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2. ATLANTIC CITY SITE REPORT[1]

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Biostratigraphy:
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SUMMARY

The Atlantic City borehole was the second site drilled as part of the New Jersey coastal plain drilling project, Leg 150X. It focused on middle middle Miocene to Oligocene "Icehouse" and middle-upper Eocene "Doubthouse" sequences known from previous rotary and cable tool wells. Recovery was not as good as at Island Beach (60% vs. 87%) because of hole stability problems; however, recovery was excellent for most of the critical lower–middle Miocene interval (390–937 ft; 81%).

The surficial Cape May Formation (uppermost Pleistocene–Holocene; 123 ft thick) contains nearshore gravelly sand and clay at the top and fluvial deposits at the base that apparently correlate with the Cape May Formation at Island Beach. The ?middle Miocene Cohansey Formation (96 ft thick) sand and sandy clay represents fluvial deposits not present at Island Beach. The ages of both units are uncertain.

Recovery of the uppermost part of the 706-ft-thick Kirkwood Formation was poor (no recovery from 293 to 390 ft), but recovery for the Kirkwood between 390 and 937 ft was excellent. The sand, silts, and clay facies expressed in the Kirkwood Formation at Atlantic City represent diverse fluvial, nearshore, and neritic (including prodelta) environments. Several upward-coarsening sequences can be recognized on the basis of lithofacies breaks, gamma-log changes, and hiatuses, corresponding with confining units at the base and aquifer units at the top. These lithostratigraphic and geohydrologic units correspond with similar units at Island Beach, and we suggest that they correlate. Numerous shell beds in the Atlantic City borehole allow preliminary dating of these sequences with Sr-isotopic stratigraphy, including the middle middle Miocene Kirkwood 3 sequence (13.3–13.5 Ma; from at least 401.7 to at least 470 ft), the upper lower Miocene Kirkwood 2 sequence 17.0–17.9 Ma; 512–666 ft), and the uppermost Oligocene to lower Miocene Kirkwood 1 sequence (20.3–25.8 Ma; 666–937 ft). The Kirkwood 1 sequence may be divided into several additional sequences that have dramatic shell beds at their base and distinct ages determined by Sr isotopes: 20.3–21.9 Ma, 23.6–23.7 Ma, and ~25.8 Ma. A sharp lithologic and gamma-log break at 741 ft may indicate another sequence boundary between 20.3 and 20.8 Ma, although Sr-isotopic resolution is not sufficient to document this hiatus unequivocally.

The upper Eocene–Oligocene may be divided further into 3 sequences based on lithologic and gamma-log changes that were dated with Sr isotopes: upper Oligocene (27.4–28.7 Ma), lower Oligocene (~33.4 Ma), and upper Eocene (36.6–37.7 Ma). Biostratigraphy is consistent with the Sr-isotopic ages and indicates additional lower upper Eocene and upper middle Eocene sequences.

The systems tracts are generally well developed for these middle Eocene through middle Miocene sequences, with a basal shell or glauconite sand at the base and sands at the top. Further biostratigraphic and Sr-isotopic studies should refine the ages of the sequences, whereas lithostratigraphic and benthic foraminifer biofacies studies should reveal details of the depositional environments and systems tracts of these well-developed sequences.

BACKGROUND AND OBJECTIVES

This chapter and Chapter 1 (Island Beach) are site reports for the first two continuously cored and logged boreholes 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 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).

Determining relative sea-level and evaluating eustatic changes requires the integration of studies from nearshore to deep-sea environments (see Chapter 2 [Mountain, Miller, Blum, et al., 1994] for discussion). 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). As outlined in the "Background and Objectives" section of Chapter 1 (this volume), 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 second borehole in the onshore project was drilled in May–July 1993 at Atlantic City, New Jersey (see Fig. 1 in Chapter 1, this

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volume). This site was selected to optimize recovery of the lower Miocene and, in particular, the lower Kirkwood sequence 1 (ECDZ 1; lower lower Miocene), which attains a maximum thickness between Atlantic City and Island Beach as shown on isopach maps (Sugarman et al., 1993). The lower Miocene section will be the most difficult to penetrate offshore because it is best expressed at proposed Sites MAT1–3 (30 m of water), which cannot be drilled with the *JOIDES Resolution.* The Atlantic City borehole provides good recovery of this critical section, particularly the lowermost portion of the Miocene. In addition, this borehole was selected for its thick Oligocene section. Before the work of Olsson et al. (1980), it was thought that there was no Oligocene represented on this margin. Preliminary analyses by the USGS showed that a considerable Oligocene section was penetrated by older cable tool wells near Atlantic City (see summary in Mullikin, 1990). The Atlantic City borehole provides an opportunity for detailed sampling of the Oligocene section. Atlantic City is 18 mi downdip of the ACGS#4 borehole, and experience there (Miller et al., 1990) indicates that the Eocene section should be particularly suitable for integrated magnetostratigraphic study.

The only disadvantage of this Atlantic City site is that it lacks a direct tie to the offshore seismic grid. Sparker profiles collected by the NJGS immediately offshore (0.5–6 mi) of Atlantic City show seismic discontinuities that will be penetrated at the onshore borehole (Waldner and Hall, 1991); the NJGS sparker grid can be tied into the *Ewing* MCS grid (see Fig. 3 in Chapter 2 [Mountain, Miller, Blum, et al., 1994]) at a later date.

OPERATIONS

Drilling began 2 June 1993 at the Atlantic City Coast Guard Station, NJ (39°22.7′N, 74°25.4′W; elevation 5 ft; Oceanville, NJ, 7.5′ quadrangle), located adjacent to Absecon Inlet and the Farley State Marina. Drilling operations were superintended by Don Queen, U.S. Geological Survey; drillers were Gene Cobbs, Glen Grissom, Todd Heibel, Mike Hoffman, and Dave Powars. Water, electricity, and garage space for core description were provided by LCDR Thomas Richey, Commanding Officer, USCG.

The first core was obtained on 2 June 1993 using a Christensen 94 (HQ) mm system, 4.25- to 4.50-in. hole diameter, and 2.5-in. core diameter. For unconsolidated sands, an extended shoe was used to contact the sample 0.75 in. in front of the bit. A hydraulic hose burst on 2 June but was replaced, and coring proceeded to 51 ft below surface. Six-inch PVC casing was set and grouted at 51 ft on the morning of 3 June 1993, to be extracted at completion. Coring continued on 3 June using Christensen 94 mm system. Recovery was poor for the day (27%) in firm clay (51–56 ft) and very coarse grained unconsolidated pebbly sands.

Coring with moderate recovery (~50%) of gravelly sands continued to 111 ft on 4 June. Intrusions of salt water into the gravels, particularly during high tide, caused mud flocculation and we increased mud weight to 9.5–10 lbs. We were concerned that the tidal effects on the gravels would cause hole collapse before 4-in. casing was set.

Coring with moderate recovery (~40%) of gravelly sands continued to 171 ft on 5 June. Tidal effects did not collapse the hole over night and the rods went to the hole bottom without the need to pump mud. The section from 141 to 151 ft recovered 0.9 ft; the next run from 151 to 153 ft recovered 5.3 ft. We top justified the 6.2-ft recovery at 146 ft because Don Queen felt that the clay layer at the top of the recovered section came from this level. On 6 June, we penetrated from 171 to 221 ft. The hole showed signs of collapsing and required constant flushing. From 161 to 191 ft, recovery rates improved markedly (almost always 100%) in uniform medium sands with subtle yellowish brown and grayish layers. Occasional thin clay layers that blocked the core diminished recovery below 191 ft.

On 7 June, rapid coring continued although the recovery was only 58%. The medium grained sands proved to be easy to drill through but difficult to capture. After drilling to 291 ft, the outer core barrel became stuck as a result of caving of coarse gravels from 65 ft. Attempts to free the barrel by pulling the hoist line and the two rear outriggers were not successful. The core barrel came loose the next morning by pulling up with the hoist line, rotating the drill bit, and pumping mud at 800 psi. In flushing out the hole, the drillers found abundant gravel in the mud and we assume that it is the gravels encountered at 65 ft that are caving into the hole. We decided to case the hole to prevent further caving.

From 9 through 11 June, the drill team reamed out the hole to set casing. Gravels continued to cave into the hole until 4-in. PVC casing was set to 150 ft on 12 June.

Miller departed the Atlantic City drill site on 11 June to meet the *JOIDES Resolution* at Site 902. In his absence, Dennis Kent was responsible for scientific operations; Miller communicated with the Atlantic City drill site by means of daily E-mail messages.

On 13 June, the rods were dropped and coring began again. Seven feet of material that had sloughed down into the hole and 3 ft of new material were cored as drilling proceeded to 294 ft. A highly organic/lignitic unit at that level soaked up the drilling mud. Six hundred gallons of mud were pumped into the hole and none of it returned. Several alternatives were considered to solve this problem including "blind coring" (coring ahead of the casing without circulation) for 30 ft and then casing to the new level to see if circulation could be reestablished. Although this time consuming procedure would have allowed recovery of the entire interval, Miller advised by means of FAX communication from the *JOIDES Resolution* that the best course was to drill without coring until a clay layer was encountered into which casing could be set. On 14 June, the rods and casing were pulled.

On 15 June, 6-in. PVC casing was set and grouted to 65 ft and the hole was reamed to 145 ft. The hole was drilled to 370 ft before clays were found. It was further drilled to 388 ft and cased with 4-in. PVC pipe to 378 ft. No cores were obtained between 293 and 388 ft, although cuttings were taken every 10 ft for this interval. All sediment was pumped out of the hole before a new 10 ft interval was drilled. Rods were dropped on 18 June in preparation for coring.

On 19 June, the rods were dropped to 388 ft and the hole was flushed and prepared for drilling. Coring resumed 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). Cores from 390 to 408 ft contained a semi-consolidated, laminated, dark green, fine sand to silt, with zones of abundant shell hash. A hose break momentarily slowed operations.

On 20 June, a lip protruding inside the rods prevented the inner core barrel from reaching the outer core barrel. Drilling stopped while the rods were pulled to find and replace the defective rod. At the suggestion of Dave Powars (USGS Reston), the science party assumed responsibility for washing the drilling mud off of the cores. Rapid coring with excellent recovery continued between 20 and 22 June from 408 to 588 ft through shelly silts and muds. Recovery dropped at 511 ft in sands and interbedded sands and clays. To capture the fine sands that were apparently being washed away, we increased downpressure to force the sands up inside the barrel before they were washed away by the drilling fluid. The Water Resources Bureau scientists began to sample the cores, taking 1-ft half-round samples for pore-water studies.

On 23 June, the slide base support cracked and required welding by a private contractor. Smooth coring resumed, ending for the day at 648 ft. The relatively consistent lithology allowed for very good recovery. The only mishap occurred at 618–628 ft when the core was accidentally pushed out of the inner core barrel before the receiving trays were in place. The position and orientation of the pieces from this core are uncertain.

Drilling was smooth and fast on 24 June between 648 and 738 ft. Recovery was generally above 90% except during two short runs (0.5 ft between 678 and 679 ft and 4.4 ft between 679 and 688 ft). Water Resources Bureau personnel added fluorescent plastic microspheres to the drilling fluid at the beginning of the day to determine the extent of contamination of the cores by the drilling fluid.

Coring slowed with poor recovery on 25 June while drilling through sands; 15.9 ft of core was recovered from 31 ft of drilling. The inner core barrel became blocked while drilling the interval from 758 to 768 ft. Flushing the hole with heavy drilling mud cleared the blockage. On 26 June, 49 ft of fine sand with clay plugs was drilled with 71% recovery.

Drilling was delayed on 27 June by morning thundershowers. Part of the first run (808-818 ft) was heavily contaminated with cavings from higher in the hole. This dubious section was labeled and boxed, but not photographed. Laminated, stiff, dry, dark clay was recovered between 818 and 828 ft with 68% recovery. The Water Resources Bureau personnel completed their sampling of the confining units.

On 28 June, coring began at noon because of mechanical problems. While bringing up the second core of the day, the major mud feed line burst and the core slipped out of the barrel; it was subsequently retrieved. The rest of the day was spent replacing all hoses. The drillers removed 200 ft of rod from the hole to ensure that it would not be caught in the hole. As a result, the first core did not come out of the ground until 1100 hr on 29 June. Coring went well the rest of the day.

On 30 June, shell beds and glauconite to medium- to coarse-grained glauconitic quartz sands were recovered between 900 and 937 ft. Very large and thick oyster shells were found between 911 and 914 ft, 908 and 911 ft, and 922 and 923 ft. Between 923 and 933 ft, the cores either slipped or washed out of the barrel with no recovery. Recovery improved by changing to the long shoe (4 ft drilled with 2.5 ft of recovery).

On 1 July, 4.6 ft of coarse glauconitic quartz sands were recovered between 937 and 944 ft. The rest of the day was spent pulling rods and putting heavy mud in the hole to prevent collapse over the long weekend. Drilling was suspended from 2 to 6 July.

On 8 July, the drillers began running two shifts each day (400–1300 hr and 1200–2100 hr). The first shift drilled from 944 to 948 ft and the inner barrel became blocked. Two rods, at 60 and 480 ft, were crimped and had to be replaced. Drilling resumed in the afternoon. Recovery was generally poor in medium to coarse, clayey glauconite sands. Coring ended at 1001 ft.

On 9 July, the drill rods snapped in the hole and could not be retrieved until 11 July. All rods were pulled from the hole. The rods were being pinched in the hole by expanding clays above the "800-foot Sand." Rather than case the hole, the decision was made to ream the hole with a 3⅞-in. bit. During removal, several of the rods were deformed and had to be beaten back to round before they could be used again. On 16 July, the rods were extended to 1000 ft; a crimped rod at 150 ft had to be removed. While putting the rods in the hole the interval, from 1001 to 1013 ft was inadvertently washed away. On 17 July, the rods became stuck again as a result of swelling clays. The rods were freed and pulled out to 653 ft. To prevent the rods from sticking in the hole, the drillers began a 24 hr/day schedule starting July 19 with daylight coring; at night the rods were turned. On 19 July, four runs were made between 1013 and 1030 ft with no recovery and no signs that any material was getting into the core barrel.

There was no way to measure the amount of cable to determine if the inner core barrel was reaching the outer core barrel. On 20 July, the drillers painted a stripe on the wire line where they thought the inner core barrel was locking in place. They then retrieved the inner barrel and dropped the overshot to see if it went further into the hole than the inner core barrel. They found a 2- to 3-ft difference between core barrel and overshot. Because this was less than the 13 ft length of the outer core barrel they decided to try a core run. This came up empty with no evidence that core was entering the barrel. They then shortened the core barrel to see if that would lock it in place, but the next core run had no recovery. The rods were pulled. A crimped core barrel was found at around 800 ft. While pulling out the rods, they discovered that they were at 1055 ft and not at 1045 ft as previously thought; the outer core barrel was plugged with sediment from this interval. Rods were dropped in preparation for more drilling and 5.1 ft was recovered from a 6-ft run that night.

From 21 to 23 July, drilling went very smoothly with excellent recovery (88%) of glauconitic sands and silts at the top and silts and clays between 1059 and 1316 ft. On two occasions on 22 July, the core slipped out of the catcher and was later recovered. The run from 1150 to 1160 ft recovered 5 ft and the run from 1160 to 1170 ft recovered 2 ft. The drillers next ran a 0.3-ft run and recovered 9.6 ft of core. A break in this core occurs at 2.2 ft. It was assumed that this 2.2 ft plus the previous 5 and 2 ft sections of core are from the 1150- to 1160-ft run and the lower 7.4 ft is from the interval 1160–1170.3 ft.

On 24 July, we encountered several problems with the drill rig: the quill rod broke, the water swivel broke, and the rod clamp began to slip and could not be repaired. Coring ended at 1362.5 ft.

On 25 July, we returned to smooth coring with 85% recovery in the interval from 1362.5 to 1430 ft. Occasionally, the core would slip out of the barrel and fall back down the hole delaying the drilling operation; the integrity of the cores was maintained. No major problems with the rig or with core recovery were encountered.

Coring continued on 26 July to 1452 ft. Miller returned to the drill site from Leg 150. After the second 10-ft run on 26 July, the rod clamp failed and the entire drill string fell about 8 ft, jamming the drill string in the bottom of the hole. We attempted to free the rods but could not.

On 27 July, Dennis Talbot of BPB instruments obtained a gamma-ray log through the drill pipe for the entire hole (0–1452 ft). Approximately 2.3 ft was recovered. Drillers worked all day trying to free the lodged drill string by keeping high downpressures (1000 lb) and working the string up and down. By 1700 hr, the string had moved less than 6 in.

On 28 July, two 20-ton jacks were brought in to help free the drill string. The force of the jacks resulted in the parting of the drill string at 70 ft, leaving 1380 ft in the hole. Queen and Heibel returned to Reston to obtain 1000 ft of heavier rods. The BPB logger was released. Further attempts to free the drill string on 4 August were fruitless. On 5 August, the site was cleaned up and all remaining cores were moved to Rutgers, Piscataway. Plans are to return to the site with an outside contractor to extricate the rods.

We recovered 977 ft in 183 coring runs from a hole with a total depth of 1452 ft below land surface (mean recovery, 67%; median recovery, 80%; Figs. 1–4). Mean recovery for the borehole not including the interval from 292 to 390 ft, which was intentionally washed, was 72%. Cores were photographed on site in color using Tungsten lighting and 160T film. Lithologies were described on site and subsequently in August and September 1993 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 388 ft; 2-in. diameter below), and stored in 2-ft wax boxes. One hundred and thirty-eight 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.

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 and Figs. 1–5). Subsequent studies integrated preliminary descriptions with additional descriptions, biostratigraphy, biofacies studies, isotopic stratigraphy, and geophysical well logs. For the non-marine and nearshore sections (primarily the Miocene and younger section), lithofacies and log interpretations provide the primary means of recognizing unconformities and interpreting paleo-

Table 1. Core description, Atlantic City borehole, Leg 150X.

Core	Interval (ft)	Recovery (%)	Description	Color	Formation
1	6–11	0.2 ft (4%)	Soft mud, with gravel up to 3 cm.	5Y 2.5/2, black	Recent fill
2	11–16	3.5 ft (70%)	Soft mud above 12 ft; below with pebbles of up to 2.5 cm, grading down to medium-fine quartz sand with shell fragments; the section above 12 ft is fill.	5Y 4/1, dark gray	
3	16–21	3.6 ft (72%)	Muddy fine quartz sand, many heavy minerals, H_2S odor.	5Y 4/1, dark gray	Cape May Formation
4	21–26	2.2 ft (44%)	Muddy fine quartz sand, many heavy minerals, H_2S odor.	5Y 4/1, dark gray	
5	26–31	3.9 ft (78%)	Muddy fine sand and black sandy clay, H_2S odor.	5Y 3/1–5Y 2.5/1, very dark gray	
6	31–36	3.0 ft (60%)	Muddy fine sand and sandy clay, H_2S odor, shell fragments.	5Y 3/1, very dark gray	
7	36–41	0.3 ft (6%)	Sandy clay, weaker H_2S odor.	5Y 3/1, very dark gray	
8	41–46	3.0 ft (60%)	Sandy clay and firm clay, weak H_2S odor.	5Y 3/1, very dark gray	
9	46–51	5.0 ft (100%)	Homogeneous clay with little sand.	2.5Y 3/1, very dark gray	
10	51–56	1.4 ft (28%)	Clay at top with sand and gravel below.	5Y 3/1, very dark gray	
11	56–61	1.2 ft (24%)	Coarse–very coarse pebbly quartz sand with shell fragments.	5Y 5/1, gray	
12	61–66	1.6 ft (32%)	Gravels and quartz sand, poorly sorted.	5Y 6/1, gray	
13	66–71	1.2 ft (24%)	Well-sorted, rounded quartz sand and gravels up to 1.3 cm	5Y 6/1, gray	
14	71–76	1.3 ft (26%)	Coarse-grained pebbly sand, pebbles up to 5 mm.	5Y 6/1, gray	
15	76–81	1.8 ft (36%)	Well-rounded pebbly quartz sand and gravel above 77 ft and medium-coarse quartz sand below 77 ft.	5Y 6/1, gray	
16	81–86	3.0 ft (60%)	Pebbly coarse and fine to medium sand.	5Y 6/1, gray	
17	86–88.5	1.5 ft (60%)	Pebbly fine sand.	5Y 6/1, gray	
18	88.5–91	1.0 ft (40%)	Fine-medium sand.	2.5Y 6/4, light yellowish brown	
19	91–95	2.5 ft (63%)	Medium to fine sand with gravels.	2.5Y 6/2, light brownish gray	
20	95–99	0.2 ft (5%)	Gravel and coarse sand.	5Y 6/2, light olive gray	
21	99–101	2.0 ft (100%)	Subrounded gravels, little sand.	2.5Y 6/1, gray	
22	101–105.5	2.4 ft (54%)	Medium-coarse sand with rounded gravels.	2.5Y 6/2, light brownish gray	
23	105.5–111	0.1 ft (1.9%)	Gravel.	2.5Y 6/2, light brownish gray	
24	111–116	2.8 ft (56%)	Pebbly coarse sand, medium sand below 113 ft.	10YR 7/3, very pale brown	
25	116–119.5	2.7 ft (77%)	Medium sand with pebbles.	10YR 7/3, very pale brown	
26	119.5–126	3.1 ft (57%)	Clayey medium-fine sand.	5Y 6/1, gray	
27	126–131	2.3 ft (46%)	Gravels overlying sandy clay.	5Y 6/1, gray	
28	131–135	3.7 ft (74%)	Sandy silty clay with gravel clasts.	5Y 6/1, gray	
			-------------Lithologic contact 135 ft (below is the Cohansey Formation)-------------		
29	135–141	4.0 ft (67%)	Uniform medium-fine sand.	10YR 7/6, yellow	Cohansey Formation
30	141–151	5.0 ft (50%)	Gray sandy clay.	5YR 7/1, light gray	
31	151–153	1.2 ft (60%)	Sandy clay.	10YR 7/6, yellow, to 5YR 7/1, light gray	
32	153–161	1.5 ft (19%)	Clayey sand with pebbles.	10YR 7/6, yellow	
33	161–171	10.0 ft (100%)	Uniform medium sand.	2.5Y 7/2, light gray	
34	171–181	10.0 ft (100%)	Uniform medium sand.	10YR 7/2–10YR 7/6, very pale brown	
35	181–191	9.0 ft (90%)	Medium-coarse quartz sand with subrounded pebbles.	10YR 7/2–10YR 7/6,very pale brown.	
36	191–199.5	3.2 ft (33%)	Sandy clay and fine-medium sand.	5Y 7/1–10YR 7/2, light gray	
37	199.5–200.5	1.6 ft (160%)	Medium sand, well sorted and uniform.	10YR 6/4, light yellowish brown	
38	200.5–211	1.0 ft (9.5%)	Pebbles and clay overlying medium sand.	10YR 6/4, light yellowish brown	
39	211–221	7.2 ft (70%)	Pebbly medium sand with increasing clay downward. Color change at 215 ft.	10YR 6/4, light yellowish brown	
40	221–231	6.3 ft (63%)	Sandy clay.	5Y 5/1, gray	?Cohansey Formation
			-------------Lithologic contact 231.4 ft (below is the Kirkwood Formation)-------------		
41	231–241	8.9 ft (89%)	Laminated dark sandy clay and fine sand.	5GY 6/1, greenish gray	Kirkwood Formation
42	241–246	3.4 ft (68%)	Interbedded gray sand and sandy clay.	5Y 4/1, dark gray	
43	246–247	1.8 ft (180%)	Interbedded gray sand and sandy clay.	5Y 5/1, gray	
44	247–251	1.7 ft (42.5%)	Coarse sand grading downward to fine sand.	5Y 5/1, gray	
45	251–261	2.3 ft (23%)	Medium-coarse pebbly sands.	5Y 5/1, gray	
46	261–271	6.2 ft (62%)	Medium-coarse pebbly sands with lignite layer.	5Y 5/1–5Y 4/1, gray	
47	271–281	7.7 ft (77%)	Coarse to very coarse massive sand, with peat.	5YR 3/1, very dark gray	
48	281–283	1.6 ft (80%)	Medium-coarse sand.	5Y 4/1, dark gray	
49	283–291	1.0 ft (12.5%)	Medium to coarse sand with minor amount of clay.	5Y 4/1, dark gray	
50	291–293	1.7 ft (85%)	Medium sand, clayey sand with lignite.	5Y 4/1, dark gray	
			From 293 to 390 ft not recovered.		
51	390–392	1.0 ft (50%)	Interbedded green fine sand and silt.	5Y 4/1–5Y 3/1, dark gray	
52	392–398	4.7 ft (78.3%)	Laminated greenish fine sand and silt.	5Y 4/1, dark gray	
53	398–401	2.0 ft (66%)	Laminated greenish fine sand and silt.	5Y 4/1, dark gray	
54	401–408	7.4 ft (106%)	Dark green silty sand with abundant shells and lignite.	5G 4/1, dark greenish gray	
			-------------Lithologic contact 408 ft (below is the upper confining unit)-------------		
55	408–418	9.0 ft (90%)	Laminated silty clay with shells.	5G 4/1, dark greenish gray	
56	418–428	10.0 ft (100%)	Laminated silty clay with shells.	5G 4/1, dark greenish gray	
57	428–438	9.6 ft (96%)	Laminated silty clay with shells	5G 4/1, dark greenish gray	
58	438–448	9.9 ft (99%)	Burrowed silty clay.	5G 4/1, dark greenish gray	
59	448–458	10.0 ft (100%)	Mottled and laminated silty clay.	5G 4/1, dark greenish gray	
60	458–468	9.55 ft (95.5%)	Bioturbated clay with shell fragments with pebbly sand between 464.5 and 465.5 ft.	5Y 4/1–5Y 5/1, dark gray	
61	468–478	8.8 ft (88%)	Bioturbated and uniform clay, becomes siltier below 475 ft.	5Y 4/1, dark gray	
62	478–488	6.6 ft (66%)	Silty clay, rich with shell fragments.	5Y 4/1, dark gray	
63	488–498	10.3 ft (103%)	Heavily bioturbated clayey silt above and silty clay below.	5Y 4/1, dark gray	
64	498–508	9.8 ft (98%)	Interbedded clayey silt and silty clay, rich in shells.	5Y 4/1, dark gray	
65	508–518	3.2 ft (32%)	Massive silty clay with silt layers, shells visible.	5Y 3/1, very dark gray	
			-------------Lithologic contact 512 ft (below is the Rio Grande aquifer)-------------		
66	518–523	3.2 ft (3.2%)	Poorly sorted medium-coarse sand, sandy clay and silty clay below 519.4 ft.	5Y 5/1–5Y 4/1, gray to dark gray	
67	523–528	4.0 ft (80%)	Above 524.25 ft: dark greenish gray micaceous silty clay; below 524.25 ft: dark gray laminated silty clay.	5G Y4/1, dark greenish gray 5Y 3/1, dark gray	
68	528–538	4.2 ft (42%)	Laminated clay with interbedded micaceous clay.	5Y 3/1, very dark gray	

Table 1. (continued)

Core	Interval (ft)	Recovery (%)	Description	Color	Formation
69	538–548	3.0 ft (30%)	Interbedded, laminated clay and silt, coarsening to fine sand below 538.7 ft.	5Y 4/1, dark gray	Kirkwood Formation
			-------------Lithologic contact 538.7 ft (below is the lower confining unit)-------------		
70	548–558	10.5 ft (105%)	Uniform, laminated fine sand and silt.	5Y 4/1, dark gray	
71	558–568	10.1 ft (101%)	Very fine sand and silty clay with shell bed.	5Y 4/1, dark gray	
72	568–578	10.3 ft (103%)	Greenish silty clay with interbedded fine sand.	5Y 3/1, very dark gray	
73	578–588	9.7 ft (97%)	Greenish silty clay with interbedded fine sand with shells.	5Y 3/1, very dark gray	
74	588–598	10.6 ft (106%)	Laminated clay, silt and very fine sand.	5Y 4/1, dark gray	
75	598–608	10 ft (100%)	Laminated clay, silt and very fine sand.	5Y 4/1, dark gray	
76	608–618	10.6 ft (106%)	Laminated clay, silt and interbedded fine sand, micaceous.	5Y 4/1, dark gray	
77	618–628	10.0 ft (100%)	Laminated clay, silt and fine sand, micaceous.	5Y 4/1, dark gray	
78	628–638	10.5 ft (105%)	Laminated clay, silt and fine sand, micaceous.	5Y 4/1, dark gray	
79	638–648	10.3 ft (103%)	Laminated clay, silt and fine sand, micaceous, with shells at 644 ft.	5Y 4/1, dark gray	
80	648–658	9.35 ft (93.5%)	Laminated silty clay, silt and fine sand, micaceous.	5Y 4/1, dark gray	
81	658–668	10.5 ft (105%)	Laminated clay, silt and fine sand, micaceous.	5Y 4/1, dark gray	
			-------------Lithologic contact 666 ft (below is the upper sand aquifer)-------------		
82	668–678	9.7 ft (97%)	Fine sand in upper 1.1 ft; pebbly coarse sand, decrease in grain size to medium clean quartz sand, fine sand, silt, and silty clay from 669.1 to 677.7 ft, with lignite.	5Y 3/2, dark olive gray	
83	678–679	0.5 ft (50%)	Clayey pebbly coarse sand.	5Y 2.5/2, black	
84	679–688	4.4 ft (48%)	Fine-medium quartz sand interbedded with silty clay and clayey silt, clayey sand, micaceous.	5Y 5/1–5Y 6/1, gray	
85	688–696	9.0 ft (112.5%)	Clayey fine sand and silt with lignite at 689 ft.	5Y 3/1, very dark gray	
86	696–706.5	10.5 ft (100%)	Laminated and bioturbated fine sand, silt and silty clay.	5Y 3/1, very dark gray	
87	706.5–717	9.6 ft (91%)	Clayey fine-medium sand above 707.5 ft; from 707.5 to 716.1 ft; pebbly coarse sand in upper 1.4 ft, and change to clayey fine-medium sand below.	5Y 4/1, dark gray	
88	717–728	8.5 ft (77%)	Homogeneous sandy clay, a shell hash.	5Y 4/1, dark gray	
89	728–738	8.3 ft (83%)	Homogenous clayey medium sand with shell fragments above 733.3 ft.	5Y 4/1, dark gray	
			-------------Lithologic contact 733.3 ft (below is confining unit)-------------		
			Below 733.3 ft, laminated silty clay with medium sand and shells, micaceous.	5Y 4/1, dark gray	
90	738–741	1.9 ft (63.3%)	Firm silty clay and clayey medium sand.	5Y 4/1, dark gray	
			-------------Lithologic contact 738.8 ft (below is the lower sand aquifer)-------------		
91	741–748	5.2 ft (74.3%)	Homogeneous medium, clean quartz sand to coarse quartz sand, with organic rich layer.	N 6/0, gray	
92	748–752	1.85 ft (46.3%)	Homogeneous coarse sand.	N 6/0, gray	
93	752–758	5.6 ft (93.3%)	Pebbly quartz sand, pebbles up to 4 mm, subangular.	N 6/0, gray	
94	758–768	0.4 ft (4%)	Homogeneous coarse quartz sand.	5Y 6/1, gray	
95	768–769	0.9 ft (90%)	Homogeneous coarse quartz sand, subrounded.	5Y 6/1, gray	
96	769–778	9.0 ft (100%)	Laminated fine quartz sand.	N 6/0, gray	
97	778–788	4.0 ft (40%)	Interbedded fine sand and clay.	5Y 4/1, dark gray	
98	788–790	1.9 ft (95%)	Fine-medium sand, occasionally clayey.	5Y 4/1, dark gray	
99	790–798	7.8 ft (97.5%)	Laminated fine-medium sand.	5Y 4/1, dark gray	
100	798–808	4.5 ft (45%)	Laminated fine-medium sand.	5Y 4/1, dark gray	
			-------------Lithologic contact 808 ft (below is the composite confining unit)-------------		
101	808–818	7.8 ft (78%)	Thinly laminated clay with shell bed.	5Y 2.5/1, black	
102	818–828	6.8 ft (68%)	Stiff clay with shells.	5Y 4/1, dark gray	
103	828–838	9.3 ft (93%)	Laminated stiff clay with shells.	5Y 4/1, dark gray	
104	838–848	9.0 ft (90%)	Laminated stiff clay and fine sand with shells.	5Y 4/1, dark gray	
105	848–858	8.7 ft (87%)	Nearly pure clay at top, silt clay and silt with shells in middle.	5Y 4/1, dark gray	
106	858–868	9.2 ft (92%)	Silty clay, clayey sand with shells, burrowed.	5Y 4/1, dark gray	
107	868–878	10.1 ft (101%)	Silty clay, clayey sand with shells, burrowed; from 875.4 to 878.0 ft: silver gray clay with some glauconite sand.	5Y 2.5/1, black 5Y 5/2, olive gray	
108	878–888	7.7 ft (77%)	Micaceous silty clay, glauconite sand in clay matrix with shells.	5Y 5/2, olive gray	
			-------------Lithologic contact 880.8 ft (below is the pre-Kirkwood aquifer unit)-------------		
109	888–898	0.0 ft (0%)	No recovery.		
110	898–900	0.5 ft (25%)	Stiff glauconite sand.	5G 4/2, grayish green.	
111	900–901	0.9 ft (90%)	Bioturbated medium glauconite sand.	5G 4/2, grayish green.	
112	901–908	1.3 ft (19%)	Medium glauconite sand with weathered shells at bottom.	5G 4/2, grayish green.	
113	908–918	9.6 ft (96%)	Coarse glauconite sand with large weathered shells, shell bed with fresh oyster shells in 911.3–914.2 ft, microfossils visible.	5BG 4/1, dark greenish gray	
114	918–923	5.6 ft (112%)	Bioturbated homogenous medium glauconite sand, very fossiliferous, shell bed in 922.4 ft to bottom.	5Y 3/2–5Y 2.5/2, dark olive gray	
115	923–928	0.0 ft (0%)	No recovery.		
116	928–933	0.2 ft (4%)	Hard coarse sand (20% glauconite, 80% quartz).	5Y 3/2, dark olive gray	
117	933–937	2.4 ft (62.5%)	Hard coarse sand with weathered shells.	5Y 4/1, dark gray	
			-------------Lithologic contact 937.0 ft (below isunnamed quartz and glauconite sands)-------------		
118	937–938	0.9 ft (90%)	Coarse glauconitic quartz sands.	5Y 4/1, dark gray	Unnamed; Oligocene
119	938–944	3.7 ft (61%)	Coarse glauconitic quartz sands.	5Y 4/1, dark gray	
120	944–948	0.0 ft (0%),	No recovery.		
121	948–958	1.5 ft (15%)	Coarse clayey quartz sand with shells.	5Y 4/2, olive gray	
122	958–968	0.2 ft (2%)	Coarse clayey quartz sand with shells.	5Y 4/2, olive gray	
123	968–978	9.1 ft (91%)	Uniform coarse-medium glauconitic quartz sand, with some clay and shell fragments.	5Y 4/2, olive gray	
124	978–988	2.1 ft (21%)	Same as above.		
125	988–998	1.1 ft (11%)	Uniform coarse-medium grained glauconitic quartz sand, with some clay and shell fragments.	5Y 4/2, olive gray	

Table 1. (continued)

Core	Interval (ft)	Recovery (%)	Description	Color	Formation
126	998–1000	2.0 ft (100%)	Uniform coarse-medium grained glauconitic quartz sand, with some clay and shell fragments.	5Y 4/2, olive gray	
127	1000–1001	1.0 ft (100%)	Same as above.		
128–132	1001–1045	0.0 ft (0%)	No recovery.		
			-------------Lithologic contact (perhaps between 1024 and 1045 ft)-------------		
133	1045–1055	4.75 ft (95%)	Quartz pebbles at top 3 ft and silty clay below, micaceous.	5G 4/1, dark gray	Unnamed; Oligocene
134	1053–1059	5.1 ft (85%)	Clayey glauconite sand with shells throughout.	5GY 4/1, dark gray	
135	1059–1069	3.2 ft (32%)	Bioturbated clayey glauconite sand with shells.	5GY 4/1, dark gray	
136	1069–1074	6.5 ft (130%)	Clayey medium glauconite sand with silty clay below 1072 ft.	5GY 4/1, dark gray	
137	1074–1079	4.1 ft (82%)	Glauconitic silty clay, micaceous and with shells.	5GY 4/1, dark gray	
138	1079–1085	6.85 ft (112%)	Burrowed clayey glauconite sand with thin shells.	5Y 3/2, dark olive gray	
139	1085–1089	3.0 ft (75%)	Burrowed clayey glauconite sand with thin shells.	5Y 3/2, dark olive gray	
140	1089–1099	6.8 ft (68%)	Silty glauconitic sand with clay and shells.	5Y 3/1, very dark gray	
141	1099–1110	10.0 ft (91%)	Burrowed clayey glauconitic silt, micaceous, with abundant shells and foraminifers.	5Y 4/1, dark gray	
142	1110–1120	10.2 ft (102%)	From 1110.0 to 1111.2 ft: same as above; from 1111.2 to 1120.0 ft: burrowed and laminated silty glauconitic clay.	5Y 4/1, dark gray	
143	1120–1130	10.4 ft (104%)	Laminated silty clay with silty glauconite fine sand, shell,	5Y 4/1, dark gray	
144	1130–1140	9.0 ft (90%)	Glauconite fine sand in upper 2.2 ft, silty clay below, shells.	5Y 4/1, dark gray	
145	1140–1146	5.2 ft (87%)	Laminated and burrowed clayey medium-fine glauconite sand.	5Y 4/1, dark gray	
146	1146–1150	3.7 ft (92.5%)	Laminated and burrowed clayey medium-fine glauconite sand.	5Y 4/1, dark gray	
147	1150–1160	9.2 ft (92%)	Laminated and burrowed clayey medium-fine glauconite sand.	5Y 4/1, dark gray	
148	1160–1170.3	7.8 ft (76%)	Laminated and burrowed clayey medium-fine glauconite sand.	5Y 4/1, dark gray	
149	1170.3–1176	2.8 ft (49%)	Laminated and burrowed clayey medium-fine glauconite sand;	5Y 4/1, dark gray	
150	1176–1186	8.7 ft (87%)	From 1176.0 to 1178.3 ft: same as above; from 1178.3 to 1181.2 ft: heavily burrowed firm, clayey glauconitic fine sand-silt, with shell bed at basal 1 ft.	5Y 4/1, dark gray	
			-------------Lithologic contact 1181.2 ft (below is the unnamed upper Eocene)-------------		
			From 1181.2 to 1184.7 ft: laminated silty clay with microfossils.	5Y 4/1, dark gray	Unnamed; upper Eocene
151	1186–1196	4.3 ft (43%)	Laminated firm clay with microfossils and pyrite.	5Y 4/1, dark gray	
152	1196–1206	10.0 ft (100%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 4/1, dark gray	
153	1206–1216	10.4 ft (104%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/1, very dark gray	
154	1216–1226	10.0 ft (100%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
155	1226–1236	10.0 ft (100%)	Same as above; could not remove core from rod.	5Y 3/2, dark olive gray	
156	1236–1246	10.0 ft (100%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
157	1246–1256	10.6 ft (106%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
158	1256–1271	15.5 ft (103%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
159	1271–1276	5.0 ft (100%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
160	1276–1286	10.3 ft (103%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
161	1286–1292	5.0 ft (83%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
162	1292–1294	1.6 ft (80%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
163	1294–1304	9.5 ft (95%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
164	1304–1310	6.0 ft (100%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
165	1310–1316	6.2 ft (103%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
166	1316–1326	9.0 ft (90%)	Burrowed, laminated silty clay with microfossils and pyrite.	5Y 3/2, dark olive gray	
			-------------Lithologic contact 1325 ft. (below is the upper Shark River Formation)-------------		
167	1326–1336	7.5 ft (75%)	Laminated glauconitic silty clay with shells throughout.	5Y 3/2, dark olive gray	Upper Shark River Formation
168	1336–1342	2.0 ft (33%)	Bioturbated silty clay with microfossils.	5GY 4/1, dark gray	
169	1342–1346	4.0 ft (100%)	Bioturbated glauconite silty clay with shells throughout.	5GY 4/1, dark gray	
170	1346–1356	9.9 ft (99%)	Bioturbated glauconite silty clay with shells throughout.	5GY 4/1, dark gray	
171	1356–1362.5	6.5 ft (65%)	Bioturbated, laminated silty clay with microfossils.	5GY 4/1, dark gray	
172	1362.5–1370	4.5 ft. (60%)	Bioturbated, laminated glauconite silty clay with microfossils.	5GY 4/1, dark gray	
173	1370–1378	7.5 ft (94%)	Bioturbated, laminated glauconite silty clay with microfossils.	5GY 4/1, dark gray	
174	1378–1383	2.0 ft (40%)	Bioturbated, laminated glauconite silty clay with microfossils.	5GY 4/1, dark gray	
175	1383–1390	5.3 ft (76%)	Bioturbated, laminated glauconite silty clay with microfossils.	5GY 4/1, dark gray	
176	1390–1400	10.0 ft (100%)	Bioturbated, laminated glauconite silty clay with microfossils.	5GY 4/1, dark gray	
177	1400–1410	9.5 ft (95%)	Bioturbated, laminated glauconite silty clay with microfossils.	5GY 4/1, dark gray	
178	1410–1420	10.0 ft (100%)	Bioturbated, laminated glauconite silty clay with microfossils.	5GY 4/1, dark gray	
179	1420–1430	5.5 ft (55%)	Bioturbated, laminated glauconite silty clay with microfossils.	5GY 4/1, dark gray	
180	1430–1440	10.0 ft (100%)	Upper 1.1 ft: glauconitic silty calcareous clay with foraminifers; below 1431.1 ft: fossiliferous silty chalk	5GY 5/1, greenish gray 5GY 7/1, light greenish gray	
			-------------Lithologic contact 1431 ft (below is the lower Shark River Formation)-------------		
181	1440–1450	7.3 ft (73%)	Light gray fossiliferous silty chalk.	5GY 7/1, light gray	Lower Shark River Formation
182	1450–1452	2.0 ft (100%)	Light gray fossiliferous silty chalk.	5GY 7/1, light gray	

Note: Total depth = 1452 ft, mean recovery = 67%, median recovery = 80%.

environments. For the neritic sections (primarily the Paleogene), biostratigraphic and biofacies studies provide an additional means of recognizing unconformities and the primary means of interpreting paleoenvironments. Benthic foraminifer 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 Atlantic City borehole (Figs. 1–5).

The Cape May Formation

Age: late Pleistocene–Holocene
Thickness: 123 ft

The top of the borehole penetrated fill to 12 ft. The fill dates to construction of the base around 1942. Below this, the surficial units (12–135 ft) consist of unconsolidated sands, silts, clays, and gravels assigned to the Cape May Formation.

The Cape May Formation (Fig. 1) consists of clays near the top and gravels and sands below. Sandy clays grading down to clays

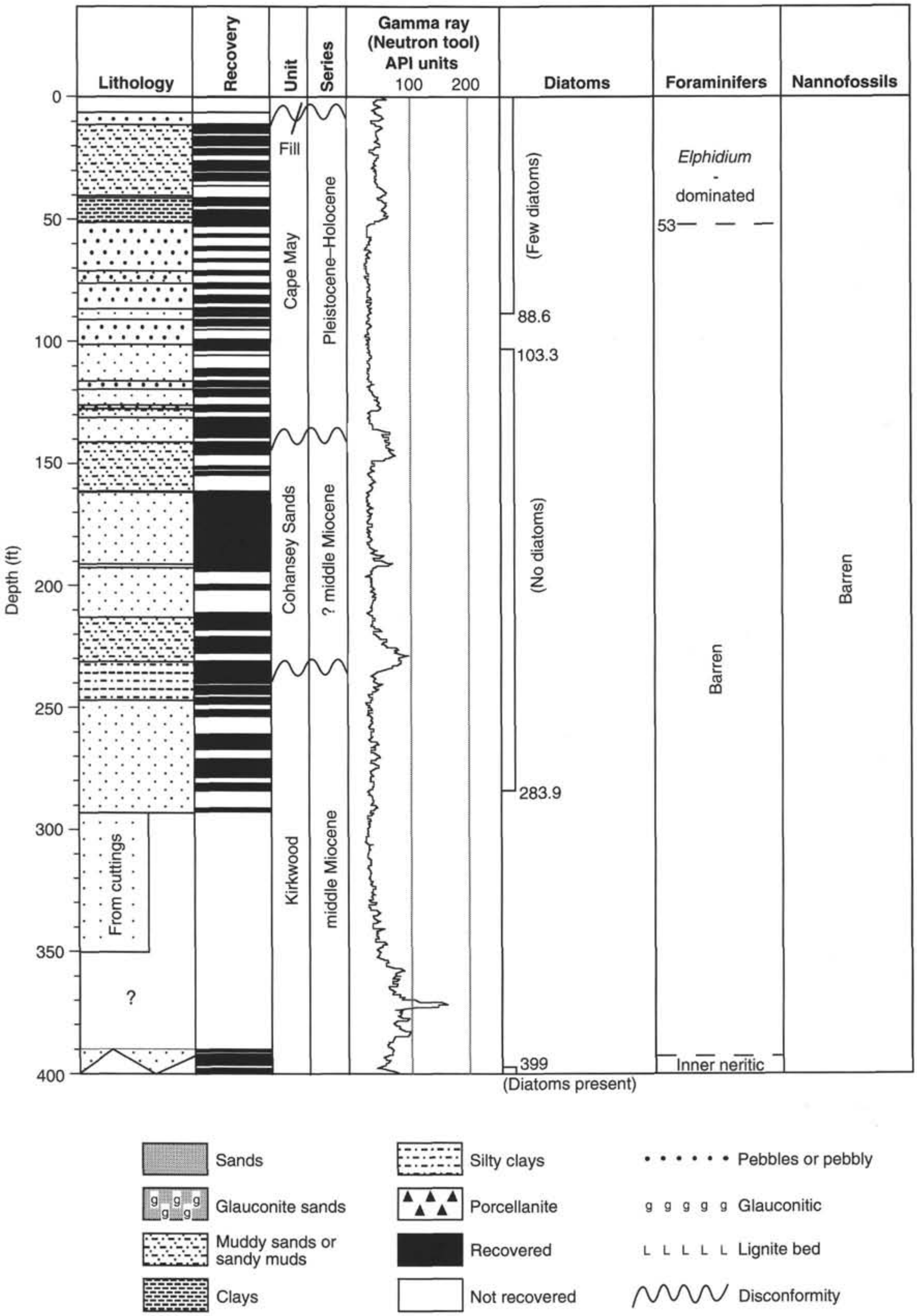

Figure 1. Cape May to upper Kirkwood Formations. Recovered intervals are shaded, unrecovered intervals are in white.

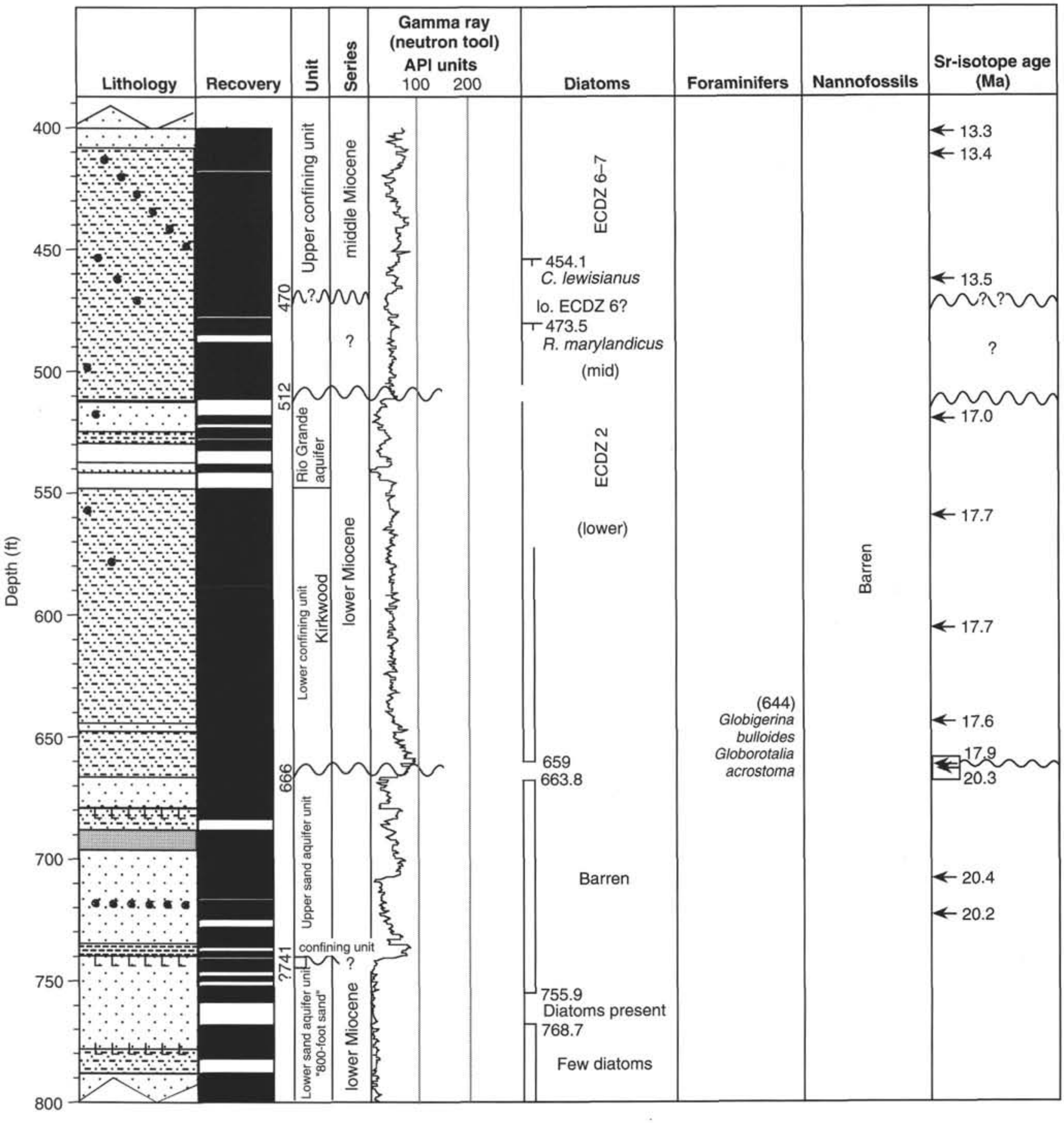

Figure 2. Portion of the Kirkwood Formation. Recovered intervals are shaded, unrecovered intervals are in white. Geohydrologic units are those of Mullikin et al. (in press).

occur from 18.3 to 52.5 ft. Sandy gravels occur below an interval of no recovery from 52.5 to 56.0 ft. Gravels, sandy gravels, and pebbly sands occur to 135 ft. "Pea gravels" with clasts over 3 cm were penetrated from 62.0 to 66.5 ft and from 76.0 to 76.8 ft. Other gravel layers were noted at 95–101, 126–127.2, and 135–137 ft. Another possible gravel layer was noted at 105.5 ft, although recovery was only 0.1 ft between 105.5 and 111.0 ft and these gravels may be caved.

The presence of pectenids and an *Elphidium*-dominated benthic foraminifer biofacies in the clays above 53 ft indicates a marine–marginal marine environment (lower estuarine, bay, or inner neritic). No shells or foraminifers were noted below ~56–57 ft. The environment of the gravels and sands below this is uncertain and they may be interpreted as nearshore or fluvial. In particular, the very coarse gravels between 62 and 66.5 ft and between 76 and 76.8 ft are similar to the coarse gravels noted near the base of the Cape May Formation at Island Beach, and these latter gravels were interpreted as possible fluvial channel deposits. Fluvial origin is supported by the poorly sorted nature of the gravels and the presence of subangular clasts. However, the presence of nearshore, marine diatoms (see "Biostratigraphy" section, this chapter) down to 88.6 ft indicates that these gravels may be nearshore. Near the base of the Cape May Formation, two to three upward-coarsening successions were noted in the cores

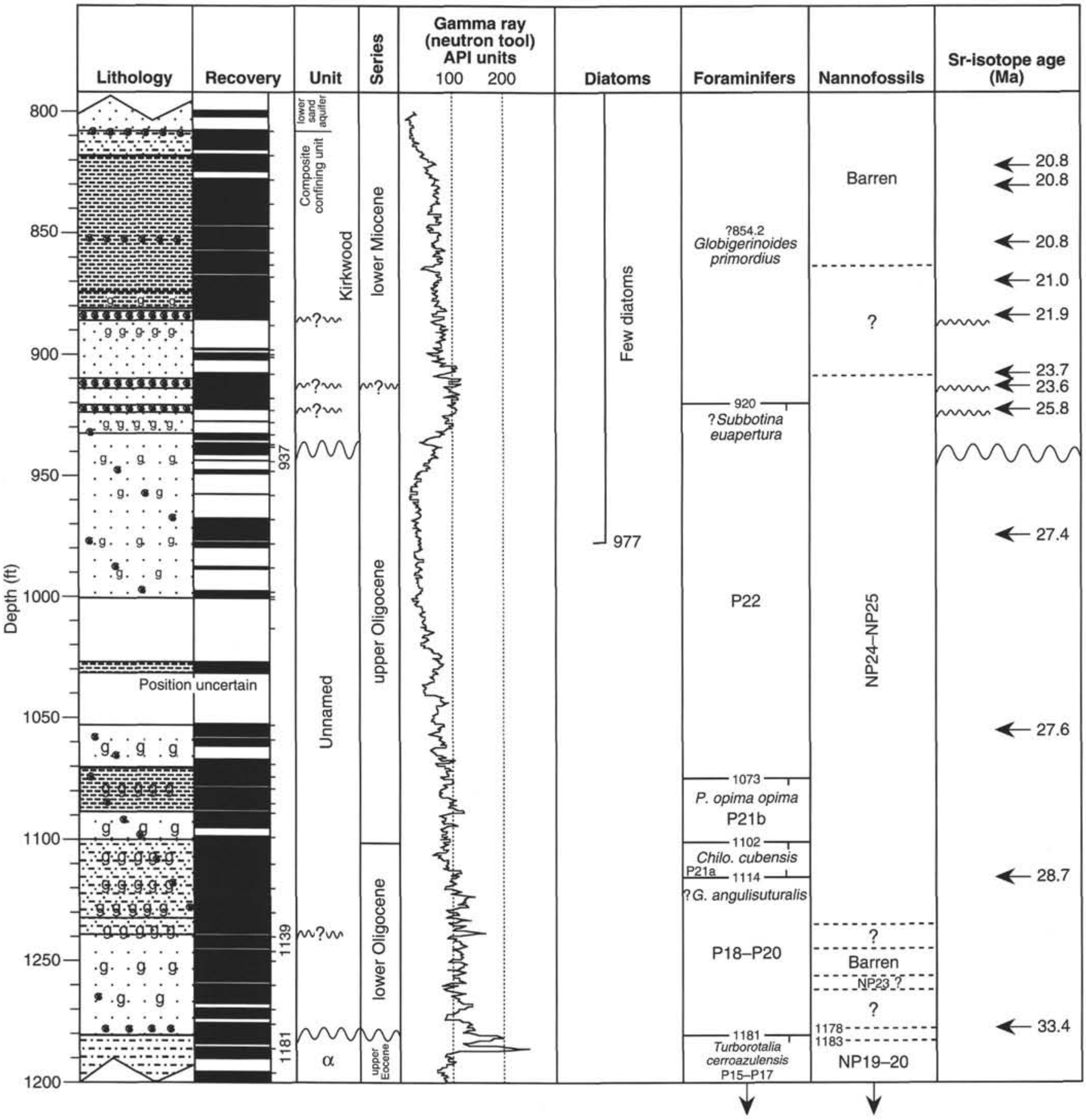

Figure 3. Portion of the lower Kirkwood Formation to unnamed upper Eocene unit.

and the gamma-ray log (139–130 and 130–119.5 ft, and possibly 118.7–116 ft). These are interpreted as point bar successions; their fluvial origin is supported by the absence of diatoms (Fig. 1).

Cohansey Formation

Age: ?middle Miocene
Thickness: 96 ft

We place the contact of the Cape May and Cohansey Formations at the top of uniform medium sands that begin at 135 ft (Fig. 1). This is consistent with the sharp gamma-ray kick associated with the clay layer at the top of the formation (136 ft uncorrected; note that this implies that log depths are 1 ft too deep relative to core depths). The sands are yellow-light gray alternating with light gray; they include some fine and coarser sand beds with occasional granules. Sandy clay layers occur at the top of the formation at 141.0–148.6 ft and at 191–192 ft as shown by distinct gamma-ray kicks. Suggestions of cross bedding are highlighted by iron staining; occasional clay interbeds were noted.

The age and environmental interpretations of the Cohansey Formation at Atlantic City are uncertain. A probable fluvial origin is indicated

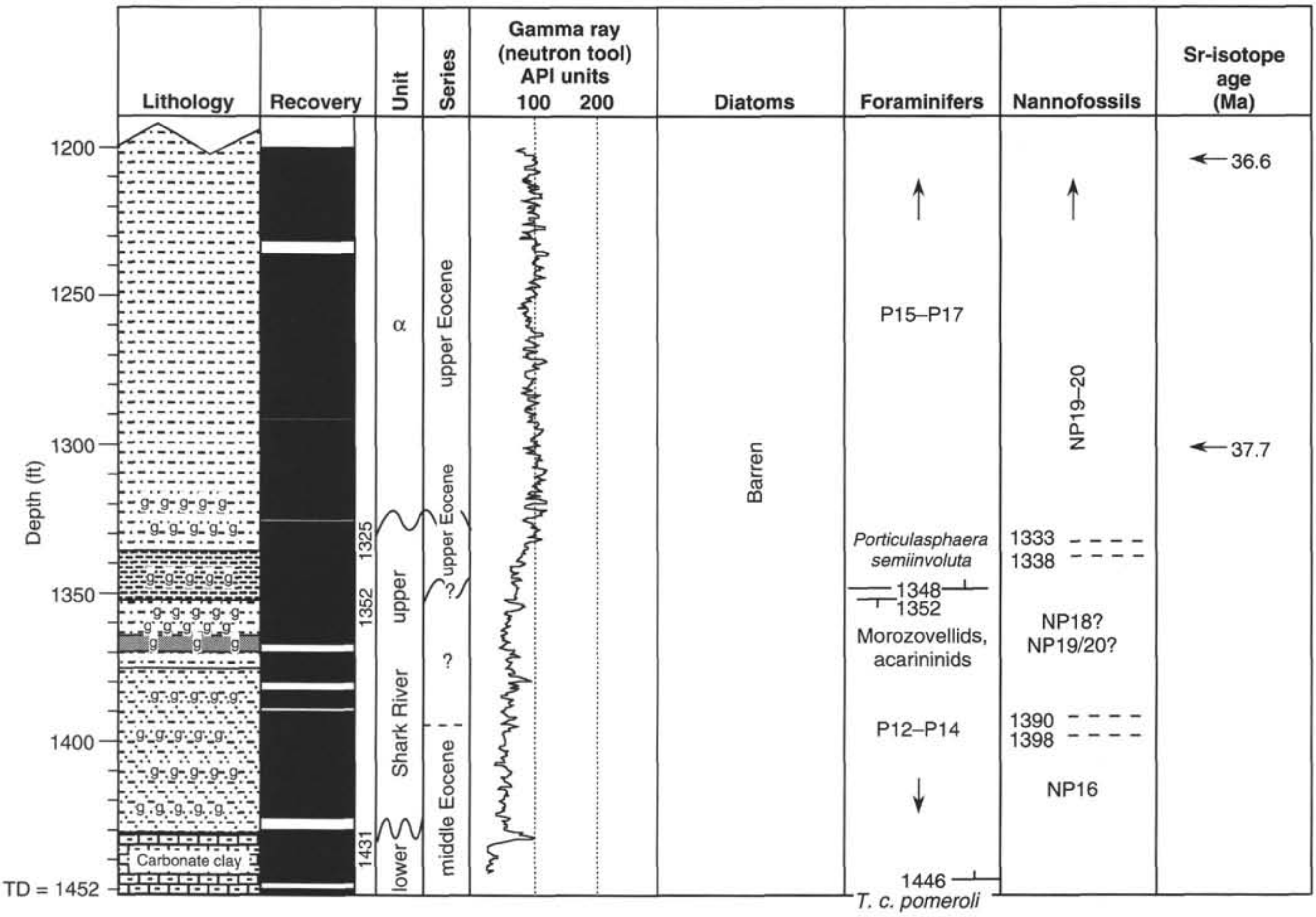

Figure 4. Portion of unnamed upper Eocene to Shark River Formation.

by absence of body fossils and bioturbation (vs. inner neritic), more heterogeneous grain sizes and poor sorting (vs. beach), and by lack of organic material (vs. delta, lagoon, or marsh). This interpretation is supported by the absence of diatoms and foraminifers from this section.

Kirkwood Formation

Age: middle Miocene to latest Oligocene
Thickness: 706 ft

The boundary between the ?middle Miocene Cohansey Formation with the middle to lower Miocene Kirkwood Formation is not certain. Definite Kirkwood silty clay with sand cross-laminations was first penetrated 231.4 ft, and this is where we place the boundary (Fig. 1). A lithologic contact is present at 215.6 ft, with yellow sands above and gray sands with increasing clays below; a gravel layer is associated with the color change. Clayey sand (217.9–218.2 ft) and sandy clay (222.6–224.0 ft) interbeds were noted in this interval, which is slightly micaceous. We tentatively place this section (215.6–231.4 ft) in the Cohansey Formation. A large increase in gamma radiation occurs between 220 and 232 ft in association with the contact between the formations (uncorrected depth; Fig. 1).

Gray clays with sandy cross laminations at the top of the Kirkwood Formation (231.4–237 ft) give way to medium-coarse gray quartz sands with thin (0.1–0.2 ft) clay interbeds that become micaceous below 247 ft (Fig. 1). Cross beds of organic-rich clay are quite prominent at 262–264 ft, and the sands are organic rich below this. A thick lignite/lignitic clay bed occurs at 291–292 ft.

We interpret the upper part of the Kirkwood Formation at Atlantic City as deltaic. The absence of foraminifers in these cross-bedded, organic-rich sands and clays suggests nonmarine conditions (e.g., delta front). The nonmarine origin is supported by the absence of diatoms (Fig. 1)

The section from 292 to 390 ft was not cored because of bad hole conditions (Fig. 1). Cuttings from this interval show that the interval is generally sand. The gamma-ray log shows an increase in baseline at 358 ft and peak values at 372 ft. The section cored below 390 ft is a silt and sand with shells; we interpret this an inner neritic (inner shelf) deposit. This is supported by the presence of marine diatoms and rare, low-diversity benthic foraminifers (*Nonionellina* and *Buliminella*). Thus, the contact between the deltaic and neritic deposits occurs in the uncored interval, probably at 372 ft at the gamma log peak.

From 390 to 519 ft, the section consists of firm, greenish gray slightly sandy clayey silts with occasional laminated sandy silt beds (Figs. 2 and 5). The top of the section is sandy (390–400 ft) (Fig. 5); by 408 ft, clays dominate. The clays are the upper confining unit of Zapecza (1989) (Figs. 2 and 5). Shells and shell hash (e.g., 401.8 ft) are abundant down to 470 ft. Shells in the upper portion are generally larger and more complete than below. Shells become much less abundant below 470 ft, although there are occasional shell hashes. Above this level, sediments are sandier and siltier. Below this level, laminated clayey silts are interbedded with silty clays. The clays are bioturbated. The silts contain small shell fragments and shell hash. From 438.0 to 464.7 ft, the section is predominantly bioturbated silty clays with occasionally clayey silt and shell fragments, and occasionally common diatoms. There may be a disconformity near 470 ft (Fig.

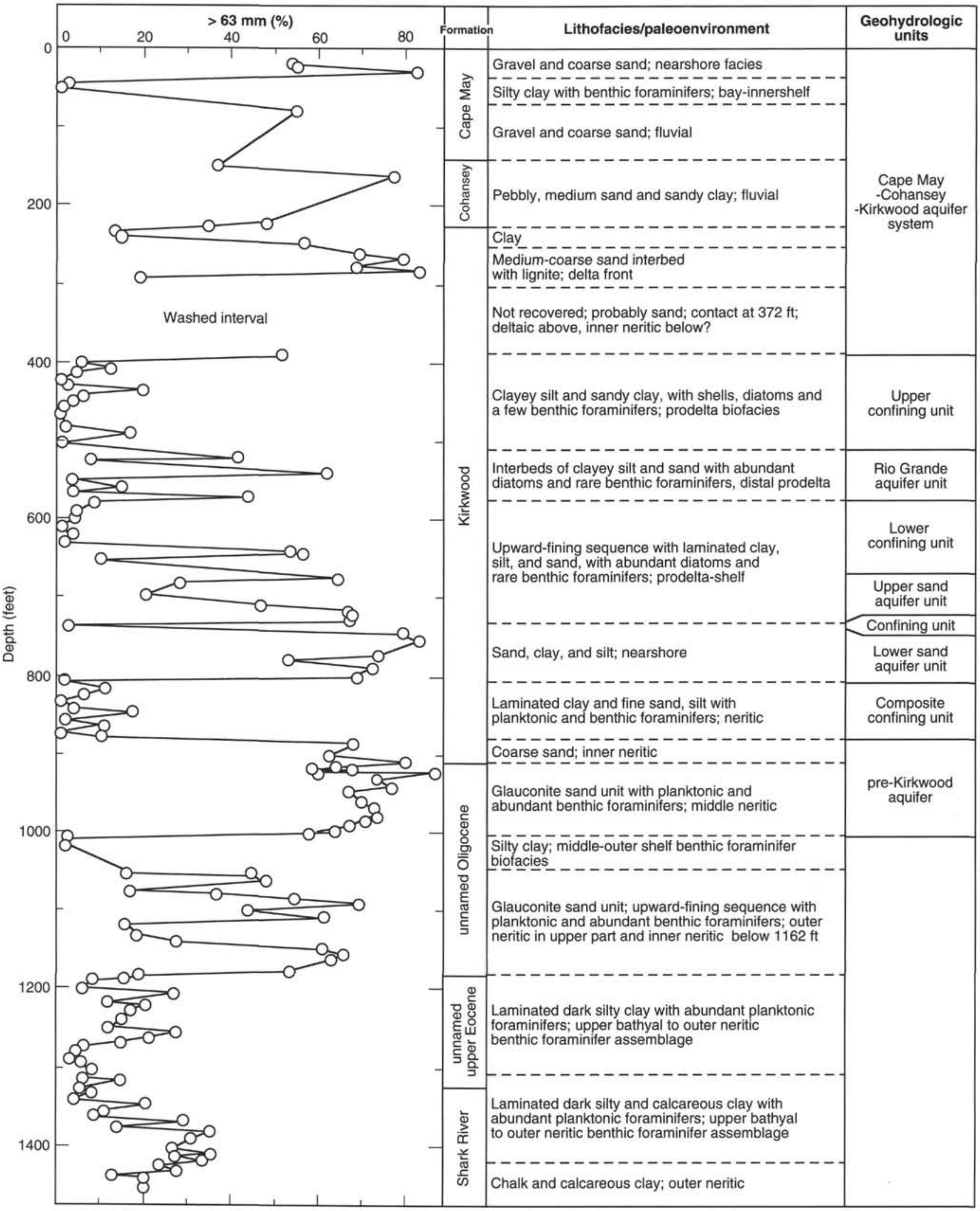

Figure 5. Percent sand, lithologic units, lithofacies, depositional environments, and geohydrologic units (the latter are those of Zapecza [1989] and Mullikin et al. [in press]).

Table 2. Sr-isotopic results, Atlantic City borehole.

Depth (ft)	$^{87}Sr/^{86}Sr$	Error (±)	Age (Ma, CK92)	Age (Ma, BKFV85)
401.7	0.708839	0.000013	13.4	13.3
411.1	0.708836	0.000009	13.5	13.4
462.6	0.708833	0.000010	13.6	13.5
519.5	0.708713	0.000011	16.7	17.0
559.7	0.708668	0.000011	17.4	17.7
605.1	0.708656	0.000011	17.6	17.7
644.0	0.708672	0.000008	17.3	17.6
661.1	0.708640	0.000008	17.8	17.9
661.2	0.708494	0.000010	19.9	20.3
708.5	0.708476	0.000011	20.2	20.4
723.2	0.708490	0.000010	20.0	20.2
821–822	0.708469	0.000011	20.3	20.8
831.4	0.708468	0.000011	20.3	20.8
854.1	0.708453	0.000011	20.5	20.8
869.2	0.708438	0.000020	20.7	21.0
884.8	0.708372	0.000012	21.7	21.9
908.3	0.708299	0.000011	23.4	23.7
913.0	0.708303	0.000011	23.3	23.6
923.2	0.708199	0.000013	25.3	25.8
974.5	0.708142	0.000011	26.4	27.4
1056.5	0.708135	0.000013	26.6	27.6
1117.0	0.708097	0.000014	27.3	28.7
1178.2	0.707936	0.000008	31.7	33.4
1204.1	0.707823	0.000013	34.8	36.6
1301.1	0.707784	0.000013	35.9	37.7

2) as indicated by (1) a gap between ECDZ 2 and ECDZ 6 (see "Biostratigraphy" section, this chapter); (2) a gamma-log peak at 466 ft; and (3) the higher abundance of shells above 470 ft that may be a condensed section immediately overlying a disconformity. This section was deposited on a shallow marine shelf. This is supported by the presence of rare to common diatoms and the generally rare, low-diversity benthic foraminifer assemblages. The slightly shelly silty clays were probably deposited below mean wave base. The laminated intervals may have been deposited more proximal to a delta.

The section becomes sandier at 510.9 ft (Figs. 2 and 5). Sands appear at 518 ft below an interval of no recovery (511.2–518 ft); the gamma log shows that sands appear at ~512 ft (uncorrected, depth). These sands are the Rio Grande aquifer unit (Zapecza, 1989; Mullikin et al., in press) (Figs. 2 and 5). This unit is medium-coarse sand with abundant shells and shell fragments. Below 519 ft, the sands contain a silt/clay matrix that binds the grains together. This appears to be an inner neritic deposit containing common diatoms and foraminifers at 521 ft.

We place a disconformity at 512 ft at the top of the Rio Grande aquifer unit in association with a distinct gamma-log kick (Fig. 2). This is consistent with Sr-isotopic evidence for a 3.5 m.y. hiatus between 462.6 and 519.5 ft (Fig. 2 and Table 2). The unconformity lies at the lower/middle Miocene boundary. This break occurs within East Coast Diatom Zone 2 (ECDZ 2; Fig. 2), with the middle part of the zone above and the lower part below. This interpretation is consistent with diatom evidence because ECDZ 2 straddles the lower/middle Miocene boundary elsewhere.

Silty clays return at 523 ft (Figs. 2 and 5). This increase in clay is shown by an increase on the gamma log (Fig. 2). An abrupt color change occurs at 524.25 ft, with dark greenish gray weakly laminated silty clay above and dark gray strongly laminated silty clay interbedded with fine sand below. The material below contains abundant fine mica, organic fragments, and diatoms. The likely environment is prodelta-inner neritic. Incomplete recovery (42%) between 528 and 538 ft was probably caused by poor recovery of sands, as shown on the gamma log.

From 548 to 664 ft, sandy silts and silty clays return. This is the "lower confining unit" between the Rio Grande and the upper sand aquifer units (Zapecza, 1989; Mullikin et al., in press) (Figs. 2 and 5). The upper part of this section has small, shelly, sandy silt beds. The environment was probably neritic and below mean wave base. This facies continues until at least 608 ft, although the thin sand beds are less common beginning at 588 ft. The section from 608 to 644 ft contains laminated clay silt with occasional cross-laminated very fine sand layers, and rare thin shell laminae. The lithology remains fairly consistent to 644 ft. The lower part of the confining unit is probably prodelta based on the scarcity of shell material, the intercalations of thin sand and silt, and the apparently higher abundance of organic carbon. The upper part of the lower confining unit contains rare-common diatoms and virtually no foraminifers.

At 644–647 ft, a shelly silty sand represents a transition into neritic environments, as indicated by the appearance of several planktonic foraminifer species. A return to laminated dark gray silty clay and fine sands occurs below the shell bed. Shelly silty sands occur at 659.5–662.2 ft and at 665.6–666 ft. This interval is interpreted as inner neritic sand and clay, as supported by the presence of diatoms and benthic foraminifers (*Nonionellina*-dominated).

A distinctive lithologic and gamma-ray change occurs at 666 ft (Fig. 6A). This is also a sequence boundary (the Kirkwood 2/Kirkwood 1 boundary of Sugarman et al., 1993); this boundary is associated with an ~2 m.y. hiatus revealed by Sr-isotopic stratigraphy (see below; Fig. 2). Medium-coarse pebbly quartz sands with occasional shells return from 666 to 676.5 ft; these sand generally fine upsection. These sands are the upper sand aquifer unit of Zapecza (1989) and Mullikin et al. (in press) (Figs. 2 and 5); the top of the sands is associated with a sharp gamma-log kick (Fig. 2). Silty clay and clayey silt layers with occasional lignite occur at 679.5–679.8, 680.8–681.5, and 682.7–683.4 ft. Interbeds of fine sands and sandy silts continue downsection to 706 ft. Pebbly coarse sands lie at 707.5–709 ft; these are underlain by fine and medium sand to 734.2 ft. The upper sand aquifer unit has a distinctive gamma-log signature showing decreasing values upsection from 709 to 736 ft and rapidly shifting values upsection from 668 to 709 ft; this is the expression of an upward-coarsening succession at the base and intercalations of sand and clay above. These sands and interbedded clays-silts are interpreted as nearshore or inner neritic deposits as supported by the presence of only scattered, rare foraminifers and diatoms.

From 733.3 to 738.8 ft, a laminated silty clay returns (Figs. 2 and 5); this represents a confining unit between the upper and lower sand aquifers units of Zapecza (1989) and Mullikin et al. (in press). A transition zone with increasing sands occurs from 738.8 to 741 ft.

Sands appear at 741 ft and continue down to 802.5 ft (Figs. 2 and 5). This lithologic and gamma-log contact (Fig. 2) may also be a sequence boundary; however, the hiatus associated with it is short (<0.5 m.y. based on mean Sr-isotopic age estimates of 20.3 Ma at 708.5–723.2 ft and 20.8 Ma at 821 ft). The sand is the "Atlantic City 800-foot Sand" (Zapecza, 1989), equivalent to the lower sand aquifer unit of Mullikin et al. (in press). The sand is lignitic between 741.5 and 742.7 ft. The sand lithology continues down to 778 ft. Two black clay plugs containing lignite occur interbedded with the sand layers at 778 and 778.8 ft. At 790 ft, a fine sand with more organic matter is present, below which the lithology returns to fine to medium sand. From 801 to 802.5 ft, the lithology changes to a stiff clayey sand. This section is interpreted as nearshore to inner neritic. The organic-rich sand facies may represent delta front environments. The presence of planktonic foraminifers at 779.1 and 790 ft indicates a neritic environment.

At 808 ft, the lithology is a thinly laminated clay with occasional fine sand beds (e.g., 815.8–816.7 ft; Figs. 3 and 5). These clays are the composite confining unit (Zapecza, 1989; Mullikin et al., in press) below the "800-foot Sand." These laminated clays continue to 875.4 ft. The contact between these clays and the "800-foot Sand" was lost (802.5–808.0 ft). The gamma-ray log shows a generally upward-coarsening succession between 808 and 821 ft. The clays contain occasional shell hashes. A sand shell bed at 852.6–854.7 ft may represent a storm deposit. We interpret these clays as prodelta based on the presence of inner-middle neritic foraminifers (at 808–824, 854, and 872.3 ft), laminations, high organic content, and presence of abundant mica.

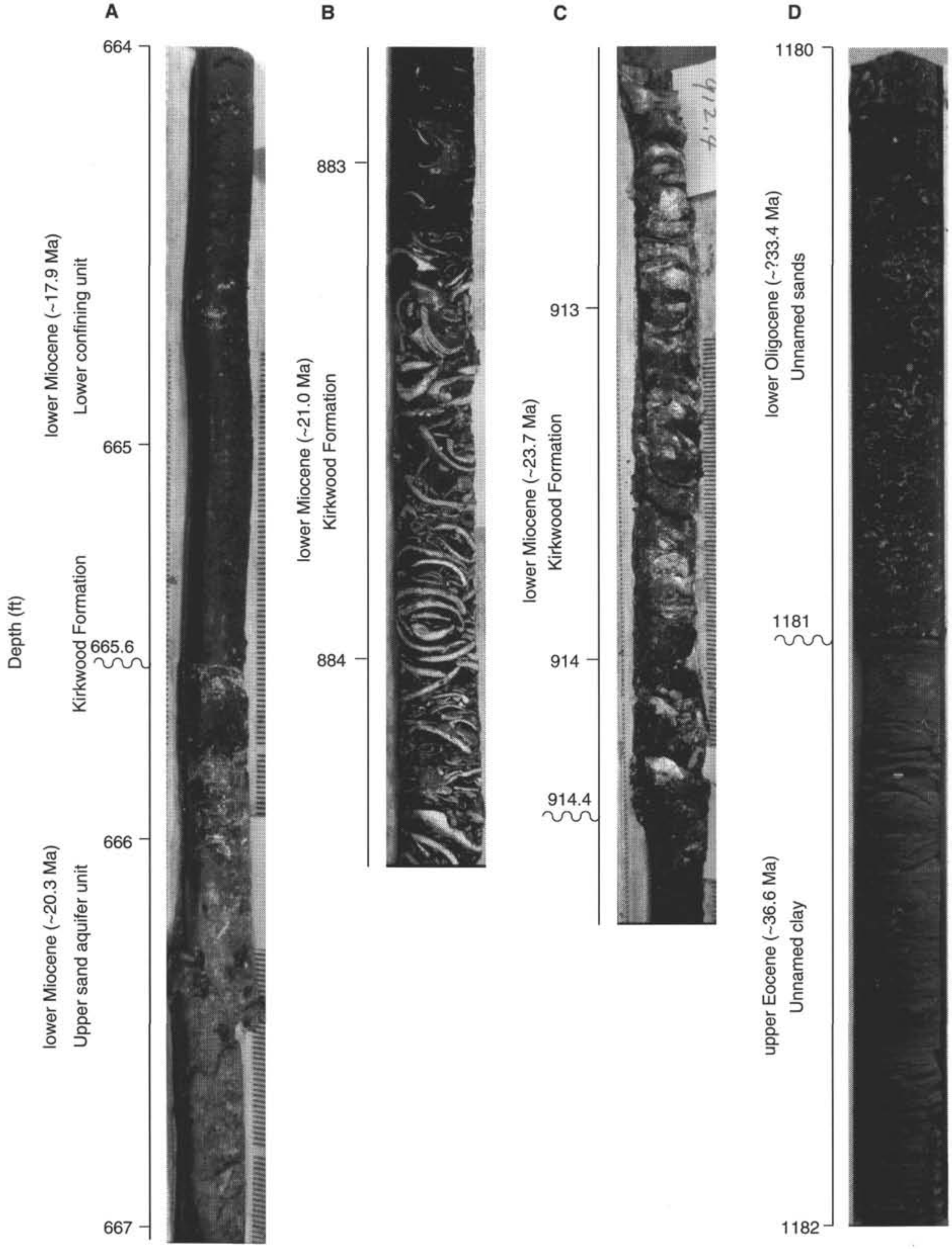

Figure 6. Core photographs, Atlantic City. **A.** Lithologic contact and disconformity at 665.6 ft separating the lower confining unit of the Kirkwood Formation above (17.9 Ma; laminated, dark gray clay) from the upper sand aquifer unit of the Kirkwood Formation below (20.3 Ma; dark olive gray, pebbly, coarse sand). **B.** Dramatic shell bed in the lower Kirkwood Formation, dated as 21.9 Ma using Sr-isotopic stratigraphy; shell bed continues above photograph. **C.** Shell bed at 910.8–914.4 ft in the Kirkwood Formation, dated as 23.7 Ma using Sr-isotopic stratigraphy. The base of the bed is probably a sequence boundary. **D.** Lithologic contact and disconformity at 1181 ft separating lower Oligocene, shelly, dark olive gray, glauconite sand above (Zone P18–P20; 33.4 Ma, based on a tentative Sr-isotopic age estimate) from upper Eocene, dark gray, silty clay below (Zones NP19–20 and P15–P17; 36.6 Ma based on an Sr-isotopic age estimate).

At 875.4 ft, there is a burrowed contact with an olive gray micaceous clay below. The clay is burrowed and contains pyrite, although it is apparently lower in organic content than the clays above. A small amount of glauconite is present in this unit and in the one above. The dominance of *Nonionellina* at 876.5 ft indicates an inner neritic paleodepth. This unit continues down to 880.8. ft

At 880.8 ft, there is another burrowed contact with clayey medium glauconitic sands below. This unit is the pre-Kirkwood aquifer unit (Fig. 5). This represents a shift in paleobathymetry from a middle-outer neritic benthic foraminifer assemblages (e.g., *Melonis, Cibicidoides, Lenticulina*) with glauconite below to inner neritic (*Nonionellina* fauna) above. From 880.8 to 937 ft, shell beds alternate with medium to coarse glauconite sands. A spectacular shell bed occurs at 883.2–885 ft; Figs. 3 and 6B). Shell size increases downsection in this bed to greater than 2 in., and shells are generally oriented parallel to bedding; this is a storm deposit. Shells constitute over 50% of the core. Another shell layer with extremely thick (3 cm in cross section) oysters occurs at 910.8–914.4 ft; Figs. 3 and 6C). A third shell bed resembling the first occurs at 922.5–924 ft. Others may have been missed by incomplete recovery. The repetition of shell beds with glauconite sands may reflect several thin sequences, with the shell beds at the base of each sequence. This is consistent with the Sr-isotope age measurements of 25.8, 23.7, and 21.9 Ma for the three major shell beds (Fig. 3).

Unnamed Oligocene Quartz and Glauconite Sands

Age: late early to late Oligocene
Thickness: 244 ft

The sediments from 937 to 1001 ft are glauconite quartz sand, with weathered shells (Fig. 3). This is the upper quartz sand unit of Olsson et al. (1980) that correlates with the Oligocene quartz sands noted at the ACGS#4 borehole (Owens et al., 1988; Miller et al., 1990). The sand content increases upsection from ~60% to 80% (Fig. 5), suggesting an upward-coarsening cycle. This is clearly a neritic (neritic) deposit; the predominance of benthic over planktonic foraminifers indicates that it probably is middle neritic (30–100 m paleodepth).

Between 1001 and 1053 ft, only 4.7 ft of micaceous silty clay was recovered (Fig. 3). The gamma-ray log places this clay at either 1024–1034 ft or 1040–1045 ft (it fits better with the former considering the thickness of the recovered clays). This clay is a middle-outer neritic deposit based on the benthic foraminifers (e.g., *Uvigerina, Bulimina, Trifarina,* and *Cibicidoides*).

From 1053 to 1111 ft, very dark clayey glauconite sand dominates (Figs. 3 and 5), with occasional clay layers providing a means to subdivide the section. A clay unit occurs from 1072 to 1089 ft, with decreasing sand content upsection. From 1089 to 1099 ft, glauconite sands return. The section contains a diverse, middle-outer neritic benthic foraminifer assemblages.

There is a gradual downsection change from sand to clay at 1099–1112 ft (Figs. 3 and 5). From 1112 to 1126 ft, a highly burrowed, brownish gray silty clay, with abundant shells and foraminifers, is present. Glauconite sand increases downward with shells and foraminifers decreasing downsection. From 1126.7 to 1129.3 ft, there is a black glauconite sand, with a clay plug from 1129.3 to 1130.0 ft, and a return to black, bioturbated glauconite sand from 1130 to 1132 ft. Bioturbation is revealed by clay infilled burrows. The black sand overlies a distinct burrowed contact at 1132 ft. Below the contact, there is a glauconite silty clay; this is piped up to 3 ft above the contact. Silty clay that becomes increasingly sandy downsection predominates from 1132 to 1139 ft.

A sharp gamma-ray kick at 1139 ft (uncorrected) has no obvious lithologic expression, although it could correspond to an interval of no recovery at 1139-1140 ft. This may be a disconformity. Biostratigraphy and Sr-isotope stratigraphy indicates a thin (79 ft; 24 m) lower Oligocene section; assuming no hiatuses, sedimentation rates are very low (3.6 m/m.y.) for the lower Oligocene. Thus, a hiatus may be indicated between 1102 and 1181 ft, consistent with interpretation of 1139 ft as a disconformity. Preliminary Sr-isotope age estimates indicate a 4.7-m.y. hiatus across this surface, although the lower age requires verification.

Heavily burrowed, clayey, fine-medium glauconite sand predominates from 1140 to 1181.2 ft; it contains occasional thin (<1 cm) clay laminae and infills of burrows. Shells occur from 1164 to 1166 ft and from 1178.3 to 1181.2 ft, with a shell hash at the base of the latter. Diverse benthic foraminifers indicate deposition of this unit in the middle to outer neritic zones (30–200 m); it is characterized by abundant uvigerinids/rectuvigerinids and globobuliminids along with shallower elements (*Nonionellina, Buliminella curta*).

A dramatic disconformity was recovered at 1181.2 ft (Figs. 3 and 6D), separating shell hash/glauconite sands above from laminated, burrowed, dark gray, silty clay below. Glauconite sand is burrowed into the clay. This contact is the upper of two distinct gamma-ray peaks (1182 ft uncorrected). This contact is the disconformable Eocene/Oligocene boundary, with Eocene foraminifers having their highest occurrences at 1181 ft (see "Biostratigraphy" section, this chapter). This is a classic unconformity, separating more regressive clays below (i.e., the Highstand Systems Tracts) from the shell hash above (the "condensed section"; upper Transgressive–lower Highstand Systems Tracts).

Unnamed Clays and Sands

Age: late Eocene
Thickness: 144 ft

Dark gray silty clay occurs from 1181.2 to 1324 ft. (Figs. 3–4). Foraminifers and shells are very common; glauconite is present but rare. Pyrite occurs as nodules and infillings of voids throughout. Benthic foraminifers indicate middle neritic environments in this unit (e.g., large lenticulinids, dentilinids, guttulinids, and siphoninids). This thick (>143 ft) unit at Atlantic City correlates with the upper Eocene ACGS#4 unit at Mays Landing, where it is 140 ft thick (Owens et al., 1988), and with the unnamed upper Eocene unit at Island Beach borehole, where it is ~77 ft thick (see Chapter 1, this volume). Several depositional cycles occur in this unit at the ACGS#4 borehole (Owens et al., 1988). The uniform lithologic and log nature of the upper Eocene section at Atlantic City (Fig. 4) resists stratigraphic subdivision, although benthic biofacies studies should determine if there are bathymetric cycles in this unit that correlate with the ACGS#4 upper Eocene cycles.

Shark River Formation

Age: middle to early late Eocene
Thickness: >127 ft

A color change to greenish gray takes place at 1325 ft, reflecting the greater abundance of glauconite (Fig. 4). We tentatively place the top of the Shark River Formation at this contact. The boundary is associated with a decrease in the gamma-ray log, and we interpret it as a disconformity (Fig. 4). Interbedded glauconite sands and clays are found from 1328.0 to 1332.6 ft (Fig. 4). A lithologic contact at 1332.6 ft separates sands above from a return to uniform, laminated, burrowed, dark gray, silty clay below. The lower clay has lower abundances of glauconite than the one above.

Glauconite sand increases downsection from 1346 to 1352.2 ft, where there is a return to more uniform clays. The contact at 1352.2 ft is sharp and is marked by a kick on the gamma-ray log; it may be a disconformity separating the middle Eocene from upper Eocene strata (Fig. 4).

The lithologic unit from 1332.6 to 1352.2 ft should probably be assigned to the Shark River Formation. Foraminifers indicate that the base of the upper Eocene is at 1348–1352 ft, although nannofossils indicate that the middle/upper Eocene boundary may lie as deep as 1390 ft (see "Biostratigraphy" section, this chapter). Thus, the uppermost part of the Shark River Formation is lower upper Eocene, as it is at the ACGS#4 borehole (Miller et al., 1990). Foraminifers indicate middle-outer neritic paleodepths (diverse benthic assemblages with common rectuvigerinids, lenticulinids, globobuliminids, and planktonic foraminifers). Further study of this enigmatic interval (1325–1390 ft) is needed to determine its age and lithostratigraphic correlation.

From 1352.5 to 1365.5 ft, uniform, laminated, slightly glauconitic, greenish gray, silty clay returns that is similar to the unit from 1332.6 to 1346 ft (Fig. 4). As in the section above, benthic foraminifers indicate middle-outer neritic paleodepths.

Glauconitic sand increases downsection from 1365.5 to 1370.5 ft, developing cross-laminations of clayey sands and clays near the base. From 1370.5 to 1376.6 ft, silty clays return. Uniform glauconite sandy clay occurs from 1376.6 to 1425.2 ft. A clayey glauconite sand from 1430 to 1431 ft lies at the base of this unit; these clayey sands yield a sharp gamma-ray peak.

A distinct contact with glauconite sand occurs at 1431 ft, overlying uniform light greenish gray ("ash") carbonate clay to clayey chalk. This disconformity is associated with a sharp gamma-log peak (Fig. 4). This is the contact with the upper/lower Shark River Formation as described at Island Beach (see Chapter 1, this volume). This is equivalent to the Deal/Shark River contact sensu Olsson and Wise (1987) and Miller et al. (1990). This lithology continues to the base of the borehole (1452 ft). High relative abundances of planktonic foraminifers together with benthic foraminifers indicate middle-outer neritic paleodepths.

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 Geomagnetic Polarity Time Scale (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 BKFV85, realizing that the ages must be recalibrated.

Planktonic Foraminifers

Summary

The planktonic foraminifer zonation of Berggren and Miller (1988) can be applied to the Eocene and Oligocene section, although planktonic foraminifer zonation for the Miocene and younger sediments was not possible. The Miocene and younger sediments are largely barren of planktonic foraminifers, although small-sized globigerinids and paragloborotalids occasionally occur in the benthic foraminifer-dominated assemblages. The lower Oligocene and the lower part of upper Oligocene (1181 to ~920 ft) contain low-diversity assemblages without diagnostic taxa in most cases. The middle and upper Eocene (1452–1181.2 ft) contain generally well preserved and diverse planktonic foraminifer assemblages.

Neogene

Quaternary sediments are essentially barren of planktonic foraminifers and no foraminiferal correlations are possible. The presence of benthic foraminifers provide constraints on the environment of deposition (see "Lithostratigraphy" section, this chapter).

Miocene and younger sediments only sporadically contain diagnostic taxa and zonation is not possible because of the rare occurrence of planktonic foraminifers above 852.6 ft in the section. Primitive *Globigerina* (*praebulloides*) is common when planktonic taxa occur in the section. The occurrence of *Globorotalia* (*Jenkinsella*) *acrostoma* (range = Zones N4–N11), *G.* (*J.*) *mayeri*, and *Globigerina bulloides* at 644 ft provide positive evidence that this interval is lower to middle Miocene. The presence of *Globigerinoides primordius* at 854.2 ft is the only positive biostratigraphic evidence for placement of the Oligocene/Miocene boundary below 854 ft. The presence of ?*Subbotina euapertura* at 920 ft indicates penetration of probable Oligocene strata (discussed below). Taxa found in the Miocene section are listed in Table 3.

Oligocene

The Oligocene starts at approximately 920 ft and ranges to 1181 ft where a sharp lithologic contact separates the Oligocene from the Eocene. Compared with the Island Beach borehole, the Oligocene in Atlantic City borehole is much more fossiliferous. Although benthic foraminifers are the dominant microfossils and the planktonic assemblage is characterized by low diversity and nondiagnostic, long-ranging taxa, planktonic foraminifer zonation is possible for the Oligocene. However, because of their scarcity, the planktonic foraminifer zonation for the Oligocene is easily biased by preservational factors or rare occurrences of the marker species.

Zone P22 spans approximately 920 to 1072.9 ft. The top of this zone, which is also the Oligocene/Miocene boundary, cannot be unequivocally placed because the marker species for the base of Zone N4, *Paragloborotalia kugleri*, is not found in the borehole. The highest occurrence (HO) of ?*Subbotina euapertura* at 920 ft (Fig. 2) may approximate the top of this zone according to Li et al. (1992), who used this taxon as the top of Oligocene in Austral region. If its range was the same in the northern temperate region, the Oligocene/Miocene boundary would be at 920 ft; this is supported well by the Sr-isotopic stratigraphy (25.8 Ma at 923 ft; Table 2). The base of Zone P22 is at 1073 ft, based on the HO of *Paragloborotalia opima opima*. The planktonic foraminifer assemblage in Zone P22 is similar to that below in Zone P21b; dominant taxa are globigerinids and paragloborotalids (Table 3).

Zone P21 ranges from 1073 to 1114 ft and is subdivided into Subzones P21b (1073–1102 ft) and P21a (1102–1114 ft) by the HO of *Chiloguembelina cubensis* (Fig. 3). The base of Zone P21 is at 1114 ft (the lowest occurrence [LO] of ?*Globigerina angulisuturalis*). This zonal boundary is not definitive because the sample at 1114 ft is the only one that contains the marker species. The diversity of planktonic foraminifers is very low (Table 3) as a result of global and local effects: that is, the extinction of early Paleogene taxa and the paleoenvironmental restriction of the majority of pelagic taxa.

Zones P20, P19, and P18 (1114–1181 ft) are not separable in the section because of the absence of "*Turborotalia*" *ampliapertura* and the lack of a reliable HO of *Pseudohastigerina* spp. in the section. The HO of "*T.*" *ampliapertura* defines the base of Zone P20, and the HO of *Pseudohastigerina* spp. separates Zones P19 and P18. The reason for the absence of *Pseudohastigerina* spp., which are generally well preserved and abundant in most lowermost Oligocene sections, can result from the fact that (1) Zone P18 is represented by the depositional hiatus at 1181 ft or (2) the taxon was environmentally excluded. Environmental exclusion is possible because samples from the 1181 to 1162-ft interval contains predominantly benthic taxa whereas planktonic taxa are rare or absent. However, it is equally likely that Zone P18 (34.0–36.6 Ma) was removed, as evidenced by the thin lower Oligocene section; this is supported by an Sr-isotope age estimate of 33.4 Ma at 1178.2 ft (see below), although this age must be verified. Zones P18–P20 contain a low-diversity fauna (Table 3).

The HO of *Turborotalia cerroazulensis* spp. (used to recognize the top of Eocene and Zone P17) is at 1181 ft, coinciding with a sharp lithologic contact between silty clay below and severely bioturbated and burrowed glauconite shelly sand above (Fig. 3). The duration of

Table 3. Occurrences of planktonic foraminifers in the Atlantic City borehole.

- Miocene
  - *Globigerina bulloides, G. pseudobesa, G. praebulloides, G. ouachitaensis ouachitaensis, Globorotalia (Jenkinsella) acrostoma, Gr. (J.) semivera, Gr. (J.) mayeri, Catapsydrax unicavus, Guembelitria triseriana*
- upper Oligocene
  - Zones P21b–P22: *Subbotina euapertura, Globigerina praebulloides, G. ouachitaensis, G. ciperoensis augustiumbilicata, G. ciperoensis angulisuturalis, Globorotalia (Jenkinsella) semivera, Gr. (J.) mayeri, Paragloborotalia opima nana, Globorotaloides suteri, Tenuitella gemma, Praetenuitella praegemma, Catapsydrax unicavus, C. dissimilis, Cassigerinella chipolensis, Globigerina labiacrassata, Guembelitria triseriana*
- lower Oligocene
  - Zones P21a: *Chiloguembelina cubensis, ?Subbotina praeturritilina, ?S. euapertura, Catapsydrax dissimilis, Globigerina praebulloides praebulloides, G. praebulloides leroyi, G. praebulloides occlusa, G. ouachitaensis gnaucki, G. ciperoensis augustiumbilicata, G. ciperoensis angulisuturalis, Paragloborotalia opima nana, P. opima opima, Globorotaloides suteri, Praetenuitella impariapertura, P. patefacta, Tenuitella munda*
  - Zones P18–P20: *Chiloguembelina cubensis, Ch. victoriana, ?Subbotina angiporoides, ?S. praeturritilina, ?S. euapertura, Catapsydrax dissimilis, Globigerina praebulloides, G. increbescens, G. ouachitaensis, G. ciperoensis augustiumbilicata, Paragloborotalia opima nana, P. opima opima, Globorotaloides suteri, Praetenuitella impariapertura, P. patefacta, P. praegemma, Tenuitella munda, Globigerina corpulenta*
- upper Eocene
  - Zones P15–P17: *Porticulasphaera semiinvoluta, Subbotina frontosa, S. eocaena, S. cryptomphala, S. galavisi, S. linaperta, S. euapertura, S. yeguaensis, S. angiporoides, S. hagni, ?S. corpulenta, ?S. gortani, ?S. praeturritilina, Globigerina praebulloides, G. ouachitaensis, Turborotalia cerroazulensis pomeroli, T. cerroazulensis possagnoensis, T. cerroazulensis cerroazulensis, ?T. griffinae, ?T.* cf. *praecentralis, Globorotaloides suteri, G. carcoselleensis, G. higginsi, Truncorotaloides collactea, Globigerinatheka subconglobata subconglobata, G. subconglobata micra, G. senni, G. index, G. mexicana, Globanomalina chapmani, Pseudohastigerina micra, P. sharkriverensis, Praetenuitella praegemma, Catapsydrax dissimilis, Hantkenina alabamensis, H. primitiva, H. liebusi, H. longispina, Chiloguembelina victoriana, Ch. cubensis*
- middle Eocene
  - Zones P12–P14: *Morozovella lehneri, M. spinulosa, Subbotina frontosa, S. eocaena, S. cryptomphala, S. inaequispira, S. galavisi, S. linaperta, S. euapertura, S. hagni, ?S. lozanoi, Acarinina bullbrooki, A. acarinata, A. aspensis, A. spinuloinflata, A. crassata, A. pseudotopilensis, A. matthewsae, Igorina broedermani, Globigerina praebulloides, G. ouachitaensis, ?G. medizzai, Turborotalia cerroazulensis pomeroli, T. cerroazulensis possagnoensis, T. cerroazulensis cerroazulensis, T. cerroazulensis cocoaensis, Truncorotaloides rohri, T. pseudodubia, T. collactea, T. topilensis, T. libyaensis, T. haynesi, Globigerinatheka subconglobata subconglobata, G. senni, G. index, G. mexicana, Globanomalina chapmani, Pseudohastigerina micra, P. sharkriverensis, Hantkenina alabamensis, H. primitiva, H. liebusi, H. longispina, Guembelitria columbiana, Chiloguembelina victoriana, Ch. cubensis*

the hiatus separating undifferentiated Zones P15–P17 from Zones P18–P20 is not clear.

Eocene

The Eocene in the Atlantic City Borehole spans from 1181 ft to the base of the core (1452 ft). As in the Island Beach Site, planktonic foraminifer assemblages in the Eocene are abundant, diverse, and generally well preserved. Diversity as well as abundance of oceanic taxa are even higher at Atlantic City than at Island Beach, perhaps because of a more pelagic setting at the site. Acarininids and subbotinids are the most common taxa. Morozovellids are less frequent compared with these two genera, but they are more common than at Island Beach. Species of *Turborotalia* (*cerroazulensis* lineage) are abundant or even dominant in many intervals of the upper middle and upper Eocene. *Pseudohastigerina, Globanomalina, Chiloguembelina, Guembelitria,* and *Praetenuitella* occur frequently in finer (<150 µm) size fraction. *Globigerina* (s.s.) also occurs in the Eocene.

The upper Eocene (approximately Zones P15–P17) is not separable into the standard planktonic foraminifer zones because of absence of *Cribrohantkenina inflata* (the marker for the total range Zone P16) in the section. The base of Zone P15 (upper middle Eocene) is marked by the LO of *Porticulasphaera semiinvoluta* at 1348 ft (Fig. 3). Because all morozovellids, acarininids, and most truncorotaloides became extinct in the late middle Eocene, planktonic foraminifer taxa observed in this interval are mostly the long-lasting subbotinids, primitive globigerinids, remnant truncorotaloides, pseudohastigerinids, and biserial chiloguembelinids (Table 3).

The borehole penetrated middle Eocene strata. The planktonic foraminifer biostratigraphy of the upper middle Eocene uses the LO of *Porticulasphaera semiinvoluta* to define the base of Zone P15 (Berggren and Miller, 1988); this event occurs at 1348 ft. This taxon first occurred at 41.3 Ma, about 1.3 m.y. older than the middle/late Eocene boundary (BKFV85). Thus, Zone P15 straddles the middle/upper Eocene boundary. The HO of morozovellids and acarininids is at 1352.5 ft (Fig. 4); these taxa disappeared at 40.2 Ma (BKFV85) and are used here to approximate the middle/upper Eocene boundary at 1352.5 ft. Zones P12–P14 cannot be differentiated because of the absence of *Globigerapsis beckmanni,* whose total range defines Zone P13.

The base of the borehole penetrated the lower part of Zone P12, which has the base at the HO of *Morozovella aragonensis.* The absence of *Morozovella aragonensis* in the section can be either the result of the environmental exclusion of this oceanic taxa or a younger age of the sediments. The latter is more likely the case because common occurrences of other pelagic taxa (including two species of *Morozovella*) indicate an outer neritic paleoenvironment. Other evidence includes the occurrence of *M. lehneri* at near the base of the borehole (1451.8 ft) and the LO of *Turborotalia cerroazulensis pomeroli* at 1446 ft (Fig. 4). According to BKFV85, the first appearance datum (FAD) of *M. lehneri* and the last appearance datum (LAD) of *M. aragonensis* (43.6 Ma) are nearly synchronous and the FAD of *T. cerroazulensis pomeroli* is younger than both. Recognition of an advanced specimen of *M. lehneri* at 1451.8 ft and *T. cerroazulensis pomeroli* 5 ft above this places the base of the borehole in the lower part of Zone P12. Planktonic foraminifer taxa retrieved in Zones P12–P14 include a diverse fauna (Table 3).

Calcareous Nannofossils

Smear slides prepared from samples taken at ~5-ft intervals were examined for calcareous nannofossil stratigraphy. All levels between 74 and 854 ft are barren. Calcareous nannofossils are scarce between 864 and 904.1 ft, few to common between 909.8 and 1135.1 ft, and common below 1187.7 ft. The interval between 1145.0 and 1178.0 ft is barren. In general, preservation is poor as a result of secondary silicification. As a corollary, diversity is rather low.

The interval from 909.8 ft and 1135.1 ft is upper Oligocene. Based on the presence of *R. abisecta* and *H. recta,* and the absence of representative of *Sphenolithus,* it is assigned to Zone NP25–NP24 undifferentiated. The sample from 1178–1178.1 ft yields a scarce assemblage without *R. abisecta* that may belong to Zone NP23.

The interval from 1182.7 to 1333.5 ft belongs to upper Eocene Zone NP19–20. The sequential disappearances of *R. reticulata* (1221 ft), *D. barbadiensis* (1187.4 ft), and *D. saipanensis* (1182.7 ft) suggest a continuous uppermost Eocene section. The lower boundary of Zone NP19–20 is uncertain. *Ismolithus recurvus* occurs discontinuously between 1338.8 and 1390.1 ft. This interval may belong to Zone NP19–20 or to Zone NP18 (if the presence of *I. recurvus* is anomalous). The reworking of middle Eocene sediment in it is indicated by the presence of taxa such as *C. grandis* (in particular at 1348.1 ft).

The upper Eocene is unconformable with middle Eocene Zone NP16, which extends from 1398.0 to 1442.4 ft (lowest sample examined). Preservation is considerably improved in this zone. The assemblages, rich in *Pemma* spp., vary greatly in composition; in particular, *Chiasmolithus* spp. (*C. solitus, C. expansus*) are abundant at levels and absent at others. *Sphenolithus furcatolithoides* is rare; *Discoaster bifax* has its HO at 1439.1 ft.

Diatoms

Few diatoms are present in sediments from 14 to 88.6 ft. These generally consist of nearshore, brackish water forms and include *Cocconeis* spp, *Diploneis bombus,* and *Nitzschia granulata.* A few open-ocean forms, such as *Thalassiosira oestrupii,* were also observed. Because so few diatoms were present in these samples, it was not possible to determine the age. The presence of *T. oestrupii,* however, indicates that the sediment is younger than the Miocene/Pliocene boundary. Samples from 103.3 to 283.9 ft contained no diatoms, although an occasional fragment was observed.

Diatoms were present in samples from 399 to ~659.6 ft. Concentrations ranged from very abundant to sporadic, but generally preservation was good. Samples from 399 to 448.4 ft contained *Delphineis penelliptica* and *D. novaecaesaraea,* species that are markers for the East Coast Diatoms Zones (ECDZ) of Andrews (1988). The absence of *Coscinodiscus lewisianus* from these levels suggest that it is probably equivalent to the upper part of ECDZ 6 and 7 of Andrews (1988). The LO of *C. lewisianus* in the sample from 454.1 ft suggests that this sample is in the lower part of ECDZ 6 or perhaps older. The continued presence of *Delphineis penelliptica* and *D. novaecaesaraea,* however, indicates that this sample cannot be older than ECDZ 3–4. The LO of *Rhaphidodiscus marylandicus* at 473.5 ft suggests that this is the middle part of ECDZ 2 of Andrews. This zonal identification is somewhat complicated by the fact that this sample also contains *D. novaecaesaraea,* a form which, according to Andrews (1988), first occurs in ECDZ 3–4. No definite level of FO is given for *Delphineis penelliptica,* so the presence of this species does not present a problem. It is very possible that *D. novaecaesaraea* ranges lower than the level indicated by Andrews (1988) because his stratigraphic scheme is based upon outcrop data rather than continuous sections. Given these considerations, the section down to 659.6 ft, which contains diatoms, is older than the middle part of ECDZ 2. Samples from 663.8 to 755.9 ft contain no diatoms, but they reappear in samples at 755.9 and 768.7 ft. Diatoms are few in number in these two samples, and no age designation other than lower Miocene is possible. The remainder of the samples down to a depth of 977 ft contain few diatom fragments or are barren of them.

ISOTOPIC STRATIGRAPHY

Twenty-five Sr-isotopic age estimates were obtained from shells at the Atlantic City borehole (Table 2 and Figs. 2–4). 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 procedures). Ages were assigned using both BKFV85 and CK92 time scales (Table 2); results are discussed using BVFK85 to compare with previous Sr-isotopic studies of the New Jersey subsurface (Miller et al., 1990; Sugarman et al., 1993). 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.

The data presented here concentrated on three sequences identified in the Kirkwood Formation by Sugarman et al. (1993). Three age estimates from shell beds between 491.7 and 462.6 ft are 13.3–13.5 Ma (Fig. 2) and are thus correlated to the upper (Kirkwood 3) sequence (= ECDZ 6 of Andrews, 1988). Samples between 519.5 and 661.1 ft yielded age estimates of 17.0–17.9 Ma (Fig. 2) and correlate to the middle (Kirkwood 2) sequence (= ECDZ 2 of Andrews, 1988). A third group of analyses between 661.2 and 913 ft are 20.3–23.7 Ma (Figs. 2–3) and are equivalent to the lower (Kirkwood 1) sequence (= ECDZ 1 of Andrews, 1988), although an older portion of this sequence was recovered at Atlantic City for the first time. These three sequences may be further subdivided by integrated stratigraphic studies. For example, we have tentatively identified three uppermost Oligocene–lowermost Miocene sequences with dramatic shell layers at their bases: 663–885 ft (20.3–21.9 Ma), 885–914 ft (23.7 Ma), and 914–924 ft (25.8 Ma) (Fig. 3 and Table 2).

The Oligocene/Miocene boundary lies between 913 ft (23.6 Ma) and 923.2 ft (25.8 Ma) (Table 2). This is consistent with the planktonic foraminifer correlation, which indicates the top of the Oligocene at 920 ft based on a secondary criterion (the LO of ?*S. euaperta*).

An uppermost Oligocene surface at 937 ft (Fig. 3) is associated with possible 1.6-m.y. hiatus (25.8 Ma at 923.2 ft and 27.4 Ma at 974.5 ft); further analyses are needed to confirm this hiatus.

As discussed above (see "Lithostratigraphy" section, this chapter), much of the lower Oligocene may not be represented. The Sr-isotope data are consistent with a tentative unconformity at 1139 ft (Fig. 3) separating strata of 28.7 Ma (1117 ft) from 33.4 Ma strata (1178.2 ft). The latter age must be confirmed. It is possible that reworking of Eocene material by the disconformity at 1181 ft resulted in an anomalously young age.

Sr-isotopic ages from 1204.1 and 1301.1 ft confirm the presence of an upper upper Eocene unit (36.6–37.7 Ma).

SCIENTIFIC ACCOMPLISHMENTS, ATLANTIC CITY BOREHOLE

1. Upper Pleistocene to Holocene section that apparently correlates with Island Beach.
2. Much better middle Miocene section than at Island Beach (e.g., excellent recovery of upper middle Miocene Cohansey Sands that are not represented at Island Beach).
3. Thick lower to middle Miocene Kirkwood Formation with excellent recovery of several relative sea-level cycles between 400 and 900 ft; superb facies representation of fluvial, deltaic, and inner neritic environments.
4. Numerous Oligocene–Miocene shell beds for Sr-isotopic age estimates, including remarkable thick (>10 ft) shell layers not previously described from New Jersey.
5. Thick upper middle Eocene to Oligocene neritic sections recording several sea-level cycles; the upper Oligocene here contains a better representation of "New Jersey" regressive cycles than any other location drilled onshore.

Ms 150XIR-112

SHORE-BASED LOG PROCESSING

Hole Atlantic City

Total penetration: 1452 ft; 442.57 m
Total core recovered: 977 ft; 297.79 m (67.3%)

Logging Runs

The recordings were performed by BPB Inc., using slim-hole logging tools.
Logging string 1: Gamma Ray/Neutron Porosity

Casing

The logs were recorded through PVC casing; therefore, caution is recommended if the data are used quantitatively.

Processing

These data were not recorded with the standard Schlumberger logging tools that are ordinarily used offshore in the Ocean Drilling Program. No count rates were recorded that would allow for gamma-ray reprocessing. Any quantitative comparison of the Atlantic City data with Leg 150 offshore data must be made cautiously because of the different tool responses.

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

Cristina Broglia	or	Elizabeth Pratson
phone: 914-365-8343		phone: 914-365-8313
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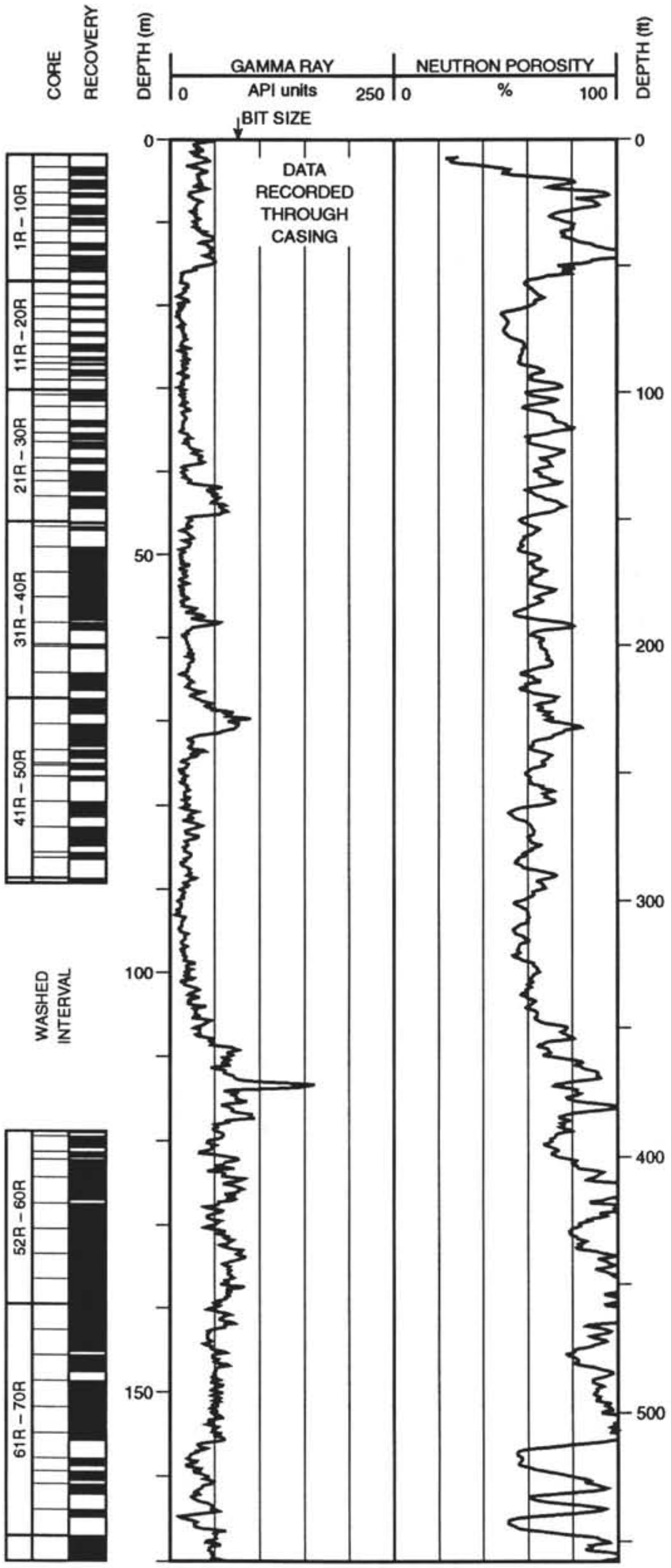
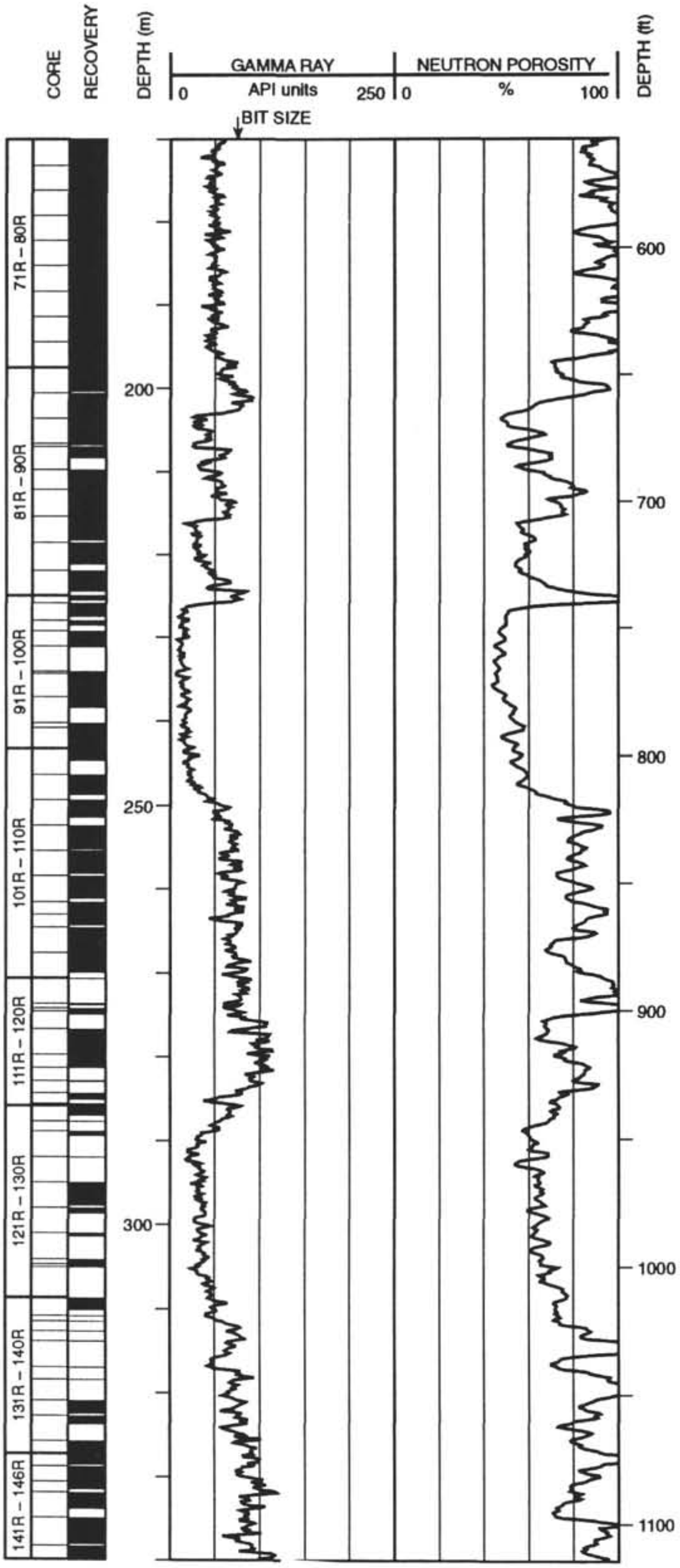
email: chris@ldeo.columbia.edu		email: beth@ldeo.columbia.edu

Hole Atlantic City: Natural Gamma Ray-Porosity Log Summary



Hole Atlantic City: Natural Gamma Ray-Porosity Log Summary (continued)



Hole Atlantic City: Natural Gamma Ray-Porosity Log Summary (continued)