 2.9 ft, fine sand in middle, and coarse sand in lower 0.9 ft.	5Y 3/1, very dark gray	
97	472–477	5.0 ft (100%)	Burrowed silt to fine sand in upper 2.6 ft; silty medium coarse glauconitic sand, with partially pyritized wood.	5Y 3/1–5Y 2.5/1 5GY 4/1, gray	
98	477–486	9.0 ft (100%)	Glauconitic, medium to coarse quartz sand with burrowed fine sand at the base.	5Y 3/1, very dark gray	
99	486–493	7.0 ft (100%)	Dark brown silty to sandy clay, bioturbated, with weathered shell fragments at 492 ft.	5Y 2.5/2, black	
100	493–498	4.9 ft (98%)	Clayey silt with fine sand and shell fragments throughout.	5Y 3/1, very dark gray	
101	498–507	9.1 ft (101%)	Clayey silt with change to clayey glauconite sand at base.	5Y 2.5/1, black	
			-------------Lithologic contact 505 ft (below is the Oligocene)-------------		
102	507–511.2	4.2 ft (100%)	Medium to coarse, glauconitic or slightly glauconitic, quartz sand with shell fragments at 508.9 ft; foraminifers are visible.	5Y 2.5/2–5Y 2.5/1, black	Unnamed; Oligocene
103	511.2–518	7.0 ft (103%)	Medium glauconite sand.	5Y 3/1–5Y 2.5/1, black	
104	518–519.2	1.5 ft (100%)	Firm, medium, glauconite sand, weathered shell fragments.	5Y 2.5/1–2, black	
105	519.5–522	1.4 ft (56%)	Shelly, medium, glauconite sand.	5Y 2.5/1–2, black	
106	522–528	2.6 ft (43%)	Hard, muddy, medium-coarse, glauconite sand with shells in upper 0.7 ft.	5Y 2.5/2, black	
107	528–533	2.6 ft (52%)	Hard, dark olive green, pebbly, coarse, glauconitic sands with hard sandy mud at 529.7–530 ft.	5Y 2.5/1–2, black	
108	533–538	5.7 ft (114%)	Medium to coarse, muddy, glauconite sand.	5Y 2.5/1–2, black	
109	538–548	5.8 ft (58%)	Medium glauconite sand.	5Y 2.5/1, black	
110	548–548.5	0.5 ft (100%)	Medium glauconite sand.	5Y 2.5/1, black	
111	548.5–553	1.2 ft (27%)	Muddy, medium-coarse, glauconite sand.	5Y 3/2, dark olive gray	
112	553–558	4.25 ft (85%)	Muddy, glauconite, fine sand at top with pebbly medium-coarse glauconitic sand at base.	5Y 2.5/1, black	
113	558–563	0.9 ft (18%)	Muddy, fine to medium, glauconite sand with coarse sand and pebbles.	5Y 3/2–5Y 2.5/2, dark olive gray to black	
114	563–565	1.2 ft (60%)	Silty glauconitic clay with lignite horizons.	5Y 3/2–5Y 2.5/2, dark olive gray to black	

Table 1. (continued)

Core	Interval (ft)	Recovery (%)	Description	Color	Formation
115	565–565.3	0.35 ft (117%)	Hard, silty, glauconitic clay with lignite.	5Y 3/2, dark olive gray	
116	565.3–568	2.5 ft (93%)	Clayey, fine, glauconite sand and silty glauconitic clay.	5Y 3/2, dark olive gray	
117	568–573	3.3 ft (66%)	Fine, sandy, glauconite clay with lignite.	5Y 4/2–5Y 3/2, olive gray to dark olive gray	
118	573–575.5	1.7 ft (68%)	Clayey, fine, glauconite sand and lignite.	5Y 4/2–5Y 3/2, olive gray to dark olive gray	
119	575.5–578	0.9 ft (36%)	Fine, glauconite sand with lignite.	5Y 4/2–5Y 3/2, olive gray to dark olive gray	Unnamed; Oligocene
120	578–583	2.0 ft (40%)	Fine-medium glauconite sand.	5Y 3/2, dark olive gray	
121	583–588	0.5 ft (10%)	Medium glauconite sand.	5Y 3/2, dark olive gray	
122	588–598	10.4 ft (104%)	Firm and uniform, medium, glauconite sand.	5Y 3/1–5Y 3/2, dark olive gray	
123	598–601	3.4 ft (113%)	Medium glauconitic sand with clay layer at 599.4–599.6 ft.	5Y 3/2, dark olive gray	
124	601–608	0.7 ft (10%)	Hard, lithified, coarse, glauconite sand with some sticky clay.	5Y 3/2, dark olive gray	
125	608–609.5	1.5 ft (100%)	Firm, glauconitic, sandy clay.	5Y 3/2, dark olive gray	
126	609.5–618	3.1 ft (36.5%)	Firm, coarse, glauconite sand.	5Y 3/2, dark olive gray	
127	618–620	1.7 ft (85%)	Firm, coarse, glauconite sand.	5Y 3/2, dark olive gray	
128	620–628	3.4 ft (42.5%)	Firm, muddy, glauconite sand with shell fragments.	5Y 3/2, dark olive gray	
129	628–634	3.2 ft (53%)	Coarse, loose, glauconite sand and clayey glauconite sand, with Scaphopod shell.	5Y 3/2, dark olive gray	
130	634–638	3.2 ft (80%)	Coarse glauconite sand.	5Y 3/2, dark olive gray	
131	638–648	2.7 ft (27%)	Coarse glauconite sand.	5Y 3/2, dark olive gray	
132	648–653	0.0 ft (0%)	No recovery.		
133	653–658	3.6 ft (72%)	Hard, clayey, coarse, glauconite sand.	5Y 3/2, dark olive gray	
134	658–663	5.1 ft (102%)	Firm, burrowed, clayey, medium, glauconite sand with weathered shells.	5Y 2.5/2, black	
135	663–668	5.1 ft (102%)	Firm, burrowed, clayey, medium, glauconite sand with weathered shells.	5Y 2.5/2, black	
136	668–678	10.2 ft (102%)	Firm, burrowed, clayey, medium, glauconite sand with weathered shells and lignite.	5Y 2.5/2, black	
137	678–686.5	8.6 ft (101%)	Firm, burrowed, clayey, medium, glauconite sand with weathered shells and lignite.	5Y 2.5/2, black	
138	686.5–694.1	7.7 ft (101%)	Firm, burrowed, clayey, medium, glauconite sand with weathered shells and lignite.	5Y 2.5/2, black	
139	694.1–698	3.9 ft (100%)	Firm, burrowed, clayey, medium, glauconite sand with corals; firm brownish clay at base.	5Y 2.5/2, black	
140	698–708	10.5 ft (105%)	From 698 to 701.3 ft: firm, burrowed, glauconitic, brownish clay.	5Y 4/1, dark gray	
			-------------Lithologic contact 701.3 ft (below is the upper Eocene)-------------		
			From 701.3 to 708 ft: burrowed, firm, clayey, medium, glauconite sand, with clay lamination and weathered shells.	5Y 3/1–2.5/2, very dark gray to black	Unnamed; upper Eocene
141	708–712.8	4.75 ft (99%)	Firm, gray clay with fine glauconite sand and weathered shell.	5Y 3/1, very dark gray	
142	712.8–719	6.2 ft (100%)	From 712.8 to 717.3 ft: uniform firm clay with weathered shells; from 717.3 to 719 ft: medium-coarse, sandy clay with large shells.	5Y 3/1, very dark gray; 5Y 3/1–5Y 3/2, very dark gray to dark olive gray	
143	719–724.5	5.5 ft (100%)	Medium-coarse sand and sandy clay with shell fragments.	5Y 4/1–5Y 3/1, dark gray	
144	724.5–729	5.0 ft (111%)	Medium-coarse glauconitic clay with shell fragments.	5Y 4/1, dark gray	
145	729–739	10.3 ft (103%)	Medium–coarse glauconite sand and sandy clay with shell fragments.	5Y 3/1, very dark gray	
146	739–749	10.1 ft (101%)	Medium-coarse sandy glauconite sand with weathered shell fragments.	5Y 3/2, dark olive gray	
147	749–754	5.6 ft (112%)	Medium to coarse glauconite sand with clay and quartz matrix, burrowed and mottled.	5Y 3/2, dark olive gray	
148	754–759	4.9 ft (98%)	Medium-coarse quartz glauconite sand becoming pebbly below 758.4 ft.	5Y 3/2, dark olive gray	
149	759–764	5.0 ft (100%)	Bioturbated medium to coarse glauconite sand with abundant clay matrix.	5Y 3/1–5Y 4/1 dark gray to very dark gray	
150	764–769	5.0 ft (100%)	Bioturbated medium to coarse glauconite sand with abundant clay matrix.	5Y 3/1–5Y 4/1 dark gray to very dark gray	
151	769–779	10.7 ft (107%)	Medium to coarse, quartzose, bioturbated, glauconite sand with clay chunks; abundant megafossils at bottom; clay content increases with depth to a glauconitic mud; at 778.6 ft, there is a contact with a sandy clay below.	5Y 3/2, dark olive gray	
			-------------Lithologic contact 778.6 ft (below is the upper Shark River Formation)-------------		
152	779–784	5.3 ft (106%)	Interbedded, shelly, glauconitic, sandy clay and fine sand.	5Y 3/2, dark olive gray	Upper Shark River Formation
153	784–789	5.35 ft (107%)	Interbedded, glauconitic, sandy clay and fine sand with shell fragments.	5Y 3/2, dark olive gray	
154	789–794	8.3 ft (166%)	Double-cored interval; glauconitic fine sand with clay interbeds; shell fragments common.	5Y 3/2, dark olive gray	
155	794–799	6.2 ft (124%)	Burrowed, firm, clayey, glauconite sand with shells and corals.	5Y 3/2, dark olive gray	
156	799–804	5.5 ft (57%)	From 799 to 799.65 ft: clayey, fine-medium, glauconite sand.	5Y 3/2, dark olive gray	
			-------------Lithologic contact 799.65 ft (below is the lower Shark River Formation)-------------		
			From 799.65 to 804.35 ft: glauconite sandy clay; with abundant visible foraminifers (*Lenticulina*).	5Y 6/2–5Y 6/1, light olive gray	Lower Shark River Formation
157	804–809	5.2 ft (104%)	Fossiliferous medium clayey sand and sandy clay; benthic foraminifers visible.	5Y 6/2–5Y 6/1, gray to light olive gray	
158	809–810.5	1.5 ft (100%)	Firm, finely laminated, fossiliferous sandy clay; foraminifers visible.	5Y 6/2–5Y 6/1, light olive gray	
159	810.5–819	9.7 ft (112%)	Alternating firm, finely laminated, fossiliferous sandy clay and clayey sand; foraminifers visible.	5Y 6/2–5Y 6/1, light olive gray	
160	819–829	8.7 ft (87%)	Firm, finely laminated, fossiliferous sandy clay; foraminifers visible.	5Y 6/2–5Y 6/1, light olive gray	
161	829–834	5.4 ft (108%)	Firm, glauconitic, sandy clay with subtle laminations.	5GY 6/1, greenish gray	
162	834–839	6.0 ft (120%)	Firm, glauconitic, sandy clay with subtle laminations.	5GY 6/1, greenish gray	
163	839–849	10.3 ft (102.5%)	Firm, glauconitic, sandy clay with subtle laminations.	5GY 6/1, greenish gray	
164	849–859	10.0 ft (100%)	Firm, glauconitic, sandy clay with subtle laminations, and fine-medium clayey glauconite sand; becomes almost pure glauconite at 855.7 ft with fine quartz sand below.	5GY 6/1, greenish gray	
165	859–869	9.0 ft (90%)	Clayey fine sand and firm greenish sandy clay; no glauconite from 861.8 to 867.3 ft; sharp change at 861.8 ft.	5GY 5/1–5Y 6/1, greenish gray to gray	

Table 1. (continued)

Core	Interval (ft)	Recovery (%)	Description	Color	Formation
			-------------Lithologic contact 861.8 ft (below is the Manasquan Formation)-------------		
166	869–879	9.6 ft (96%)	Firm clay and very fine sandy clay, with shell fragments.	5GY 6/1, greenish gray	Manasquan Formation
167	879–889	10.2 ft (101.5%)	Firm, uniform, very fine, sandy clay; shell fragments throughout.	5GY 6/1, greenish gray	
168	889–894	5.8 ft (116%)	Firm, greenish, laminated, clayey sand and sandy clay with abundant foraminifers; glauconite in lower part.	5GY 6/1, greenish gray	
169	894–895	1.0 ft (100%)	Well-consolidated, greenish siltstone, with abundant microfossils.	5GY 6/1, greenish gray	
170	895–899	4.3 ft (107.5%)	Well-consolidated, greenish siltstone, with abundant microfossils.	5GY 6/1, greenish gray	
171	899–904	4.5 ft (90%)	Firm, laminated, greenish clay, abundant microfossils, and consolidated clayey silts.	5GY 6/1, greenish gray	
172	904–909	5.8 ft (116%)	Alternating layers of clayey silt and sandy clay; visible foraminifers.	5GY 6/1, greenish gray	
173	909–919	10.0 ft (100%)	Bioturbated, firm, clayey sand with visible foraminifers; porcellanite at 914–915 ft.	5GY 4/1, dark greenish gray	Manasquan Formation
174	919–924	5.1 ft (102%)	Bioturbated, firm, sandy clay with porcellanite bed.	5GY 4/1, dark greenish gray	
175	924–929	4.6 ft (92%)	Bioturbated, firm, sandy clay with foraminifers visible.	5GY 4/1, dark greenish gray	
176	929–939	7.8 ft (78%)	Indurated, porcellanite clay, with foraminifers.	5GY 4/1, dark greenish gray	
177	939–944	5.6 ft (112%)	Indurated, greenish clay.	5GY 4/1, dark greenish gray	
178	944–949	5.2 ft (104%)	Porcellanite and indurated clay with visible foraminifers.	5GY 4/1, dark greenish gray	
179	949–959	9.0 ft (90%)	Porcellanite and indurated clay with visible foraminifers.	5GY 4/1, dark greenish gray	
180	959–964	5.0 ft (100%)	Bioturbated, semi-indurated, porcellanitic, and laminated sandy clay with abundant foraminifers.	5GY 5/1, greenish gray	
181	964–968	5.0 ft (125%)	Bioturbated, semi-indurated, porcellanitic, and laminated sandy clay with abundant foraminifers.	5GY 5/1, greenish gray	
182	968–978	9.1 ft (91%)	Bioturbated, semi-indurated, porcellanitic, and laminated sandy clay with abundant foraminifers.	5GY 5/1, greenish gray	
183	978–988	10.3 ft (102.5%)	Bioturbated, porcellanitic, and laminated sandy clay with abundant foraminifers; not as indurated.	5GY 5/1, greenish gray	
184	988–998	10.2 ft (102%)	Bioturbated, semi-indurated, porcellanitic, and laminated sandy clay with abundant foraminifers.	5GY 5/1, greenish gray	
185	998–1005	6.8 ft (97%)	Sandy-silty clay, bioturbated and slightly laminated.	5GY 4/1, dark greenish gray	
186	1005–1008	3.4 ft (113%)	Firm, laminated, sandy clay with microfossils.	5GY 4/1, dark greenish gray	
187	1008–1015	6.6 ft (94.3%)	Firm, laminated, sandy clay with microfossils.	5GY 4/1, dark greenish gray	
188	1015–1022	6.6 ft (94.3%)	Firm, laminated, sandy clay with microfossils.	5GY 4/1, dark greenish gray	
189	1022–1027	5.0 ft (100%)	Firm, laminated, sandy clay with microfossils.	5GY 4/1, dark greenish gray	
190	1027–1035	8.0 ft (100%)	Firm, laminated, sandy clay with microfossils.	5GY 4/1, dark greenish gray	
191	1035–1038	2.8 ft (93.3%)	Firm, laminated, sandy clay with microfossils.	5GY 4/1, dark greenish gray	
192	1038–1048	6.0 ft (60%)	Firm, laminated, sandy clay with microfossils.	5GY 4/1, dark greenish gray	
193	1048–1054	2.2 ft (36.6%)	Firm, laminated, sandy clay with microfossils.	5GY 4/1, dark greenish gray	
194	1054–1057	2.0 ft (66.7%)	Firm, laminated, sandy clay with microfossils.	5GY 4/1, dark greenish gray	
195	1057–1058	0.8 ft (80%)	Firm, laminated clay with microfossils and shell fragments and glauconite sand.	5GY 4/1, dark greenish gray	
196	1058–1063	5.2 ft (104%)	Firm, laminated, silty clay with glauconite sand and microfossils.	5GY 4/1, dark greenish gray	
197	1063–1068	5.1 ft (102%)	Firm, laminated, silty clay with minor amount of glauconite sand with microfossils.	5GY 4/1, dark greenish gray	Manasquan Formation (upper Paleocene)
198	1068–1078	10.5 ft (105%)	Bioturbated, firm, laminated silty clay with minor glauconite sand, with microfossils; glauconite sand in basal 3 ft.	5GY 4/1, dark greenish gray	
			-------------Lithologic contact 1075.7 ft (below is the Vincentown Equivalent)-------------		
199	1078–1087.5	10.4 ft (109.5%)	Firm, laminated clay with minor silt and sand.	5GY 4/1, dark greenish gray	Vincentown Equivalent
200	1087.5–1097	10.4 ft (107.8%)	Cyclic, bioturbated, firm, laminated silty clay with minor glauconite sand.	5GY 4/1, dark greenish gray	
201	1097–1103	5.0 ft (83.3%)	Uniform clay with silty clay interbeds.	5Y 3/1, very dark gray	
202	1103–1108	5.2 ft (104%)	Burrowed uniform clay with silty clay interbeds.	5Y 3/1, very dark gray	
203	1108–1117.5	10.2 ft (107%)	Firm clay with silty cross-bedded clay laminations, with shells and burrowing.	5Y 3/1, very dark gray	
204	1117.5–1127.5	10.3 ft (103%)	Firm silty clay with laminated, bioturbated glauconitic clay.	5Y 3/1, very dark gray	
205	1127.5–1137	5.0 ft (50%)	Firm, fine sandy clay with shell hash and bioturbation and lamination at the basal 3 ft.	5Y 4/1–5GY 4/1, dark to dark greenish gray	
206	1137–1138	0.55 ft (55%)	Firm, silty clay with shell hash.	5Y 3/1, dark gray	
207	1138–1148	5.5 ft (55%)	Bioturbated, sandy clay and clayey fine sand.	5Y 4/1–5GY 4/1.	
208	1148–1153	4.8 ft (96%)	Dark sandy clay in upper 1.2 ft, fine-medium sand below.	5Y 3/1, dark gray, dark to dark greenish gray	
209	1153–1158	5.3 ft (106%)	Fine, clayey, glauconitic quartzose sand, bioturbated.	5Y 3/1, very dark gray	
210	1158–1164.5	6.6 ft (101.5%)	Upper 6.45 ft: fine-medium, clayey, glauconite sand, bioturbated; basal 0.15 ft: lignite layer with shells.	5GY 4/1, dark greenish gray	
211	1164.5–1168	3.8 ft (95%)	From 1164.0 to 1167.1 ft: laminated, medium-fine, clayey sand.	5Y 3/2, dark olive gray	
			-------------Lithologic contact 1167.1 ft (below is the Hornerstown Equivalent)-------------		
			From 1167.1 to 1167.8 ft: laminated to slightly bioturbated, clayey silt-silt interbeds	5Y 3/2, dark olive gray	Hornerstown Equivalent
212	1168–1173	5.4 ft (108%)	Laminated to slightly bioturbated, clayey silt-silt interbeds.	5Y 3/2, dark olive gray	
213	1173–1178	5.0 ft (100%)	Laminated to slightly bioturbated, clayey silt-silt interbeds.	5Y 3/2, dark olive gray	
214	1178–1188	6.25 ft (62.5%)	Intercalated porcellanite(?) and dark clay, silty clay.	5Y 3/1– 5Y 3/2, very dark gray to dark olive gray	
			-------------Lithologic contact 1188 ft (below is the Navesink/Red Bank Formations)-------------		
215	1188–1193	2.1 ft (42%)	Silty clay, sandy clay with lignite and glauconite sand, bioturbated.	5Y 4/1–5Y 3/1, dark gray	Navesink/Red Bank Formation
216	1193–1198	4.75 ft (95%)	Firm, glauconite sandy clay, bioturbated and with pyrite.	5Y 4/1–5Y 3/1–5Y 6/3, dark gray to pale olive	
217	1198–1208	3.6 ft (36%)	Glauconitic sandy clay.	5Y 4/1–3/1, dark gray to very dark gray	
218	1208–1218	0.0 ft (0%)	No recovery.		
219	1218–1223	3.0 ft (60%)	Glauconitic sandy clay to coarse–very coarse glauconite sand, bioturbated.	5Y 7/1, light gray	

Note: Total depth = 1223 ft, mean recovery = 87%, median recovery = 98%.

Smooth coring resumed on 27 April with 40 ft drilled from 1063 to 1103 ft (103% recovery). On 28 April, 45 ft was drilled with only 70% recovery due to loss of a part of a core.

On 29 April, we penetrated the top of a lignite bed at 1164.5 ft uncorrected; the actual depth of this lignite was measured at 1164 ft and the depths must be adjusted for clay expansion. Core recovery was excellent on 29 April with 103% recovered from 1148 to 1178 ft.

On 30 April, 4.75 ft of section broke off from a 10-ft core run between 1178 and 1188 ft. Only 2 ft were recovered on the next core run of 5 ft (1188–1193 ft); it appeared that the upper 1.5 ft of the section was from the interval at 1178–1188 ft. The next 5-ft core run (1193–1198 ft) recovered 6.25 ft, 1.5 ft of which was from the previous run. A core run from 1198 to 1208 ft recovered no section. Drilling was rapid and we suspected penetration of unconsolidated sands. Therefore, we switched from the rock shoe to the long shoe out of core; we still failed to recover any section in the next run (1208–1218 ft). In pumping the hole, little sand was recovered. Therefore, we anticipated that some of the core may have become lodged in the core barrel.

On 1 May, the run from 1218 to 1223 ft easily penetrated the first 5 ft, then became blocked. We recovered 3.6 ft of core and later determined that some of this came from the interval above. Mud pressure shot to over 1000 psi but the barrel would not clear. We pulled the rods on 1 May. On 2 May, we determined that there was core in the outer core barrel. Extrusion compressed the section to 3.3 ft with a diameter of 2–2.5 in.; original length must have been at least 4 ft. Therefore, the 3.6 ft recovered on 1 May must have come from 1219 ft and above. It is possible that this 3.6-ft came from the top of the cored interval (1198–1201.6 ft). This interval is similar in lithology to the core recovered from 1193 to 1198 ft and differs from the section recovered from 1218 to 1223 ft. We subsequently determined that unconsolidated sands were adhering to the core barrel and saved two jars of this slightly glauconitic quartz sand for the inferred interval from 1201 to 1218 ft.

On 2 May, we reinstalled the rods to 620 ft. On 3 May, crimped rods prevented removal of the inner barrel. We kept cutting the wireline and pulling the rods, but we could not flush the hole with pump pressures as high as 1000 psi. We pulled the remaining rods and found 43 ft of sand in the core barrel and lower rods. We cleaned the rods and barrel and began to run rods, inspecting the quad latch and overshot to ensure smooth operation. At the end of the day, we had 500 ft of rods in the ground. We continued to add rods on 4 May, but had problems with sandy clay in the inner barrel. In addition, we had to recut the hole from ~660 to 750 ft. This zone of swelling would have formed a bridge that would have prevented penetration of the logging tools.

On 5 May, we flushed the hole every 20 ft down to 1000 ft, circulating 300 gal of mud to clear out caving glauconitic sands. On 6 May, we had a problem with sands clogging the inner barrel; we pulled 640 ft of rods out. On 7 May, we pulled the remaining 400 ft of rods, put on a 3.25 in. drag bit, and added rods to 400 ft. We dropped rods from 400 to 1040 ft by pumping every 100 ft. At 1040 ft, we began to ream the hole to 1100 ft. On 8 May, we added 10 ft of rods and lost circulation. Then, extreme head pressure caused a 20-ft rod to blow off while being unscrewed. We pulled the rods back to 980 ft and flushed again, continuing to circulate with lighter bentonite mud for an hour. Reaming continued to 1223 ft. At 1218 ft, we lost all circulation for 5 min (?air pocket); circulation inexplicably returned within 5 min. We mixed a biodegradable red dye and pumped for 1.5 hr, but never saw the dye. Because of these problems and the fact that we had reached our target depth, we decided to log the hole.

On 8 May, Dennis Talbott from BPB Instruments obtained a gamma log through the rods to 1219.5 ft. On 9 May, we pulled 1223 ft of rods between 7 and 11 AM. The hole stayed open to the bottom. Dennis Talbott obtained the following logs down to 1221 ft: 1) focused electric (resistivity); 2) multichannel sonic; 3) dual-spaced neutron; 4) gamma density caliper; 5) dipmeter; and 6) temperature. Logging runs went smoothly. Only the temperature log failed to reach total depth (1120 ft was attained). The density log may have been affected by mud caking the hole. All logs except for resistivity were run from land surface; resistivity was run from below 4 in. casing (450 ft). The sonic log showed significant changes in the upper 450 ft, although the effects of casing on sonic calibration are not known. The caliper log showed that the hole expanded by 4 in. in each direction between 780 and 795 ft, the interval that was double cored. Vertical analysis of the borehole shows a sharp westward deviation at 750–800 ft, consistent with caliper logs and our suggestion that double coring occurred at 789–794 ft. Deviation of the hole from vertical was less than 5 ft at total depth. The gamma-ray log shows ~10 ft of vertical offset at total depth compared to the log from the nearby Island Beach water well; the second of two sharp gamma-ray kicks occurs at 1210 ft at this hole versus 1200 ft at the water well. The upper kick is associated with an interval of no recovery spanning the Cretaceous/Tertiary boundary (1183.5–1188 ft). The lower is probably the top of the Navesink Formation. In addition, "hot" gamma-ray kicks are associated with the following formational boundaries: top of the Shark River Formation (778.6 ft); top of the lower Shark River Formation (798 ft); top of the Manasquan Formation (862 ft); top of the Vincentown Formation (1075 ft); and top of the Hornerstown Formation (1164 ft).

On 10 May, we began to pull the 4 in. PVC casing, but it separated ~30 ft down. Further attempts to remove the casing were unsuccessful, and the BPB logger was released. Grouting began on 11 May and the hole was sealed on May 12. All 6-in. casing was removed; ~400 ft of 4-ft casing was grouted inside and out. The hole was dry-capped and covered with macadam.

We recovered 1060 ft from a total hole of 1223 ft (mean recovery = 86.7%; median recovery = 98%; Table 1 and Fig. 2). Cores were photographed on site in color using Tungsten lighting and 160T film. Lithologies were described on site and subsequently at the Rutgers core facility; these descriptions form the basis of the preliminary lithologic descriptions. Samples were obtained at ~2- to 5-ft intervals for planktonic foraminifer, nannofossil, and diatom biostratigraphy. Cores were cut into 2-ft sections, labeled at the top and bottom of each section, placed into split PVC pipe (3-in. diameter to 453 ft; 2-in. diameter below), and stored in 2 ft wax boxes. One hundred and seventy-three core boxes were moved to interim storage at the Rutgers core library for: 1) further lithologic description; and 2) sampling for paleomagnetic and other studies. The cores will ultimately be stored and archived as ODP cores at the East Coast Repository.

LITHOSTRATIGRAPHY

Summary

The on-site scientific team provided preliminary descriptions of sedimentary textures, structures, colors, fossil content, identification of lithostratigraphic units (NJGS Information Circular 1, 1990), and surfaces (Table 1). Subsequent studies integrated preliminary descriptions with additional descriptions, biostratigraphy, biofacies studies, isotopic stratigraphy, and geophysical well logs. For the nonmarine and nearshore sections (primarily the Miocene and younger section), lithofacies and log interpretations provide the primary means of recognizing unconformities and interpreting paleoenvironments. For the marine sections (primarily the Paleogene), biostratigraphic and biofacies studies provide an additional means of recognizing unconformities and the primary means of interpreting paleoenvironments. Benthic foraminiferal biofacies were used to recognize inner (0–30 m), middle (30–100 m), outer (100–200 m) neritic and upper bathyal (200–600 m) paleodepths. Unconformities were identified on the basis of physical stratigraphy, including irregular contacts, reworking, bioturbation, major facies changes, gamma-ray peaks, and paraconformities inferred from biostratigraphic breaks. Recognition of these surfaces allow identification of sequences at the Island Beach borehole (Figs. 3–9).

Table 2. Occurrences of planktonic foraminifers in the Island Beach borehole.

lower Oligocene

Zones P19–P21: *Chiloguembelina cubensis, Ch. victoriana, Globigerina ampliapertura, G. praebulloides, "G." corpulenta, "G." tripartita, Guembelitria* sp., and *Paragloborotalia opima nana.*

Zone P19: *Chiloguembelina cubensis, Ch. victoriana, "Globigerina" corpulenta, "G."? medizzai, Praetenuitella impariapertura, P. patefacta, P. praegemma.*

Zone P18: *Chiloguembelina cubensis, Globigerina increbescens, G. praebulloides, Globorotalia opima nana, Praetenuitella impariapertura, P. patefacta, P. praegemma, Pseudohastigerina micra, P. sharkriverensis, ?Globigerina corpulenta, ?G. medizzai.*

upper Eocene

Zones P15–P17: *Chiloguembelina cubensis, Ch. victoriana, "Globigerina" corpulenta, "G." praeturritilina, "G."? medizzai, Globigerinatheka index, Praetenuitella praegemma, Pseudohastigerina micra, P. naguewichensis, P. sharkriverensis, Subbotina cryptomphala, S. linaperta, S. yeguaensis, Turborotalia cerroazulensis cerroazulensis, T. cerroazulensis pomeroli, T. cerroazulensis possagnoensis.*

middle Eocene

Zones P12–P14: *Acarinina acarinata, A. bullbrooki, A. spinuloinflata, Chiloguembelina cubensis, Ch. victoriana, Globigerinatheka senni, G. index, G. subconglobata subconglobata, Guembelitria* sp., *Hantkenina alabamensis, Morozovella lehneri, M. spinulosa, Pseudohastigerina micra, P. sharkriverensis, Subbotina cryptomphala, S. eocaena, S. frontosa, S. inaequispira, Truncorotaloides pseudodubia, T. rohri, Turborotalia cerroazulensis pomeroli,* and *Turborotalia cerroazulensis possagnoensis.*

Zone P11: *Acarinina bullbrooki, A. pentacamerata, A. spinuloinflata, Chiloguembelina cubensis, Ch. victoriana, Globanomalina chapmani, G. renzi, Globigerapsis kugleri, Globigerinatheka mexicana, Guembelitra* sp., *Morozovella aragonensis, M. lehneri, M. spinulosa, Pseudohastigerina micra, P. sharkriverensis, Subbotina eocaena, S. linaperta, S. frontosa,* and *Truncorotaloides pseudodubia.*

middle/lower Eocene

Zones P9–P10: *Acarinina bullbrooki, A. primitiva, A. soldadoensis angulosa, A. soldadoensis soldadoensis, Chiloguembelina* spp., *Globanomalina chapmani, G. renzi, Globigerinatheka subconglobata micra, Guembelitria* sp., *M. aragonensis, Parasubbotina varianta, Pseudohastigerina micra, P. sharkriverensis, Subbotina eocaena, S. frontosa, S. linaperta, Truncorotaloides haynesi,* and *T. pseudodubia.*

lower Eocene

Zone P8: *Acarinina pentacamerata, A. primitiva, A. soldadoensis angulosa, A. soldadoensis soldadoensis, A. wilcoxensis, Chiloguembelina* spp., *Guembelitria* sp., *Morozovella aragonensis, M. caucasica, M. lensiformis, Parasubbotina varianta, Pseudohastigerina micra, P. sharkriverensis, Subbotina eocaena, S. linaperta, "S."? lozanoi,* and *Truncorotaloides haynesi.*

Zone P7: *Acarinina broedermanni, A. mckannai, A. pentacamerata, A. primitiva, A. pseudotopilensis, A. quetra, A. soldadoensis angulosa, A. soldadoensis soldadoensis, A. wilcoxensis, Chiloguembelina crinita, Ch. midwayensis, Eoglobigerina spiralis, Globanomalina chapmani, G. pseudoscitula, G. renzi, Morozovella aequa, M. aragonensis, M. edgari, M. formosa formosa, M. formosa gracilis, M. marginodentata, M. subbotinae, Parasubbotina varianta, Pseudohastigerina wilcoxensis, P.? pseudoimitata, Subbotina hornibrooki, S. linaperta, S. velascoensis,* and *S.* cf. *triloculinoides.*

Zone P6c: *Morozovella acuta, M. aequa, M. edgari, M. subbotinae, M. marginodentata, M. occlusa, M. formosa gracilis, M. formosa formosa, Acarinina aquiensis, A. wilcoxensis, A. nitida, A. soldadoensis soldadoensis, A. soldadoensis angulosa, A. broedermani, A. mckannai, A. primitiva, A. quetra, A. pseudotopilensis, Chiloguembelina midwayensis, Ch. crinita, Globanomalina chapmani, G. pseudoscitula, G. renzi, P.? pseudoimitata, Pseudohastigerina wilcoxensis, Subbotina linaperta, S. velascoensis, S. hornibrooki, S.* cf. *triloculinoides, Eoglobigerina spiralis,* and *E.* cf. *eobulloides.*

upper Paleocene

Zone P6a: *Morozovella velascoensis, M. acuta, M. aequa, M. edgari, M. subbotinae, M. marginodentata, M. occlusa, Acarinina wilcoxensis, A. soldadoensis soldadoensis, A. mckannai, A. primitiva, A. quetra, Chiloguembelina crinita, Globanomalina chapmani, Parasubbotina varianta, Pseudohastigerina* sp., *Subbotina linaperta, S. hornibrooki, S.* cf. *triloculinoides,* and *Eoglobigerina* cf. *eobulloides.*

Zone P4: *Globanomalina pseudomenardii, G. pseudoimitata, G. chapmani, Chiloguembelina midwayensis, Subbotina triloculinoides, S. triangularis, Parasubbotina pseudobulloides, Eoglobigerina spiralis, Morozovella occlusa, M. angulata, M. aequa, M.? convexa, Acarinina mckannai,* and *A. aquiensis.*

Zone P3: *Globanomalina compressa, G. chapmani, Morozovella angulata, M. conicotruncata, Praemurica uncinata, Parasubbotina pseudobulloides, Subbotina triloculinoides, Igorina albeari* (senior synonym of *I. leavigata*), and *I. pusilla.*

lower Paleocene

Zone P2: *Praemurica uncinata, Subbotina triloculinoides, Parasubbotina pseudobulloides, P. varianta, Globanomalina compressa, Woodringina hornerstownensis, Guembelitria cretacea,* and *Eoglobigerina eobulloides.*

Zone P1: *Parasubbotina pseudobulloides, Globoconusa daubjergensis, Eoglobigerina eobulloides, Chiloguembelina midwayensis, Guembelitria cretacea, Subbotina triloculinoides, Globanomalina planocompressa, G. compressa,* and *Woodringina hornerstownensis.*

Uppermost Cretaceous

Globotruncana arca, G. aegyptica, Rugoglobigerina hexacamerata, R. subcircumnodifer, R. rugosa, R. subpennyi, R. macrocephala, Archeglobigerina blowi, Globigerinelloides subcarinata, G. prairiehillensis, Globotruncanella citae, G. havanensis, G. petaloidae, Hedbergella monmouthensis, H. holmdelensis, Heterohelix globulosa, H. striata, H. navaroensis, H. reussi, Pseudotextularia elegans, Pseudoguembelina palpebra, P. costulata, and *Guembelitria cretacea.*

Cape May Formation

Age: uppermost Pleistocene–Holocene
Thickness: 71 ft

The surficial units (7–78 ft) consist of unconsolidated sands, silts, clays, and gravels containing lignite and shell layers (Figs. 3–4). These units correspond to the undifferentiated Cape May Formation. At the Island Beach Site, the Cape May Formation is inferred to be upper Pleistocene–Holocene.

The interval from 7 ft (shallowest sample) to 39.1 ft is primarily medium to coarse sand containing shells. It is interpreted to be a near-shore deposit; this is supported by the continuity of facies from the

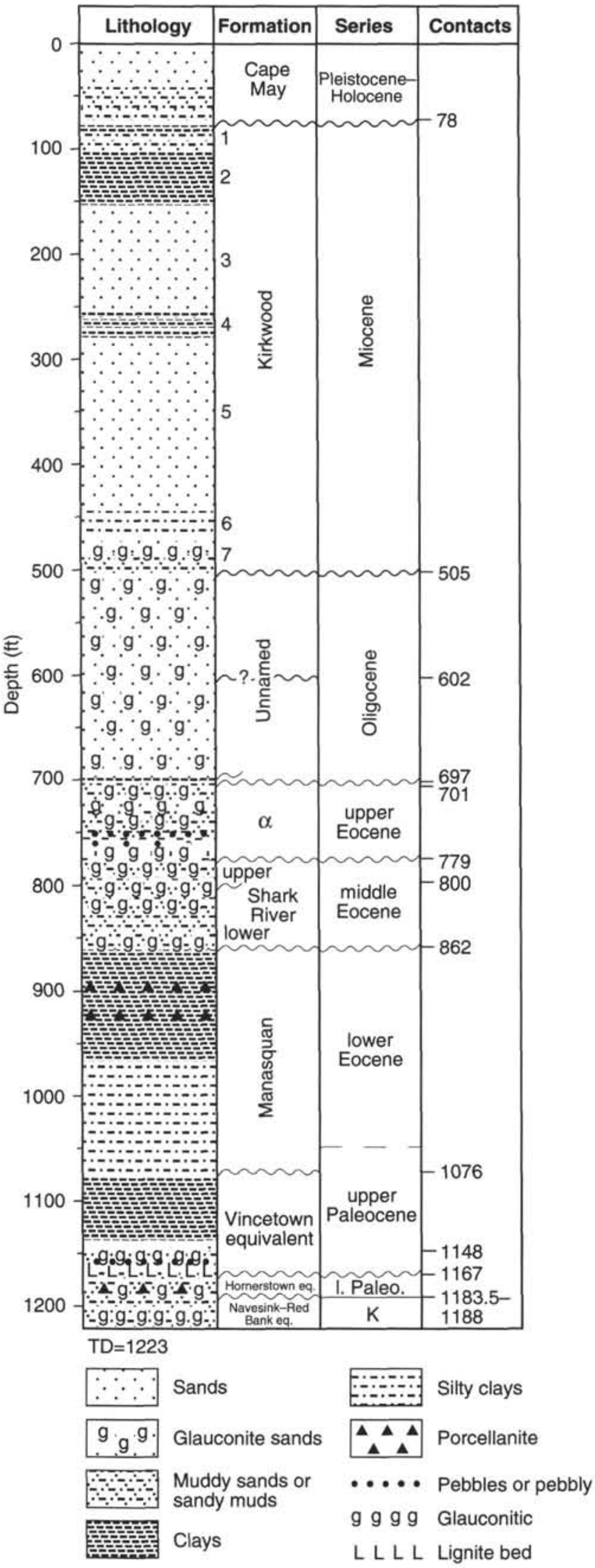

Figure 3. Lithologic summary, Island Beach borehole.

present-day barrier island to this level. There is a facies change in an interval of no recovery (39.1–43.0 ft) with sands lying above a fining-upward succession of pebbly coarse sands to sandy muds (43–51 ft). The NJGS gamma log places the contact at 40 ft (Fig. 4). We interpret this surface as a either a disconformity or transgressive surface. The section above this is Holocene as established by an accelerator mass spectrometer (AMS) radiocarbon age measurement of 4532 ± 58 yr on a lignite layer at 24.75 ft (measurement made by Geochron Laboratories); a Holocene age is supported by amino acid racemization age estimates from this level at a shallow borehole drilled by the NJ Geological Survey less than 1 mi north of the Island Beach drill site (J. Weymiller, pers. comm., 1993).

From 40 to 70 ft, there are two upward-fining successions from pebbly very coarse sand to sandy clays (40–51 and 51–70 ft), which are visible in the lithology on the gamma-ray log, with surfaces separating the successions at 51 and 70 ft (Fig. 4). The muddy sands and sandy clays are interpreted as lower estuarine, lagoonal, or innermost neritic; this is supported by an *Elphidium*-dominated biofacies in this section. A conventional radiocarbon age of 5,625 ± 200 yr was obtained from a lignite at 58.1 ft (measurement by Geochron Laboratories). This suggests that the facies are lagoonal or shelf deposits of the Holocene transgression and may be part of the sequence that include the present-day barrier; however, this date requires confirmation because it implies extremely high sedimentation rates (34 ft/k.y.; ~10 m/k.y.) between 24.75 and 58.1 ft.

A basal coarse gravel at 75.7 ft becomes finer upsection and is capped by a sulfide-rich clay at 70 ft. This succession is interpreted as a fluvial gravel/point bar/overbank deposit.

A distinct facies break from gravels above to stiff clays below occurs between 75.7 ft and 78 ft. The gravels represent the base of the Cape May Formation at the Island Beach Site that disconformably overlies the Miocene Kirkwood Formation. Although the actual contact occurs in a 2.3 ft interval of no recovery, the gamma log (Fig. 4) shows that the contact occurs at the base of the gravels recovered (75.7 ft). The Cohansey Formation is not represented here and was probably eroded by the channel penetrated at 75.7 ft.

Kirkwood Formation

Age: lower middle to lower Miocene
Thickness: 427 ft

The middle to lower Miocene Kirkwood Formation was first recovered at 78 ft (Fig. 4), where it consists of silty clay and sand units. It can be divided into several informal lithologic units consisting of predominantly sand (Units 1, 3, and 5) or clay-silt (Units 2, 4, and 6).

Unit 1

Interval: 78–103 ft

This unit immediately underlies the surficial Cape May Formation. The top of the unit is a homogeneous gray silty clay (78–88 ft). It grades downward into a very dark gray clay containing medium-coarse quartz sand and lignitic interbeds (88–103 ft). The sandy bed at the base is clear on the gamma log (Fig. 5). From 103 to 108 ft, the clays become prevalent and very stiff, grading down into Unit 2. The presence of diatoms indicate a marine (prodelta or inner neritic) environment (see "Biostratigraphy" section, this chapter). The sandy lower part of this unit may be equivalent to the Rio Grande aquifer unit and the overlying clay unit to the upper confining unit at Atlantic City (see "Lithostratigraphy" section in Chapter 2, this volume). This lithostratigraphic correlation indicates that the top of these sands (88 ft) at Island Beach may be a sequence boundary, because at the Atlantic City site, most of the upper confining unit is correlated with the youngest sequence (Kirkwood 3 = ECDZ 6) of Sugarman et al. (1993). The highest occurrence (HO) of *R. marylandicus* at 88 ft indicates correlation of this unit at Island Beach to younger than

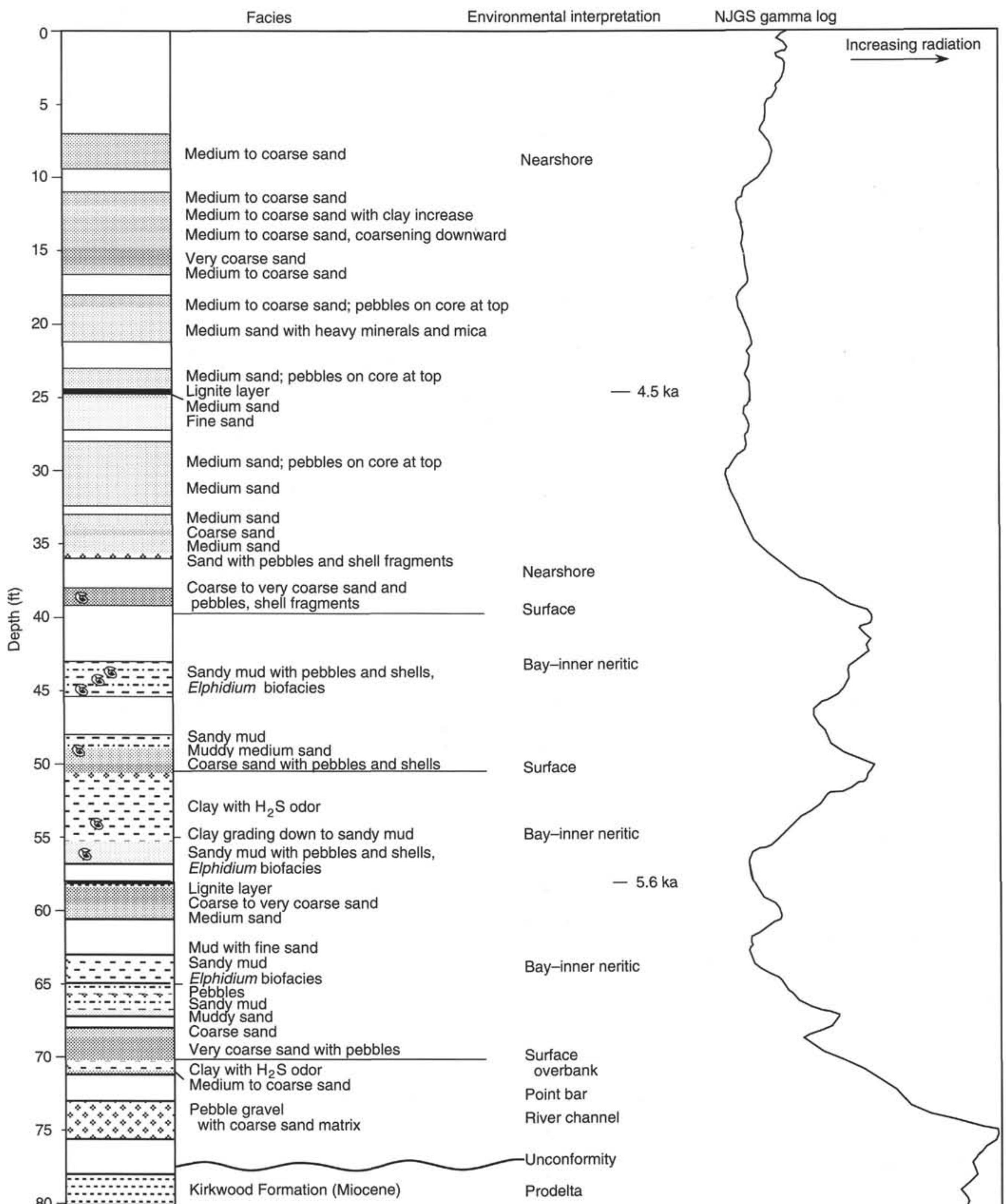

Figure 4. Cape May Formation lithostratigraphy, sequences, and New Jersey Geological Survey (NJGS) gamma log. Open interval are sections with no recovery. Ages are radiocarbon age measurements (see text).

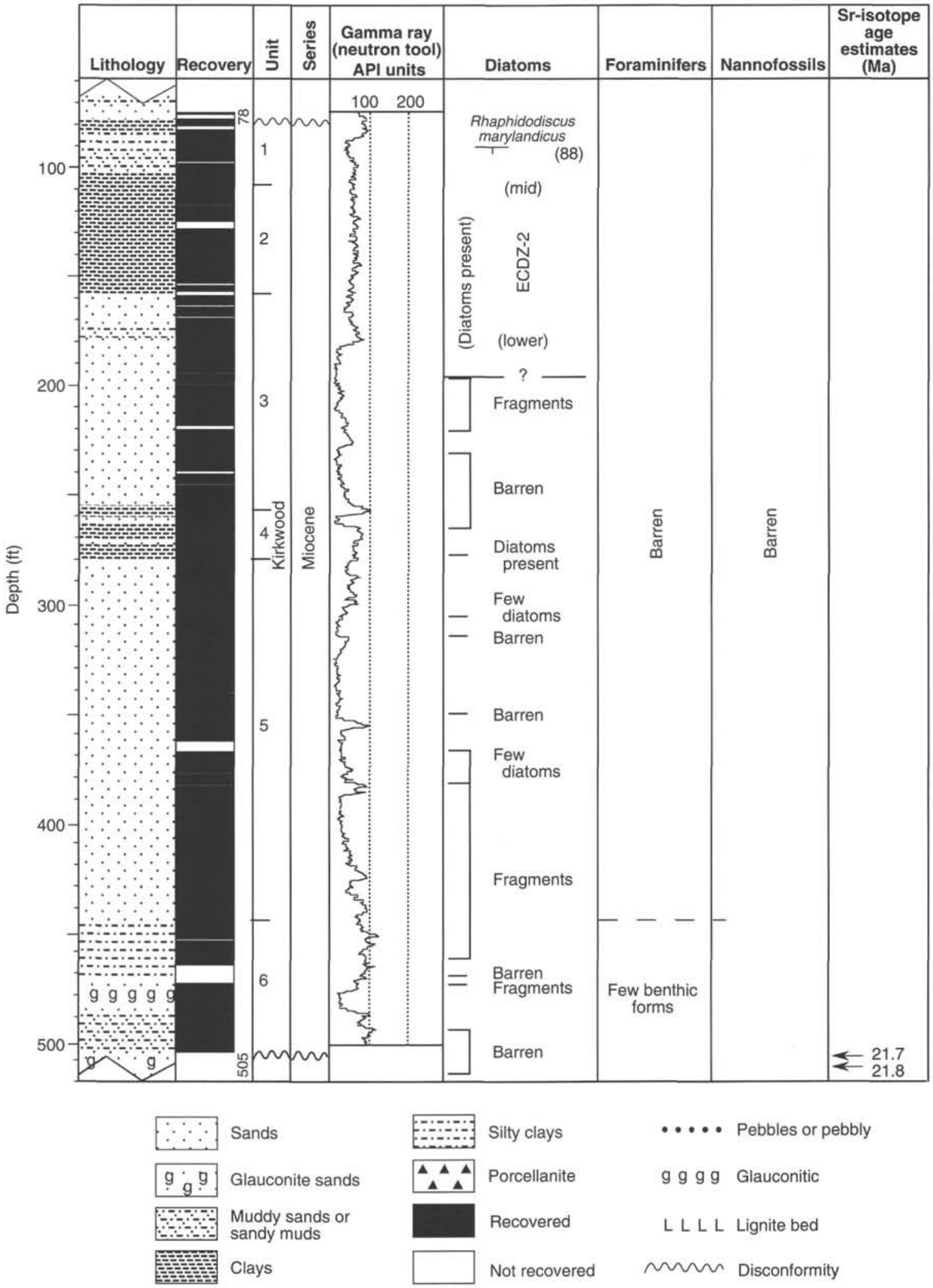

Figure 5. Kirkwood Formation lithostratigraphy, biostratigraphy, and recovery. Open intervals are sections with no recovery. Gamma log is the BPB log.

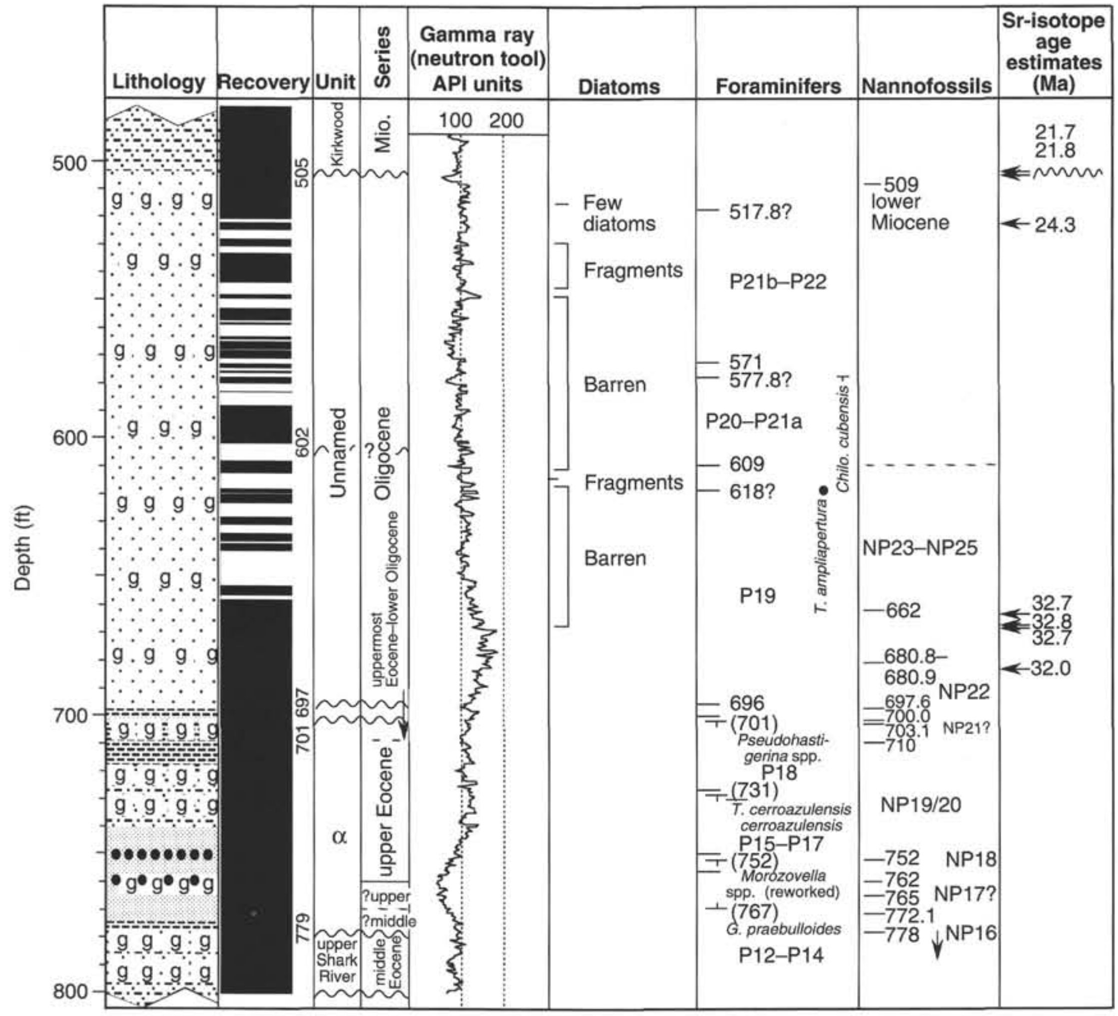

Figure 6. Upper Eocene–Oligocene lithostratigraphy, biostratigraphy, and recovery. Open intervals are sections with no recovery. Gamma log is the BPB log.

ECDZ 2, consistent with correlation to ECDZ 6. ECDZ 3–5 are generally not represented in the New Jersey coastal plain (Sugarman et al., 1993).

Unit 2

Interval: 108.0–155.9 ft

This section consists of stiff, uniform gray clay that is very dark grayish brown on fresh exposure ("chocolate clays"). The gamma log illustrates the uniform nature (Fig. 5). The interval from 158 to 163 ft may contain the contact with the sands of Unit 3; it was not recovered because the sands were washed out of the core barrel. The base of this unit could be placed by convention at 155.9 ft at the bottom of the clays recovered. Alternatively, gamma logs indicate that the base of this unit may be better placed at 181 ft (Fig. 5) at the base of a distinct clay layer. Diatoms indicate the that this unit is marine; we interpret these chocolate clays as prodelta or muddy inner neritic (e.g., Owens and Gohn, 1985); this is consistent with descriptions at the ACGS#4 borehole (Owens et al., 1988; Sugarman et al., 1993). This informal unit may be equivalent to the lower confining unit at Atlantic City (see "Lithostratigraphy" section in Chapter 2, this volume). It is assigned to lowermost middle to upper lower Miocene ECDZ 2 (see "Biostratigraphy" section, this chapter); thus, it corresponds to the Kirkwood 2 sequence of Sugarman et al. (1993). This sequence (= lower confining unit and Rio Grande aquifer; Fig. 9) is 17.0–17.9 Ma at Atlantic City (based on Sr-isotopic stratigraphy; see Fig. 2 in Chapter 2, this volume).

Unit 3

Interval: 158.0–256.5 ft

Unit 3 consists of sands with occasional thin clay layers (Figs. 5 and 9). From 158 to 173 ft, the section is predominantly medium to coarse sands, with silts and fine sands from 173.0 to 183.5 ft; the finer units give a distinct gamma-ray peak at 181 ft (Fig. 5) and as noted above, the top of Unit 3 could be placed here and not at 158 ft. Pebbly medium to very coarse sands occur from 183.5 to 233 ft, with muddy sand cross beds noted at 204.0–207.3 ft. The section from 227 to 233 ft contains at least two upward-fining successions from medium-coarse sands to clays (229.2–233 ft) and coarse to medium sands (227–228 ft). Two additional upward-fining successions occur between 233 and 248 ft (from coarse to medium sands) and between 248 and 256.5 ft (from medium sands to sandy clay). The upward-fining successions are interpreted as fluvial (point bar) based on the absence of shells, obvious burrows, and diatoms from the lower part of unit 3. The heterogeneous sands of the upper part of unit 3 also appear to be nonmarine, although the presence of marine diatom indicate that they are marine. This unit may be equivalent to the upper sand aquifer unit at Atlantic City, where it is ~20.3 Ma (see Fig. 2 and "Isotopic Stratigraphy" section in Chapter 2, this volume).

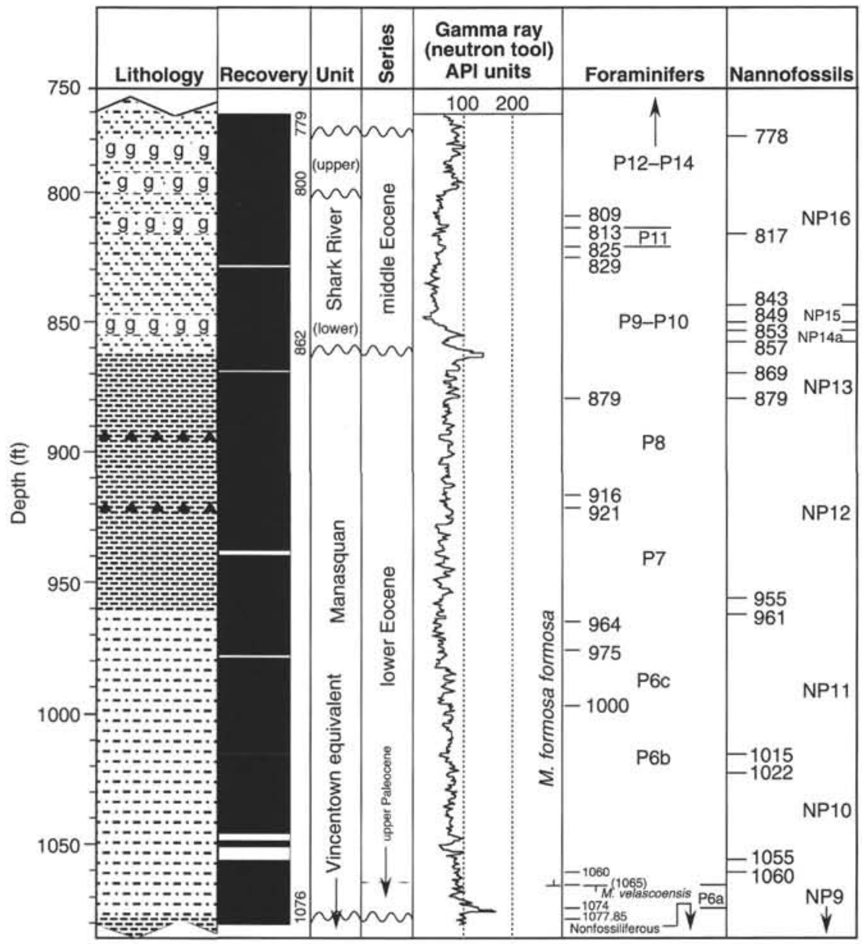

Figure 7. Shark River and Manasquan Formation lithostratigraphy, biostratigraphy, and recovery. Open intervals are sections with no recovery. Gamma log is the BPB log.

Unit 4

Interval: 256.5–278.5 ft

This section is again stiff, gray clay, although not as uniform as in Unit 2. There are pebbly sand interbeds up to 2 ft thick. This unit may be interpreted as prodelta or shallow shelf based on the presence of diatoms (Fig. 5). This unit may be equivalent to the confining unit at Atlantic City between the upper sand and lower sand (= "800-foot sand") aquifer units at Atlantic City (see "Lithostratigraphy" section in Chapter 2, this volume). The base of this unit may be a sequence boundary within the Kirkwood 1 (= ECDZ 1) sequence of Sugarman et al. (1993) at both boreholes, although further studies are needed to document this.

Unit 5

Interval: 278.5–443.0 ft

Unit 5 consists of sands with sporadic thin clay, silt, and lignitic interbeds. The sand is often micaceous and cross bedding was noted as were occasional pebbles. As in unit 1, the absence of shells makes the interpretation problematic, although the presence of lignitic interbeds is most consistent with a delta front environment. Scarce diatoms scattered in this unit indicate a marine component to the delta front. This unit may be equivalent to the lower sand (= "800-foot sand") aquifer unit at Atlantic City, where it lies between strata dated as 20.3 and 20.8 Ma (see Fig. 2 and "Isotopic Stratigraphy" section in Chapter 2, this volume).

Unit 6

Interval: 443.0–467.0 ft

Uniform silty clay to sandy silt returns in Unit 6. As in Unit 2, we interpret the paleoenvironment as prodelta or inner neritic silts and clays. From 467 to 477 ft, silty fine sand gives way to medium to coarse glauconitic quartz sand (477.0–483.7 ft) to sandy silty "chocolate" clay containing shells (483.7–505.5 ft). We follow Sugarman et al. (1993) in placing this glauconitic unit and the underlying "chocolate clay" in the Kirkwood Formation. This is clearly a marine shelf deposit; it is probably deeper than mean wave base (e.g., based on glauconite) and shallower than storm wave base (based on fragmented shells). This unit is lower Miocene based on Sr-isotopic evidence (~21.8 Ma; Fig. 6). This unit may be equivalent to the composite confining unit at Atlantic City (see "Lithostratigraphy" section in Chapter 2, this volume). This unit is equivalent to the lower part of the Kirkwood 1 sequence (= ECDZ 1) of Sugarman et al. (1993). At Atlantic City, three distinct shell beds lie in the lower part of this sequence; each may represent a thin sequence, as supported by distinct Sr-isotope ages (see Fig. 3 and "Isotopic Stratigraphy" section in Chapter 2, this volume). Sr-isotopic stratigraphy correlates the base of the Kirkwood Formation at Island Beach to the uppermost of these three shell beds.

Unnamed Quartz and Glauconite Sands

Age: Oligocene
Thickness: 196 ft

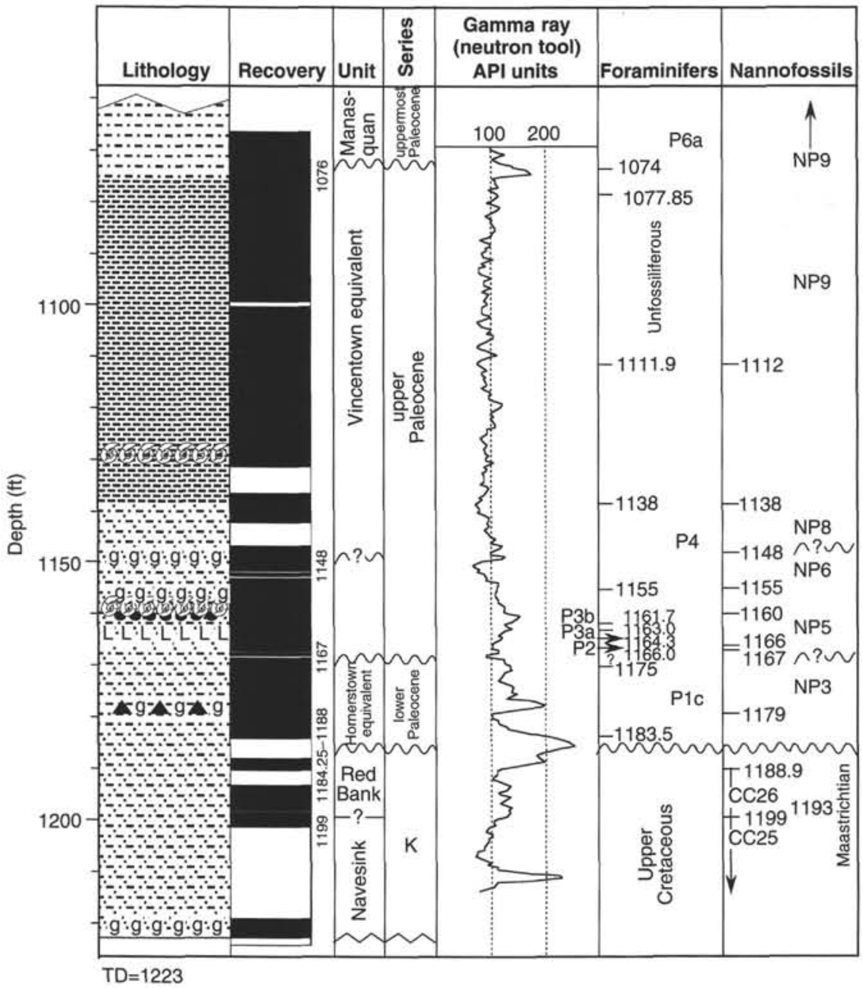

Figure 8. Vincentown, Hornerstown, and Navesink equivalents. Open intervals are sections with no recovery. Gamma log is the BPB log.

Medium to coarse glauconitic quartz sands are found again at 505.5 to 507.0 ft. This unit is separated from the Kirkwood Formation by an unconformity at 505.5 ft that is associated with a distinct gamma-log peak (Fig. 6). Sr-isotope stratigraphy indicates that the hiatus associated with this surface is from ~24.3 Ma to ~21.8 (Fig. 6). The sands grade down into slightly clayey medium glauconite sand with occasional glauconite sandy clay (563–601 ft). This unit probably corresponds to the upper "Piney Point" Formation of Olsson et al. (1980; although this name cannot be applied to the Oligocene of NJ), the ACGSβ unit of Owens et al. (1988), and the unnamed Oligocene sands of Miller et al. (1990); in Virginia, this unit is known as the Old Church Formation (Owens and Gohn, 1985). The glauconitic sands alternate between sticky and very indurated. A particularly indurated interval at 601–608 ft probably contains a disconformity in "middle" Oligocene Zones P20–P21a (Fig. 6).

Medium glauconite sand continues from 608 to 697 ft. This unit may correspond to the lower "Piney Point" Formation of Olsson et al. (1980); this lower Oligocene (~Zone P19; ~32–32.7 Ma based on Sr isotope stratigraphy; Fig. 6), medium glauconite sand was not represented at the ACGS#4 borehole (Miller et al., 1990).

A distinct contact with a firm brown clay occurs at 697 ft (Fig. 10A). This unit is lower Oligocene (697.6 ft is Zone NP22; see "Biostratigraphy" section, this chapter).

Unnamed Clays and Sands

Age: upper Eocene
Thickness: 78 ft

Another sharp contact occurs at 701.3 ft (Fig. 10B), with the brown clays overlying clayey glauconite sand to glauconite sandy clay; there is a contact at 717.3 ft with a return to medium-coarse glauconite sand with shells and lithic fragments. From this level to 729 ft, the section becomes a glauconitic sandy clay, with clayey glauconite sand from 729 to 749 ft. Based on nannofossil biostratigraphy (Fig. 6; see "Biostratigraphy" section, this chapter), the section below 710 ft is upper Eocene (Zones NP19–20, NP21, P15–P17; Fig. 6) and correlates with the informally named ACGSα unit at May Landing, NJ (Owens et al., 1988). (The age of the section from 700.0 to 703.1 ft is uppermost Eocene to lowermost Oligocene Zone NP21, and the age of 703.1–710 ft is indeterminate.) The unit becomes progressively more pebbly toward 759 ft, associated with a negative gamma-ray kick (Fig. 6). The section from 759 to 769 ft contains a pebbly, coarse, glauconite sand that is also quite clayey. From 769.0 to 778.6 ft, there is a clear upward-coarsening sequence from a glauconitic clay with shells to a clayey glauconite sand to a quartzose glauconite sand to a pebbly quartz glauconite sand, as indicated by decreasing gamma log values in this interval (Fig. 6). The age of the base of the unit (767–779 ft) and the position of the contact with the underlying Shark River Formation is uncertain, although it appears that this interval may be upper middle Eocene (Zone NP17?; Fig. 6) and thus temporally equivalent to the Shark River Formation elsewhere. This unit is clearly a marine neritic (primarily middle) deposit, based on the diverse benthic foraminifer assemblages and the dominance of benthic/planktonic foraminifers. There is a distinct change between 746.9 and 750 ft from a lower diversity benthic fauna with rare

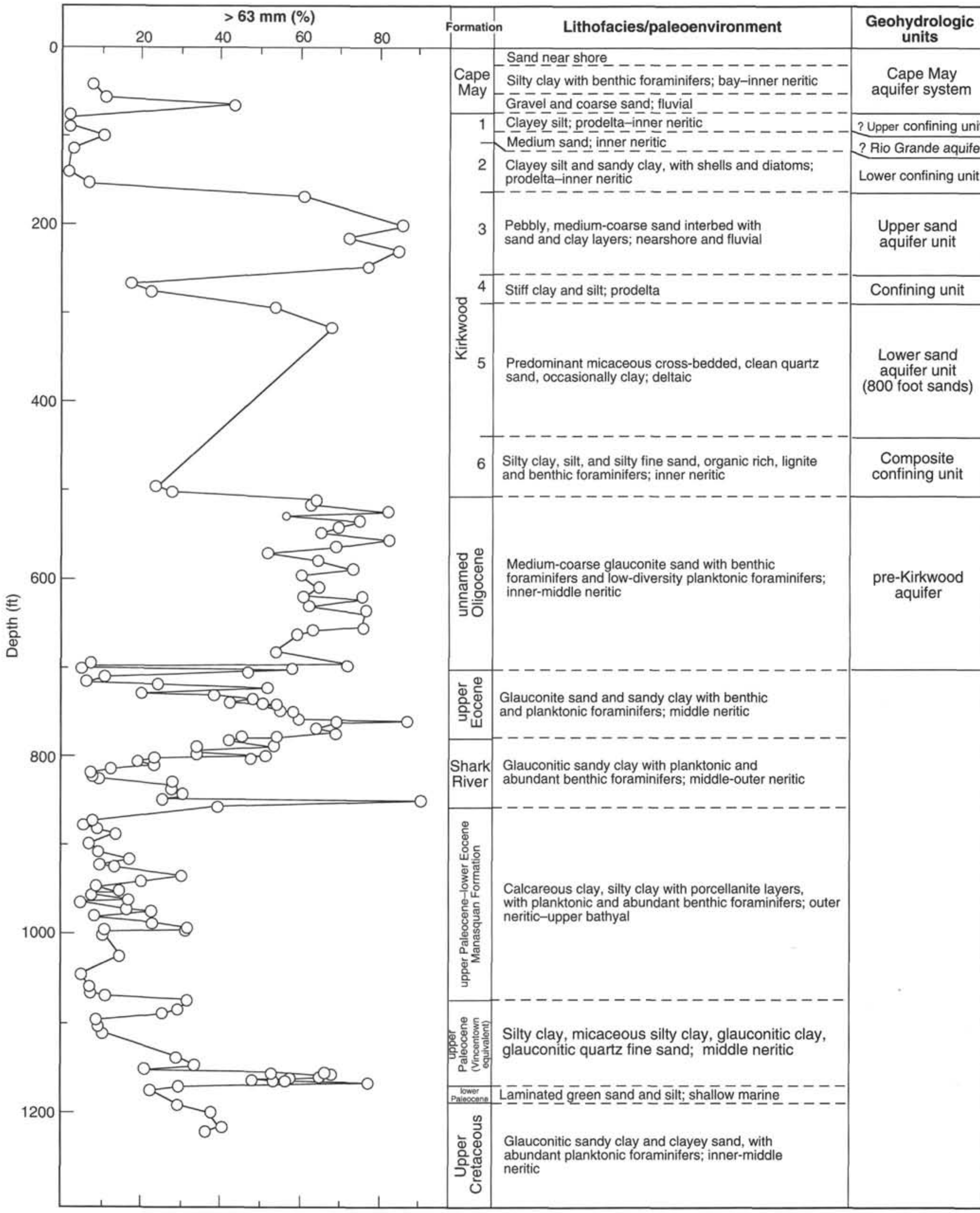

Figure 9. Percentage of >63-µm size fraction, lithologic units, facies, environments, and geohydrologic units (as recognized at Atlantic City; see Chapter 2, this volume).

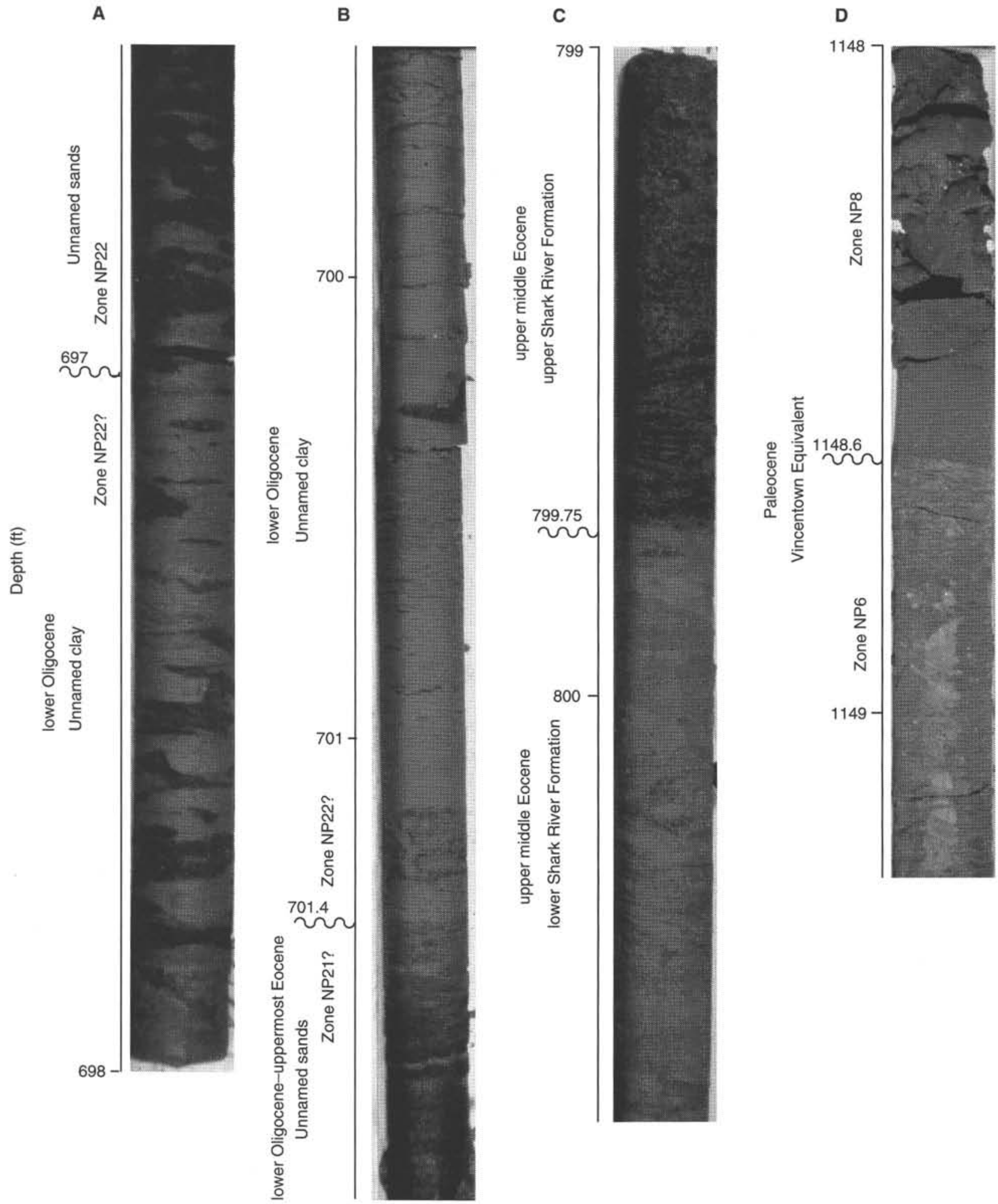

Figure 10. Core photographs, Island Beach. **A.** Lower Oligocene surface at 697 ft separating black, clayey, medium glauconite sand above from firm, brownish dark gray clay below. Note piping of glauconite sand downward and reworking of lighter clay upward. **B.** Uppermost Eocene–lowermost Oligocene surface at 701.4 ft separating firm, brownish dark gray clay above (Zone NP22?) from clayey, medium glauconite sand below (Zone NP21?). **C.** Lithologic contact and disconformity at 799.75 ft separating the upper Shark River Formation above (dark olive gray, fine-medium glauconite sand) from the lower Shark River Formation below (light olive gray, glauconite sandy clay). **D.** Disconformity at 1148.6 ft (intra-upper Paleocene Vincentown Formation) separating dark gray, sandy clay with rip-up clasts above (Zone NP8) from dark greenish gray, fine-medium sand below (Zone NP6).

planktonic foraminifers above to a higher diversity benthic fauna with abundant planktonic foraminifers below. This biofacies break is associated with a gamma-log change (Fig. 6) and the top of the reworked zone (at 762 ft); it is likely a disconformity.

Shark River Formation

Age: middle to lowermost upper Eocene
Thickness: 83 ft

There is a contact at 778.6 ft with a slightly sandy glauconite clay below. The unit below has thin (1 mm) glauconite sandy clays/clayey sands interbedded with stiffer clays that give it a laminated appearance. This level (778.6 ft) is tentatively the contact with the middle Eocene Shark River Formation.

Glauconite sandy clay continues to alternate with clayey sand down to 799.65 ft. There is a contact at this level associated with a gamma-log kick that separates dark olive gray clayey sands above from light olive gray sandy clay below (Fig. 10C). The lower unit is very fossiliferous, contains less glauconite, and appears slightly less sandy than above. This may be the contact with the Deal Member of the Manasquan Formation sensu Miller et al. (1990). This is the finer grained lower Shark River Formation of Owens et al. (1988) and that name is tentatively retained for this unit. The section from 804 to 819 ft is finely laminated with only moderate bioturbation. Sandy clays alternating with glauconitic clayey sands continue down from 819 ft with relatively sharp contacts. There are occasional levels of almost pure grayish green at 845.7–846.6 ft.

Manasquan Formation

Age: uppermost Paleocene to lower Eocene
Thickness: 213 ft

A contact of glauconitic sandy clay overlying a clay occurs at 862 ft; the contact spans a 0.3- to 0.4-ft interval due to bioturbation. We place the Shark River/Manasquan Formation contact at this level, associated with a sharp gamma-ray peak (Fig. 7). This appears to be the same gamma-ray peak noted at the base of the Shark River Formation at the ACGS#4 borehole (Owens et al., 1988).

Alternations of porcellanite and clays begin at 894 ft within the Manasquan Formation. Distinct beds of porcellanite as thick as 1 ft were noted; the whole section is well indurated. This porcellanite is the lithologic equivalent to the porcellanite layer noted in the ACGS#4 borehole at ~850 ft (Miller et al., 1990); at that borehole, it occurs within middle Eocene Zone NP15 in the Shark River Formation sensu Owens et al. (1988). At Island Beach, the porcellanite occur in upper lower Eocene Zones P7–P8 and NP12 (Fig. 7). This porcellanite is the equivalent of upper lower to lower middle Eocene Horizon A^c "cherts" in the western North Atlantic basin (Tucholke and Mountain, 1979) and the top of the "diagenetic front" at Site 612, New Jersey slope (Poag, Watts, et al., 1987). It was also noted at Site 904 in the lower middle Eocene (see Chapter 8 in Mountain, Miller, Blum, et al., 1994). The Manasquan Formation displays alternations of laminated and burrowed intervals. This thick formation displays only minor lithologic variations and fairly uniform gamma-log characteristics (Fig. 7); it records thick accumulations of Zones NP9 through NP13 and P6α through P9 (Fig. 7; see "Biostratigraphy" section, this chapter). Therefore, although Zone P6b is missing, we recognize no definite unconformities or hiatuses in this unit, although more detailed studies may reveal short gaps.

Vincentown Equivalent

Age: upper Paleocene
Thickness: 91.6 ft

A distinct disconformable contact occurs at 1075.5 ft separating silty clay above from a clay below with a zone of rip-up clasts. This is the contact of the overlying Manasquan Formation with the Vincentown Formation. The base of the Manasquan Formation coincides with a sharp gamma-ray kick, immediately below samples (from 1165 and 1174 ft) assigned to uppermost Paleocene Zone P6a. The minor amounts of glauconite, thin cross beds, and micaceous nature of the Vincentown Formation indicates deposition in shallower neritic paleodepths than the Manasquan Formation. The Vincentown Formation displays remarkable laminations (10 mm per bed; 20 mm per couplet) between darker, more massive clays and lighter, slightly glauconitic cross-bedded, micaceous sandy silts; these laminations appear cyclic (e.g., 1087.5 to 1097 ft). These laminations may be lower shoreface or prodelta. From 1103 to 1127 ft, the interbedding is less cyclic and is dominated by clay. A shell hash was encountered in the interval from 1127.5 to 1133 ft. Sands return from 1139.5 to 1148.0 ft, whereas the laminated, interbedded sandy clays/clayey sands are again found from 1148 to 1158 ft, with the upper part containing rip-up clasts and lower part (1153–1158 ft) showing more bioturbation and increasing glauconite. This level (1148 ft) is a disconformity (Fig. 10D), as evidenced by the lithologic change, gamma-ray peak, and possible break between Zones NP6 and NP8 (Fig. 6).

The Vincentown Formation is upper Paleocene at Island Beach (Zones NP5 partim to NP9 partim; Zones P3 to P6a partim). Foraminifers indicate that it may be assigned to lower Paleocene Zone P2 also; however, nannofossils indicate that the lowermost part is upper Paleocene Zone NP5 (see "Biostratigraphy" section, this chapter).

Two lithologic contacts occur in the interval 1155 to 1164.5 ft. The first is a gradational increase in glauconite content (some of the glauconite are black minerals without the typical botryoidal shape) between 1155 and 1159.3 ft. At 1159.3–1160 ft, there is a shell layer of *Oleneothyris*. V. Owens (pers. comm., 1993) places the shell bed in the lower Vincentown Formation. From 1160 to 1164.45 ft, the section consists of clayey glauconitic sand to glauconite sandy clay containing common quartz granules up to 3 mm and shell fragments. A bed of granules lies at 1163.2 ft. The clayey nature indicates that this unit may still be assigned to the lower Vincentown Formation (i.e., updip the Hornerstown Formation is pure glauconite sand), although Olsson and Wise (1987) correlate this as the upper part of the Hornerstown Formation. The greensands are clearly the base of a "New Jersey cycle" (Owens and Gohn, 1985; Sugarman et al., 1993) that directly overlie a surface (flooding surface?) at 1164.45 ft (uncorrected depth). Although the name Hornerstown has been applied to these greensands, we retain them as the glauconite sands of the Vincentown cycle.

A lignite bed occurs at 1164.45 ft (uncorrected depth for expansion). We first thought that this bed marked the top of the Cretaceous, although subsequent foraminifer biostratigraphy places the top of the Cretaceous below 1183.5 ft. From the base of the lignite bed to 1167.1 ft, the section contains laminae of dark greenish gray clayey glauconitic sands and sandy glauconitic clays, containing rip-up clasts. Bedding contacts of the laminae are irregular. Some of the irregularity can be ascribed to bioturbation; however, the bedding appears almost convoluted. The interval from 1163.0 to 1166.8 ft is "middle" Paleocene (Zone P2–P3b and Zones NP5 to ?NP6; note that nannofossils indicate this section is lowermost upper Paleocene, whereas foraminifers indicate it is uppermost lower Paleocene; see "Biostratigraphy" section, this chapter).

?Hornerstown Formation and Equivalents

Age: lower Paleocene
Thickness: 19 ft

A sharp contact occurs at 1167.1 ft, with dark olive gray, moderately bioturbated, laminated silts with silty clay interbeds. The contact is an irregular surface interpreted as a disconformity that separates the lower Vincentown Formation (= the upper Hornerstown of Olsson and Wise, 1987) from the Hornerstown equivalent; it separates Zone

NP3 from Zone NP5 (i.e., a hiatus >1.7 m.y.) (see "Biostratigraphy" section, this chapter). The contact zone spans 0.3 in., and contains bioturbated greensands mixed with in situ silts. Laminations are pronounced below this interval.

From 1168 to 1178.85 ft, the laminated silts contains several indurated interbeds. These are also laminated. The cores "ring" like a porcellanite, although they are easily scored by a knife. This facies has not been described from the lower Paleocene of New Jersey, but must be a facies-equivalent of the lower Paleocene portion of the Hornerstown Formation sensu Olsson and Wise (1987). It probably represents a more complete representation of a "New Jersey cycle" preserving the regressive silt facies in this downdip borehole (e.g., Owens and Gohn, 1985; Sugarman et al., 1993).

Foraminifer biostratigraphy places the Cretaceous/Paleogene boundary between 1183.5 ft and 1188 ft in a section of no recovery (1184.5–1188 ft). This is the contact between the sandy, occasionally glauconitic clay and porcellanite(?) above with glauconite sandy clay to glauconite clayey sand below.

Navesink–Red Bank Formations

Age: upper Maastrichtian
Thickness: ~63 ft

We assign the uppermost Cretaceous (1188–1223 ft) glauconite sandy clay to glauconite clayey sand to the undifferentiated Red Bank–Navesink Formations. From 1201.6 to 1218 ft there was no recovery, although washings from the core barrel and the rapidity of drilling indicate that this interval was probably a sand.

This upper Cretaceous unit may be equivalent to the lower Hornerstown Formation sensu Olsson and Wise (1987) or to their New Egypt Formation. There has been considerable discussion about the placement of the Cretaceous/Tertiary boundary in New Jersey, with Olsson and Wise (1987) placing the boundary within the Hornerstown Formation. Owens and Gohn (1985) placed a disconformity separating the Cretaceous and the Paleocene at the top of the Tinton Formation in northeast New Jersey and at the top of the Navesink–Red Bank cycle in the southern part of the state. We cannot comment on the nature of the contact between the Cretaceous and the Paleocene because of the poor recovery.

BIOSTRATIGRAPHY

We used the planktonic foraminifer zonation of Berggren and Miller (1988) for the Paleogene, the zonation of Martini (1971) for the Cenozoic nannofossils, the East Coast Diatom Zonation (ECDZ) of Andrews (1988) for the Neogene, and the GPTS and biostratigraphic ages of Berggren, Kent, Flynn, and van Couvering (1985; hereafter cited as BKFV85) for the Cenozoic. The GPTS has recently been revised (Cande and Kent, 1992; hereafter cited as CK92); however, the biostratigraphic ages have not been fully recalibrated to the new GPTS. Thus, we report the ages to the BKFV85 time scale, realizing that the ages must be recalibrated.

Planktonic Foraminifers

Summary

Samples obtained from the Island Beach borehole contain barren to abundant planktonic foraminifers. The Miocene and younger sediments are generally barren of planktonic foraminifers. The Oligocene (from 731 to ~500 ft) occasionally preserves low-diversity assemblages. The Eocene (731–1065 ft), Paleocene (1065–1188.9 ft), and Upper Cretaceous (1188.9–1223 ft) contain generally well-preserved, relatively diverse planktonic foraminifer assemblages. Abundant and diverse planktonic foraminifers allow application of the zonation of Berggren and Miller (1988) to the Paleocene, Eocene, and part of the Oligocene section whereas planktonic foraminifer zonation for the uppermost Oligocene and younger sediments was not possible.

Oligocene

The Oligocene in the Island Beach borehole is poorly fossiliferous and lacks many marker taxa, although a number of planktonic foraminifer taxa have been identified (Table 2). The low diversity of planktonic foraminifers can be attributed to the extinction of taxa in the ocean and to environmental restriction at the Island Beach borehole. Species found are generally long-ranging and nondiagnostic forms (Table 2).

The highest occurrence (HO) of *Chiloguembelina cubensis,* which is the base of Subzone P21b, is found at 577.8 ft, although this assignment is based on a single specimen and the zonal boundary is uncertain. Samples above this level are not fossiliferous and differentiating Zones P21b–P22 is not possible. Zones P20–P21a are not separated because of the absence of basal Zone P21a marker species, *Globigerina angulisuturalis.*

The base of Zone P20 is recognized by the HO of *Turborotalia ampliapertura.* This taxon is found in only one sample (618 ft) at Island Beach, and the section below this is tentatively assigned to Zone P19. Zone P18 ranges from 731 ft to the HO of *Pseudohastigerina* at 700 ft. Nannofossils indicate that this section is upper Eocene, and that the HO of the zonal criterion for the base of P18 (last appearance of *T. cerroazulensis cerroazulensis*) is premature at Island Beach.

Eocene

The Eocene in the Island Beach Borehole spans from at least 731 ft to 1065 ft (?). Planktonic foraminifer assemblages in Eocene sediments are abundant, diverse, and generally well preserved. As in other temperate-region, shallow-marine sediments, the dominant taxa are acarininids and subbotinids whereas morozovellids are less common. *Turborotalia* (*cerroazulensis* lineage) is common in the upper middle and upper Eocene section. *Pseudohastigerina, Globanomalina, Chiloguembelina,* and *Guembelitria* occur frequently in finer (<150 μm) size fractions.

The top of Zone P17, which is also the Eocene/Oligocene boundary, is marked by the HO of *Turborotalia cerroazulensis cerroazulensis.* This important datum event is observed at 731 ft. Nannofossil data indicate that this must be a premature (environmentally truncated) HO because it occurs in the middle of upper Eocene Zone NP19–20 (Fig. 6).

Zones P15–17 are not separable due the absence of *Cribrohantkenina inflata* whose total range was used to define Zone P16. Because all morozovellids, acarininids, and truncorotaloides became extinct at the latest middle Eocene, planktonic foraminifer taxa observed in this interval are mostly subbotinids, globigerinids, pseudohastigerinids, and chiloguembelinids (Table 2).

The top of the middle Eocene is poorly defined because of reworking. Zones P12–P14 are not differentiated due to the absence of *Globigerapsis beckmanni,* whose total range defines Zone P13. The base of Zone P15 is characterized by the lowest occurrence (LO) of *Globigerinatheka semiinvoluta* (41.3 Ma), which was not found at this site; the disappearance of all species of *Morozovella* and *Acarinina* occurred in the latest middle Eocene (40.3 Ma; BKFV85) after the first appearance datum (FAD) of *Globigerinatheka semiinvoluta.* At the Island Beach borehole, *Morozovella* and *Acarinina* disappear at 757 ft. Therefore, Zones P12–P14 may range from 757 ft to 809 ft. However, the planktonic foraminifers are probably reworked, because the section from 752 to 762 ft has been assigned to upper Eocene Zone NP18 (Fig. 6). A similar situation occurs at the ACGS#4 borehole (Mays Landing); there, Poore and Bybell (1988) used the LO of *Globigerina praebulloides* as a positive criterion of upper Eocene in the presence of reworking of middle Eocene *Morozovella* and *Acarinina.* At Island Beach, *G. praebulloides* first occurs at 767 ft, and we place the middle/upper Eocene boundary below this. The biostratigraphy in the interval between 767 and 778 ft is obscured by reworking and the absence of taxa unique to the upper Eocene.

Middle middle Eocene Zone P11 is recognized from the LO of *Globigerapsis kugleri* (825 ft) to the HO of *Morozovella aragonensis* at 813 ft. Planktonic foraminifer assemblages of this section are diverse (Table 2).

The Zone P9/P10 boundary is defined by the LO of *Hantkenina nuttalli* (Berggren and Miller, 1988). This species is absent at Island Beach and the genus is rare. Therefore, Zones P9 and P10 are not separated at this borehole and these zones range from 829 to 879 ft (Fig. 7). The LO of *Acarinina bullbrooki* at 845 ft, may approximate the base of Zone P10 because this datum is in late Biochron P9 according to Berggren and Miller (1988). However, nannofossil stratigraphy indicates that the lower/middle Eocene boundary (= P9/P10 boundary) is between 857 and 869 ft. It is probably associated with the distinct disconformity at 862 ft (Fig. 7). The assemblages occurring in Zones P9–P10 are diverse (Table 2).

Zone P8 ranges from the HO of *Morozovella formosa formosa* (916 ft) to the LO of *Globanomalina palmerae*. Because only one specimen of *G. palmerae* is observed in one sample (879 ft), placement of the Zone P8/P9 boundary at 879 ft is uncertain. Zone P7 ranges from the LO of *Morozovella aragonensis* (975 ft) to the HO of *M. formosa formosa* (921 ft). Assemblages in this section are diverse (Table 2).

Planktonic foraminifer biostratigraphy recognizes the base of Eocene at the HO of *Morozovella velascoensis* (= base Zone P6b of Berggren and Miller, 1988). Subzone P6b is recognized at the Island Beach borehole between the HO of *M. velascoensis* (1065 ft) and the LO of *M. formosa formosa* (1000 ft). Nannofossil biostratigraphy indicates a thick Zone NP9 (>35 ft) and a moderately thick Zone NP10 (~33 ft), consistent with continuous deposition from Biochron P6a to P6c. Zone P6c spans from 1000 to 975 ft. Thirty-one taxa are identified in this interval (Table 2).

Paleocene

All Paleocene planktonic foraminifer zones (except P0, Pα, and P1a–b) were recovered. However, the Cretaceous/Tertiary (K/T) boundary was lost in an unrecovered interval (1183.5–1188.0 ft).

Zone P6a has the most highly diversified fauna of the whole Paleocene at the Island Beach borehole, with 20 species identified in samples from 1074 and 1065 ft (Table 2). The HO of *Globanomalina pseudomenardii* to the LO of *Morozovella subbotinae* were used to define Zone P5 (Berggren and Miller, 1988). However, this zone may not be valid because both these events have been observed at the same stratigraphic horizon (Berggren et al., unpubl. data, 1993). At the Island Beach borehole, the interval between the HO of *G. pseudomenardii* and the LO of *M. subbotinae* (1138–1074 ft) is not fossiliferous in the nearshore Vincentown Formation. Thus, although an apparently thick accumulation of Zone P5 is found at Island Beach, its recognition and correlation are artifacts of preservation and facies.

Zone P4 (*Globanomalina pseudomenardii* taxon range zone) is identified by the presence of the zonal marker from 1155 ft; it is common to 1138 ft. Twelve additional taxa occur in this fossiliferous interval (Table 2). The actual diversity may be slightly higher than observed because dissolution may have removed fragile species. Recrystallization also makes identification of some species difficult. The top of Zone P4 may extend much higher than 1138 ft because the next 64 ft (1138–1074 ft) are not fossiliferous. Only one sample in this interval (1097 ft) has a few non diagnostic species (*Eoglobigerina spiralis, Globanomalina chapmani, Subbotina* sp., *Acarinina aquiensis, A. nitida*).

Zone P3b (from the LO of *Igorina pusilla* to the LO of *G. pseudomenardii*) is found from 1163 to 1161.7 ft. Zone P3a is found only in one sample (1164.3–1164.4 ft) based on the LO of *Morozovella angulata* before the LO of *Igorina pusilla*. We attribute this to a slow sedimentation rate or a hiatus (the sediments are mainly fine glauconite sand).

The marker for the base of Zone P2, *Praemurica uncinata*, first occurs at 1166.0 ft. The LO of *Globanomalina compressa* is used as the base of Subzone P1c (Berggren et al., unpubl. data, 1993). The interval from 1183.5 to 1175 ft contains a Subzone P1c assemblage (Table 2).

The K/T boundary was not recovered but lies between 1183.5 and 1188 ft. This unrecovered interval perhaps includes the basal Paleocene planktonic foraminifer Zone P0 to Subzone P1b or a depositional hiatus.

Uppermost Cretaceous

Only ~35 feet of uppermost Cretaceous sediments were penetrated in the Island Beach borehole. The sediments contain abundant *Heterohelix, Globigerinelloides, Rugoglobigerina* and *Guembelitria* (Table 2); large taxa, typical of tropical-subtropical open marine taxa (e.g., *Rosita, Planoglobulina, Racemiguembelina,* and *Ventilabrella,* are not observed. Direct biostratigraphic correlation with standard Upper Cretaceous planktonic foraminifer zones is difficult due to absence of the late Maastrichtian marker species *Abathomphalus mayaroensis*. As in all other uppermost Cretaceous sections deposited on shallow shelves on the U.S. coast, the absence of this deeper water dweller is perhaps due to environmental exclusion from shallow marine environment rather than a hiatus. The occurrence of *Hedbergella monmouthensis* indicates that the section is uppermost Maastrichtian (Olsson and Wise, 1987).

Calcareous Nannofossils

Summary

Smear slides prepared from samples taken at ~5-ft intervals were examined for nannofossil biostratigraphy. Except for samples at 502.0–502.1 and 517.0–517.1 ft, all levels analyzed between 79.75–79.90 and 577.8–578.0 ft were barren. Calcareous nannofossils are few to common between 588.2–588.4 and 672.4–672.5 ft. They increase in abundance at 680.8–680.9 ft and vary from abundant to common below this level until the lowermost samples examined at 1193.0–1193.1 ft. Preservation is good to moderate, except in the Paleocene where both dissolution and recrystallization have occurred.

Calcareous nannofossils provide a firm stratigraphic control for the lower Oligocene to Paleocene section of the borehole. Although they are common in the upper Oligocene (between 588.2–588.4 and 672.4–672.5 ft) and from 509.0–509.2 ft in the Miocene, they do not provide zonal assignments because the assemblages lack index species.

Neogene to upper lower Oligocene

Depths: 79.75–79.90 to 672.4–672.5 ft

Although samples from 502.0–502.1 and 517.0–517.1 ft yield exceedingly rare coccoliths, the sample from 509.0–509.2 ft yields a relatively diverse assemblage with *Coccolithus pelagicus, Helicosphaera carteri, H.* sp. cf. *H. obliqua, Pontosphaera multipora, Reticulofenestra floridana, R. gartneri, R. pseudoumbilicus, Sphenolithus neoabies*. The presence of *H.* sp. cf. *H. obliqua* and *R. gartneri* indicates that the sample is lower Miocene.

Samples at 588.2–588.4 and 595.6–595.8 ft yield assemblages that suggest upper Oligocene, but no marker species was found, and reworking occurs. Samples at 609.0–609.2 and 672.4–672.5 ft yield assemblages that definitely indicate upper to upper lower Oligocene (with *Chiasmolithus altus* and *C. oamaruensis*). This interval is assigned to Zones NP25 to NP23 undifferentiated.

Lower Oligocene to lower Paleocene

Depth: 680.8–680.9 to 1179 ft

Except where indicated, the zonal assignments given below are based on the strict definition of the NP zones by Martini (1971) (using the HOs and LOs of Martini's index species).

The interval between 680.8–680.9 and 697.5–697.6 ft belongs to lower Oligocene Zone NP22. Samples from 700.0–700.1 and 703.0–703.1 ft are assigned to Zone NP21. A thick upper Eocene section assigned to Zone NP19–20 occurs between 710.0–710.3 and 750.0–750.1 ft. The position of the NP19–20/NP21 zonal boundary is uncertain. Rosette-shaped discoasters are generally rare, particularly in the upper part of the interval assigned to Zone NP19–20, and two broken specimens of *D. saipanensis* found at 703.0–703.1 ft are considered reworked. It is not possible to locate precisely the Eocene/Oligocene boundary (between Zones NP22 and NP21 or between Zones NP21 and NP19–20, or within Zone NP21).

The interval between 752 and 762 ft is assigned to upper Eocene Zone NP18. Calcareous nannofossils are abundant, preservation is moderate, and reworking occurs.

The biozonal position of the interval from 765.0–765.1 ft and 772.0–772.2 ft is problematic because of reworking. Upper middle Eocene Zone NP17 is an interval zone defined by the HO of *Chiasmolithus solitus* at the base and the LO of *C. oamaruensis* at the top. Although *Chiasmolithus solitus* is sporadic between 765.0–765.1 ft and 772.0–772.2 ft, *Sphenolithus obtusus,* a species thought to be restricted to Zone NP17, occurs at 772.0–772.1 ft. Thus, *Chiasmolithus solitus* is thus considered reworked and the interval is assigned to Zone NP17.

The interval between 778.0–778.1 and 817 ft is assigned to Zone NP16, whereas the interval between 843 and 849 ft is assigned to Zone NP15. The NP15/NP16 zonal boundary was determined by the HO of *Blackites gladius.*

The sample at 853.3–857.0 ft belongs to upper lower Eocene Subzone NP14a; it is characterized by the co-occurrence of *Discoaster sublodoensis, D. lodoensis,* and *D. kuepperi.*

Lower Eocene Zone NP13 is represented at 869.3–874.0 and 874.0–879.0 ft. Zone NP12 extends from 879.0–884.0 to 955.0–955.5 ft; Zone NP11 extends from 961.0–961.1 to 1015.0–1022.0 ft. The interval between 1022.0–1024.0 and 1055.0–1055.4 ft is provisionally assigned to Zone NP10. Accordingly, the Paleocene/Eocene boundary is not confidently delineated at this time. Upper Paleocene Zone NP9 extends from 1060.0–1060.1 ft to 1111.9–1112.0 ft. The sample taken from 1138.0–1138.1 ft belongs to Zone NP8. Zone N5 extends from 1160.0–1160.1 to 1166.0–1166.4 ft. Lower Paleocene Zone NP3 ranges from 1167.8–1167.9 ft to 1179 ft. Lower Paleocene Zone NP3 unconformably overlies Upper Cretaceous deposits in the borehole.

Upper Cretaceous

Depth: 1193.0–1193.1 ft

Samples from 1188.6 to 1195.9 ft have sparse to numerous *Nephrolithus frequens* and are assigned to Maastrichtian nannoplankton Zone CC26 of Perch-Nielsen (1985) and Zone NC23 of Roth (1983). The section from 1199 to 1221 ft contains *Lithraphidites quadratus* and is assigned to Maastrichtian nannoplankton Zone CC25 of Perch-Nielsen (1985) and Zone NC22 of Roth (1983).

Diatoms

Eighty-six samples were examined for diatom analyses. In general, the upper part of the section, from the top of the core to approximately 300 ft contained diatoms; although diatoms are recorded below this level, they tended to be rare, broken or non-age diagnostic. Samples from the surface to about 300 ft contained few to abundant diatoms, generally well preserved. Both pelagic and benthic forms are present, with the latter being more common. Important markers species in the top 300 ft include *Actinocyclus ingens, Coscinodiscus lewisianus,* and *Rhaphidodiscus marylandicus.* The latter two species were used by Andrews (1988) to zone Miocene sediments exposed along the east coast of the U.S. However, although *C. lewisianus* ranges from ECDZ 6 (middle middle Miocene; Andrews, 1988) to below ECDZ 1 (middle lower Miocene), *R. marylandicus* ranges from the lower middle part of ECDZ 2 to below ECDZ 1. These data indicate that the Island Beach core, between the top and about 300 ft is equivalent to the lower part of Andrew's (1988) ECDZ 2 and all of ECDZ 1. There are no biostratigraphic data indicating if the 300-ft level penetrated below ECDZ 1.

In making this correlation, it is necessary to extend the ranges of some species used by Andrews (1988) to set up his east coast diatom zones. Specifically, *Delphineis novaecaesaraea* which, ranges from ECDZ 3–4 to above ECDZ 7 in the Andrews (1988) scheme, is now seen to range down into ECDZ 2 and possibly to ECDZ 1. Similarly, note that *Delphineis penelliptica* occurs in ECDZ 2 and possibly in ECDZ 1. In contrast, Andrews (1988) indicated that this species ranges from the lower middle part of ECDZ 6 to the base of ECDZ 3–4. Andrews (1988) was careful to point out that the LO of this taxon was not certain, although he failed to find it in sediments representing ECDZ 1 and ECDZ 2.

ISOTOPIC STRATIGRAPHY

Seven Sr-isotopic age estimates were obtained from mollusk shells at the Island Beach borehole (Table 3). Shells were sonified and dissolved in 1.5 N HCl. Sr was separated using standard ion exchange techniques and analyzed on a VG sector mass spectrometer at Rutgers University (see Miller et al., 1991a, for a description of the methods used). Ages were assigned using both the BVFK85 and CK92 time scales. The Oligocene regressions are those of Miller et al. (1988) and Oslick et al. (in press), which rely on the BVFK85 and CK92 time scales, respectively. Miocene age estimates were based on Oslick et al. (in press) for both BVFK85 and CK92.

At the Island Beach borehole, Miocene shell beds occur only at the base of the Kirkwood Formations. These shells were weathered and have a soft, chalky texture. Although the shells are weathered, the age estimates obtained (21.8–21.7 Ma; Table 3) correspond to the age range of the lower Kirkwood sequence (East Coast Diatom Zone 1; 22.6–19.2 Ma) at other New Jersey onshore boreholes (Sugarman et al., 1993).

We dated an unconformity at 505.5 ft as spanning the Oligocene/Miocene boundary (24.3 Ma below and 21.8 Ma above; note that the older age is based on only one measurement); the strata below the unconformity represent some of the youngest Oligocene strata dated in the NJ coastal plain using Sr-isotopic stratigraphy. Much of the Oligocene section between 525 and 650 ft was barren of shells. Four gastropod samples between 663 and 683.6 ft yielded ages of 32.8–32.0 Ma. These are the oldest definitive Sr-isotopic ages obtained for the Oligocene of the New Jersey coastal plain, although older Oligocene strata have been dated at the Atlantic City borehole (see "Isotopic Stratigraphy" section in Chapter 2, this volume).

SCIENTIFIC ACCOMPLISHMENTS, ISLAND BEACH BOREHOLE

1. Excellent recovery of 78 ft of surficial upper Pleistocene–Holocene sediments that record at least one sea-level cycle.
2. Remarkable recovery and facies information on the Miocene Kirkwood Formation (427 ft thick at this site). Lithostratigraphic subdivisions of this formation at Island Beach correlate well with similar units at Atlantic City (see Chapter 2, this volume). Age information for much of the Kirkwood Formation at Island Beach is largely relegated to diatoms and dinoflagellates due to absence of foraminifers and shells. Diatoms indicate that the Kirkwood Formation at Island Beach is ECDZ 2 and older (approximately lower Miocene), and thus the younger Kirkwood cycle(s) (ECDZ 6) are missing as predicted. Sr-isotopic ages on well-preserved shells in the lowermost Kirkwood Formation at Island Beach indicate that it is 21.8 Ma, and thus correlate with the ECDZ 1 (Kirkwood 1) cycle determined elsewhere.

Table 3. Sr-isotopic results, Island Beach borehole.

Depth (ft)	$^{87}Sr/^{86}Sr$	Error (±)	Age (Ma, CK92)	Age (Ma, BKFV85)
503.3	0.708390	0.000015	21.4	21.7
504.5	0.708379	0.000004	21.6	21.8
522.5	0.708252	0.000005	24.3	24.3
663.8	0.707958	0.000006	31.1	32.7
668.0	0.707957	0.000012	31.1	32.7
677.8	0.707944	0.000014	31.5	33.0
683.6	0.707983	0.000006	30.4	32.0

3. Very good Oligocene to middle Eocene section, with potential for integrated dating of surfaces that are currently only precisely dated at ACGS#4 and testing of global sea-level relationships.
4. A relatively complete Paleocene/Eocene boundary section and apparently continuous lower Eocene section.
5. Excellent Paleocene section that includes several disconformities.

Ms 150XIR-111

SHORE-BASED LOG PROCESSING
Hole Island Beach

Total penetration: 1223 ft; 372.77 m
Total core recovered: 1060 ft; 323.09 m (86.7%)

Logging Runs

The recordings were performed by BPB Inc., using slim-hole logging tools.
Logging string 1: Gamma Ray/Dual Laterolog
Logging string 2: Multichannel Sonic (20-cm, 40-cm, 60-cm spacing)
Logging string 3: Gamma Ray/Neutron Porosity
Logging string 4: Gamma Ray/Density (short- and long-spaced)/Caliper
Logging string 5: Dipmeter
Logging string 6: Temperature

Casing

The PVC casing was set at 457 ft (139.3 m).

Processing

Depth shift — No depth shift between runs was required. These data were not recorded with the standard Schlumberger logging tools that are ordinarily used offshore in the Ocean Drilling Program. No count rates or sonic waveforms were recorded that would allow for gamma-ray or sonic reprocessing. Any quantitative comparison of the Island Beach data with Leg 150 offshore data must be made cautiously because of the different tool responses.

Quality Control

Hole-diameter measurements were recorded by the caliper on the density and dipmeter tool strings.
The sonic and density measurements above 457 ft (139 m) were recorded through the PVC casing. Because the density tool is a pad device, valid data are recorded only when there is proper contact of the pad with the formation; for this reason, the data in the cased interval are not presented in the log summary figures. On the other hand, the sonic data are presented in the cased interval as well, although the measurements are affected by the presence of casing. In fact, although the values are quantitatively unreliable, the trend in velocity tracks similar variations in the lithologies.
Only 60-cm-spacing velocity and short-spaced density data are presented in the log summary figures.

Note: For further information about the logs, please contact:

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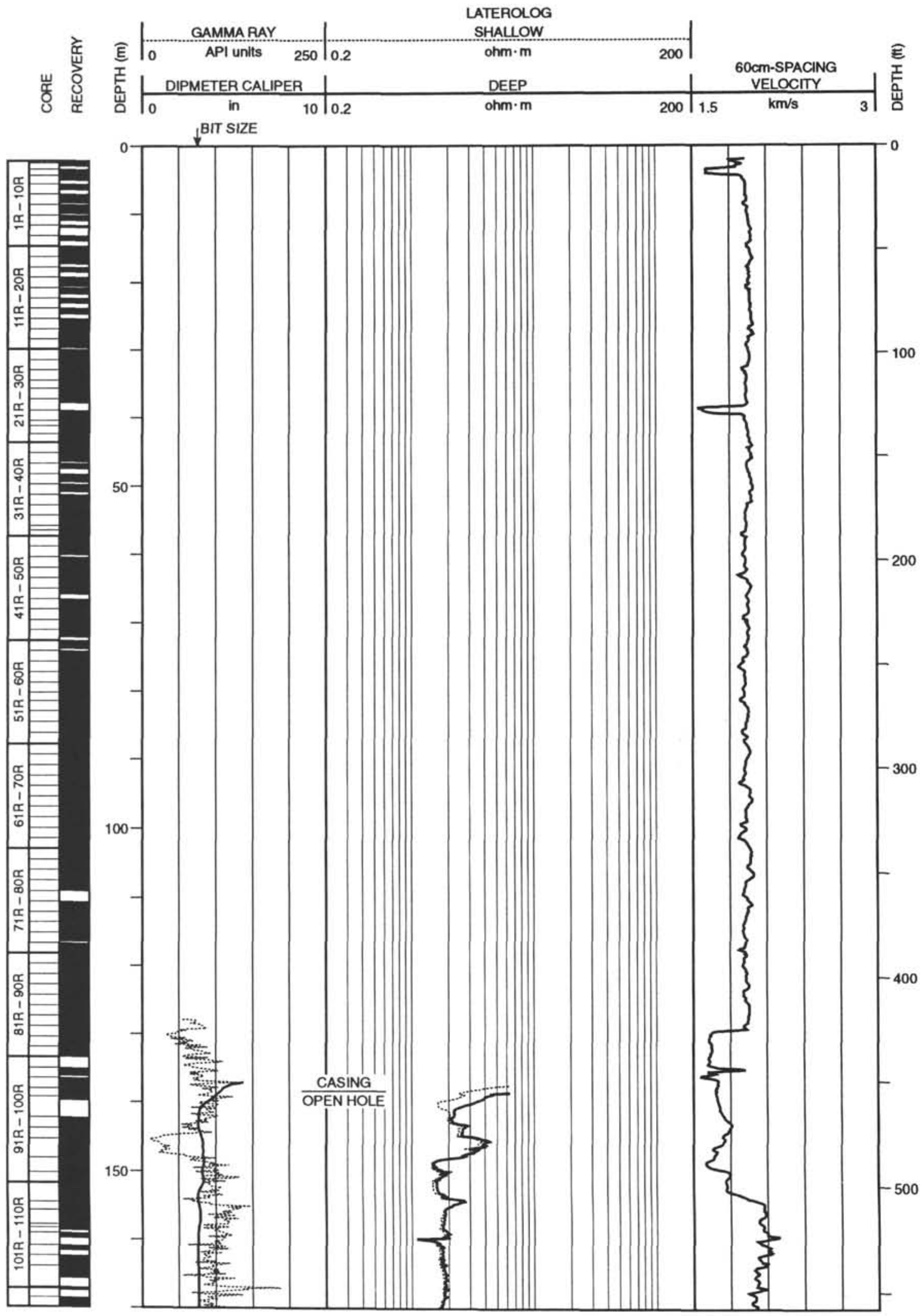
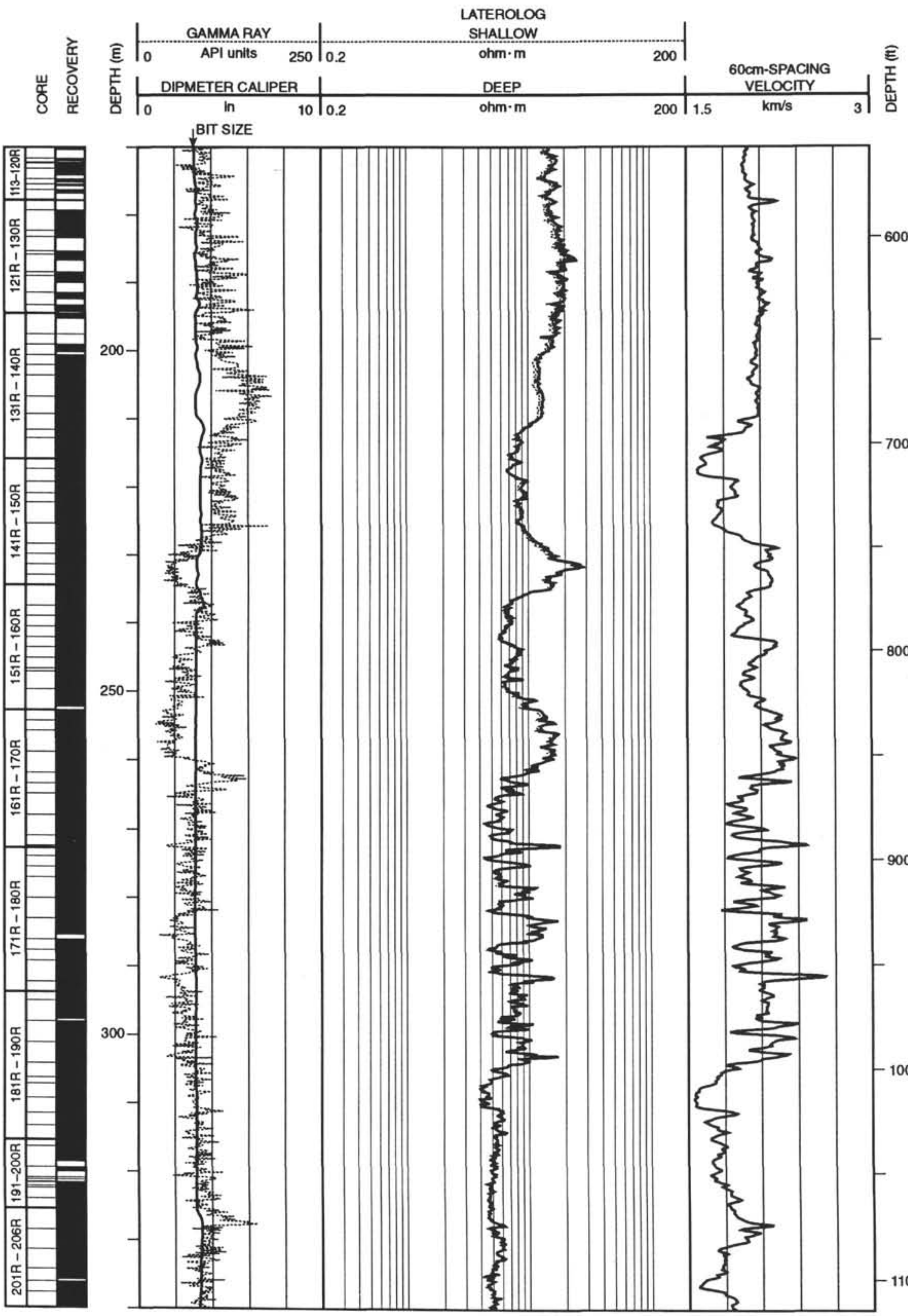
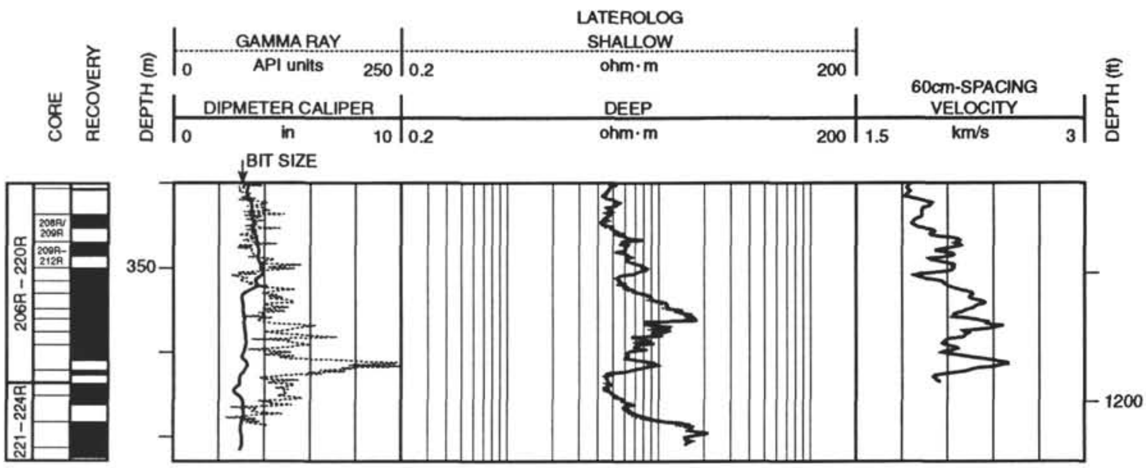
Hole Island Beach: Resistivity-Velocity-Natural Gamma Ray Log Summary



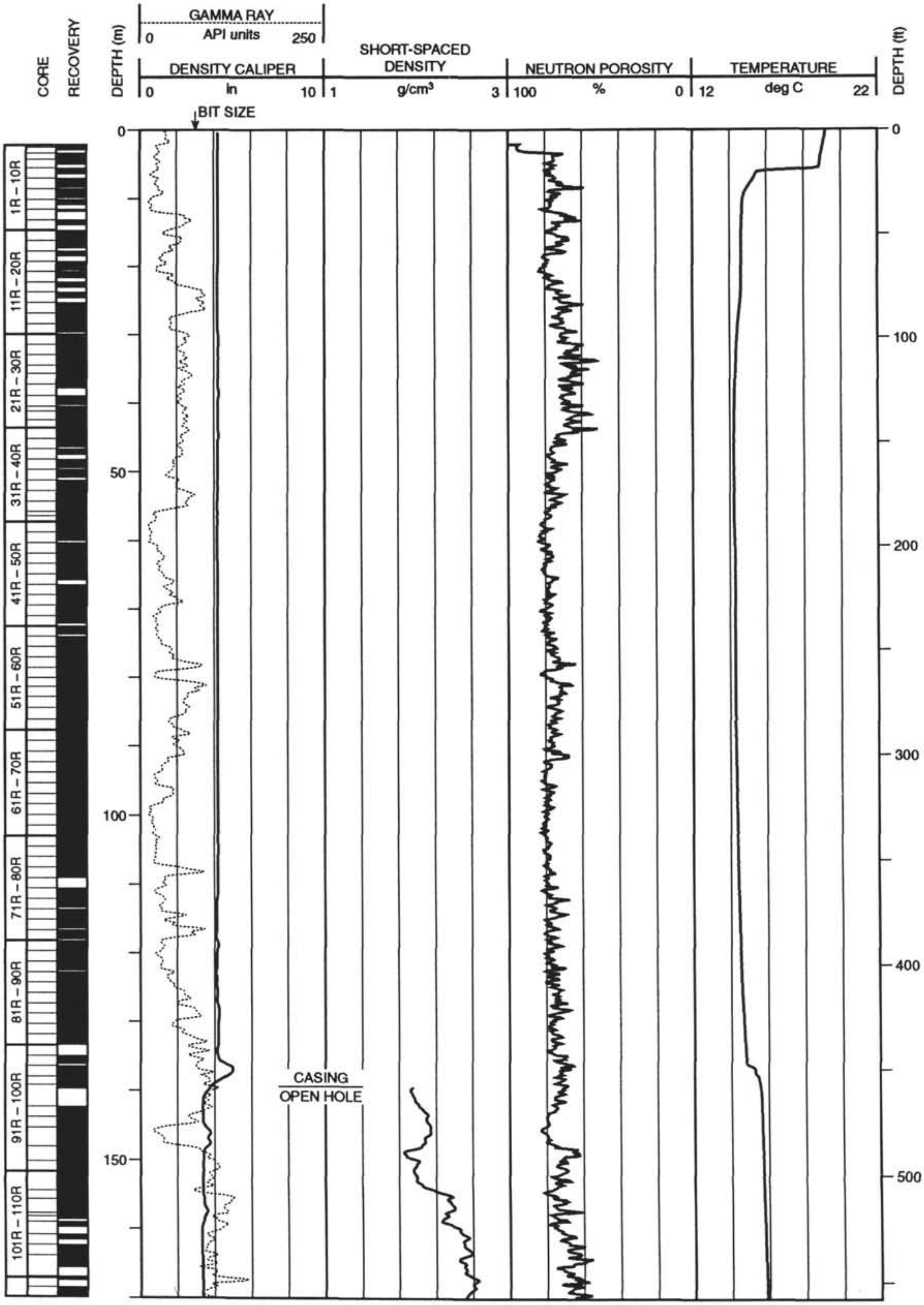
Hole Island Beach: Resistivity-Velocity-Natural Gamma Ray Log Summary (continued)



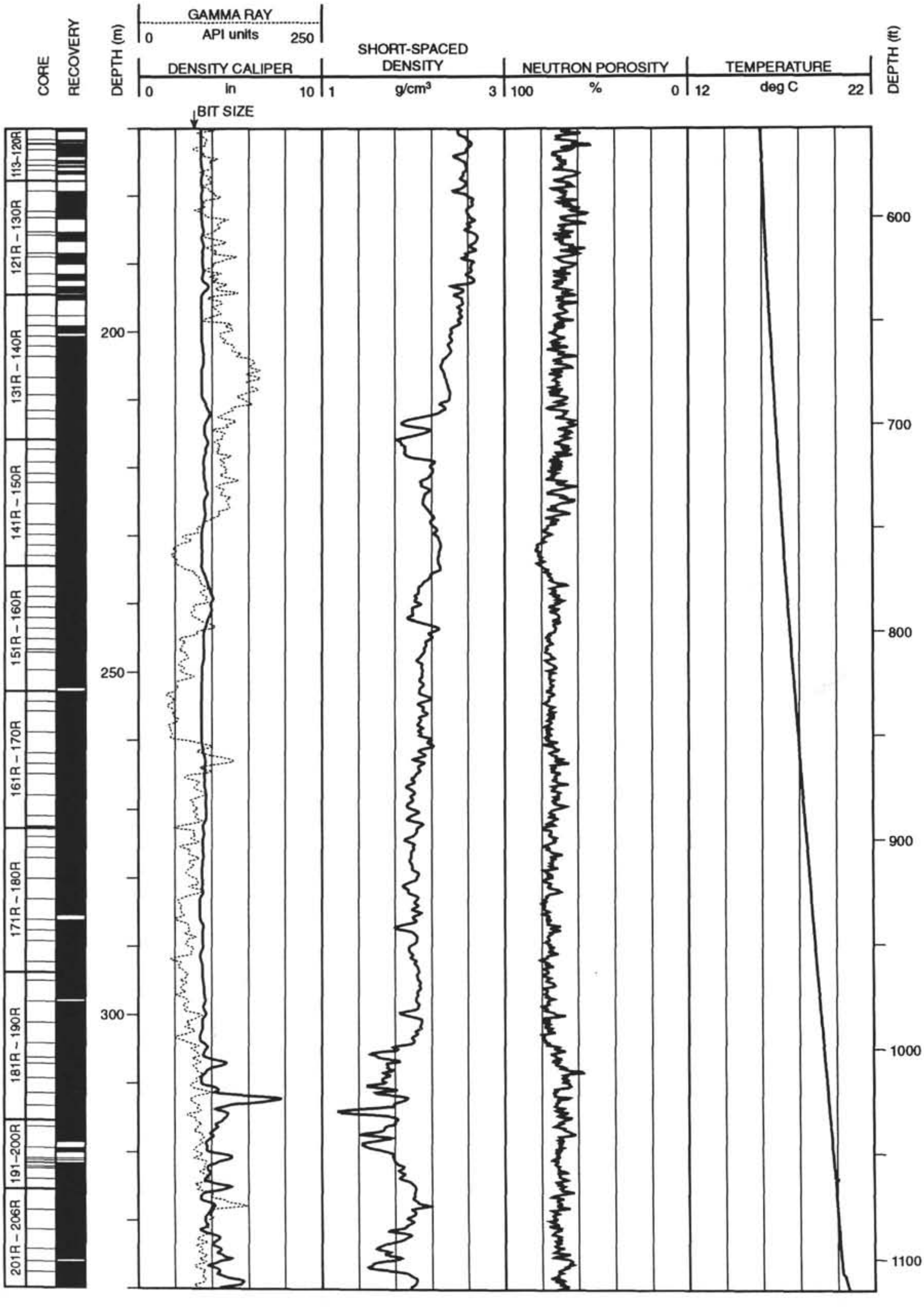
Hole Island Beach: Resistivity-Velocity-Natural Gamma Ray Log Summary (continued)



Hole Island Beach: Density-Porosity-Natural Gamma Ray-Temperature Log Summary



Hole Island Beach: Density-Porosity-Natural Gamma Ray-Temperature Log Summary (continued)



Hole Island Beach: Density-Porosity-Natural Gamma Ray-Temperature Log Summary (continued)