1. CAPE MAY SITE REPORT[1]

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The following, who are listed in alphabetic order, are responsible for the given section:

Chief Scientist: Miller
Operations: Queen, Heibel
Lithostratigraphy: Browning, Liu, Mullikin, Pekar, Powars, Sugarman, Van Fossen
Biostratigraphy:
Foraminifers: Liu
Nannofossils: Aubry
Diatoms: Burckle
Sr-isotope Stratigraphy: Feigenson, Sugarman

SUMMARY

The Cape May site was the third borehole drilled as part of the New Jersey coastal plain drilling project (Leg 150X). It focused on middle Miocene to upper Eocene sequences. Recovery was good (75% mean, 85% median), and gamma and neutron logs were obtained to a total depth (TD) of 1500 ft (457 m). This location is the most downdip onshore location in New Jersey, and the Miocene section is the thickest (823 ft; 251 m) of the three Leg 150X boreholes, with numerous shells suitable for Sr-isotopic age measurements. Unconformities are revealed by erosional surfaces, gamma-ray peaks, lithologic breaks, biofacies shifts, shell beds, indurated zones, and hiatuses determined by Sr-isotopic stratigraphy and biostratigraphy.

Good recovery of sands and clays in the top 357 ft (109 m) provide excellent examples of fluvial-estuarine and marginal marine environments, although age control on this section is poor. The top 90 ft (27 m) of the borehole recovered alternating organic-rich clays and shelly sands deposited in an inlet-marsh environment similar to the modern setting. These Pleistocene to Holocene strata are assigned to the Cape May Formation. Clays from 90 to 140 ft (27–43 m) are tentatively assigned to the Cape May Formation (?Pleistocene). The restricted-marine diatom flora and benthic foraminiferal fauna indicate a lower estuarine environment. This unit overlies a thick (140–357 ft; 43–109 m) unit of poorly fossiliferous estuarine sands and clays. Based on stratigraphic studies of the nearby Cape May airport borehole, we tentatively correlate this thick section with a Pliocene unit mapped in the Cape May peninsula (Owens et al., 1995).

Four middle Miocene sequences representing 258 ft (77 m) were recovered, including the youngest fossiliferous middle Miocene sequence sampled in New Jersey (ca. 11–12 Ma). We are uncertain if this upper unit (the Kirkwood-Cohansey sequence) correlates with the poorly dated Cohansey Formation or older middle Miocene sequences. Three additional middle Miocene sequences were recovered, including the probable equivalent of the Kirkwood 3 sequence of Sugarman et al. (1993; dated as 13.1–13.7 Ma at Atlantic City; Miller et al., 1994a, 1994b), a previously unknown sequence (dated as ~14.3–14.8 Ma), and the Kirkwood 2b sequence of Sugarman et al. (1993; 15.9–16.3 Ma). The significance and age of the 14.3–14.8 Ma sequence requires verification.

The thick lower Miocene section (565 ft; 172 m) represents at least five well-developed sequences. The Kirkwood 2a sequence (650–715 ft; 198–218 m) of Sugarman et al. (1993) is thinner than at Atlantic City where it is well dated (ca. 17.0–18.1 Ma). This sequence is a classic coarsening-upward “New Jersey” cycle: (1) basal shelly, sandy silts and clays (shelf environments); (2) medial micaceous, carbonaceous, laminated clay-silts and fine sands (prodelta environments); and (3) upper interbedded sands and carbonaceous silts (delta front environments). A thick (710–850 ft; 216–259 m), 18.6- to 19.5-Ma sequence was recovered at Cape May, but it is not present at Atlantic City, nor has it been unequivocally identified elsewhere in New Jersey. The thick (850–1062 ft; 259–324 m) Kirkwood 1 sequence (ca. 20–21 Ma) is well represented at Cape May and throughout the surface and subsurface in New Jersey. The Kirkwood 1 sequence may be divided into the Kirkwood 1b (850–942 ft; 259–287 m; ca. 20.1 Ma) and Kirkwood 1a (942–1062 ft; 287–324 m; 20.4–20.9 Ma) sequences. Although no discernible hiatus is present between these sequences, there is clearly a major disconformity indicated by gamma logs, facies shifts, and an irregular surface at the contact.

A lowermost Miocene (ca. 23.1–22.7 Ma) Kirkwood 0 sequence of glauconite sands is the thick equivalent of a sequence bracketed by shell beds at Atlantic City. The transition from the Kirkwood 0 to Kirkwood 1 sequences in the coastal plain boreholes appears to mark a fundamental change in depositional regime from shelfal to deltaic dominated, although offshore seismics suggest deltaic deposition may have locally begun earlier (Greenlee et al., 1988).

At least one upper upper Oligocene sequence (1180–1249 ft; 360–381 m; ca. 25.5 Ma) was recovered; further studies are needed to determine if this is, in fact, two sequences. Another upper Oligocene sequence may be represented by Subzone P21b (ca. 28–29 Ma). A major “middle” Oligocene unconformity separates these sequences from the lower Oligocene, with a hiatus of at least 3 m.y. The presence of “middle” Oligocene strata at Atlantic City and its absence at Cape May is attributed to minor differences in subsidence histories between locations.

Two lower Oligocene sequences represent a thick Zone P19 to P20 sequence and a thin Zone P18 sequence. The lower Oligocene (Zone P18) unconformably overlies the upper Eocene. The upper Eocene comprises uniform, neritic clays (Zone P15–P17) to TD.

Facies changes within Oligocene to middle Miocene sequences (systems tracts) are clear. The bases of the sequences contain shell beds (typically 1–2 ft [0.3–0.6 m] thick) that grade up to clays/silts (typically 15–90 ft [4.5–27 m] thick) and sands (typically 40–120 ft [12–37 m] thick). Capping the Miocene sequences are indurated zones that may reflect subaerial exposure. At the Atlantic City and Cape May boreholes, Oligocene sequences contain glauconite through out;

[1]Miller, K.G., et al., 1996. *Proc. ODP, Init. Repts.*, 150X (Suppl.): College Station, TX (Ocean Drilling Program).

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the glauconite in the medial silts and upper sands is probably recycled from Eocene and older strata and tends to obscure the facies succession. Further biostratigraphic and Sr-isotopic studies are needed to refine the ages of the sequences, whereas further lithostratigraphic and benthic foraminifer biofacies studies should reveal details of the depositional environments and systems tracts of these well-developed sequences. Recovery and dating of upper Eocene to middle Miocene sequences at the three Leg 150X boreholes will allow us to attain our primary goal: to evaluate the roles of glacioeustasy, tectonics, and changes in sediment supply on the development of sequences.

BACKGROUND AND OBJECTIVES

This chapter is the site report for the third continuously cored and logged borehole drilled onshore as part of the New Jersey Sea Level Transect. The geological background and scientific justification for the Transect are provided by Miller and Mountain (1994). The Transect is an integration of Ocean Drilling Program Leg 150 slope and rise drilling (Mountain, Miller, Blum, et al., 1994; Mountain, Miller, Blum, Poag, and Twichell, 1996), future shelf, and onshore Leg 150X drilling (Miller et al., 1994a, 1994b, this chapter). The Transect is intended to document the response of passive continental margin sedimentation to glacioeustatic changes during the Oligocene to recent "Icehouse World," a time when glacio-eustasy was clearly operating, and to document the ages and nature of Eocene and older "Doubthouse" sequences, a time when mechanisms for sea-level change are poorly understood (Miller et al., 1991b).

Determining relative sea level and evaluating the timing and facies changes within sequences requires the integration of studies from nearshore to deep-sea environments (e.g., Miller and Mountain, 1994). The goal of onshore drilling is to recover updip counterparts of well-developed sequences imaged on the continental shelf (Greenlee et al., 1988, 1992; Miller and Mountain, 1994). The Cenozoic shelf sequences have only been sampled by a few industry wells (Greenlee et al., 1992) and a few boreholes with discontinuous recovery (Hathaway et al., 1976); thus, the ages of the sequences were poorly constrained (±1 m.y. or worse; Greenlee et al., 1992). These shelf sequences were traced on seismic profiles to the continental slope; Leg 150 (Mountain, Miller, Blum, et al., 1994; Mountain, Miller, Blum, Poag, and Twichell, 1996) drilled and dated the sequences on the slope, improving on preliminary dates provided by Deep Sea Drilling Program slope and rise drilling (Legs 93 and 95; Poag, Watts, et al., 1987; Van Hinte, Wise, et al., 1987). Although the slope-rise sites may be used to date shelf sequences, they yield little facies information. In contrast, drilling onshore not only provides another setting in which to date the sequences but also provides shallow-water (neritic and shallower) facies information that allows evaluation of sequence stratigraphic models (e.g., Posamentier et al., 1988).

The onshore drilling program was sponsored by the National Science Foundation, Earth Science Division, Continental Dynamics, and 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. The JOIDES planning committee endorsed the onshore drilling as an ODP-related activity that was designated Leg 150X.

We drilled two boreholes in 1993 at Island Beach State Park (TD = 1223 ft [373 m] in Maastrichtian) and Atlantic City (TD = 1452 ft [443 m] in upper middle Eocene); preliminary results from these boreholes were published as Miller et al. (1994a, 1994b). The third borehole was drilled in March and April 1994 at Cape May (TD = 1500 ft [457 m] in upper Eocene). The onshore sites were located downdip, close to the present-day shoreline, to maximize the thickness (and minimize the number of hiatuses) of the Oligocene to middle Miocene section and to be close to offshore multichannel seismic ties (Fig. 1). The sites were chosen to maximize recovery of different portions of the section. The Cape May borehole recovered the most complete and thickest Miocene section because of its downdip location; boreholes to the north (updip) penetrated progressively older portions of the Paleogene. This strategy was successful in assembling a mosaic of coastal plain sequences that record uppermost Cretaceous to Holocene relative sea-level changes.

The Leg 150X Cape May borehole was selected to optimize recovery of the upper middle Miocene section (e.g., East Coast Diatom Zones 5–6 and younger), which isopach maps (fig. 3d in Sugarman et al., 1993) show attains maximum thickness in the Cape May peninsula. The only continuously cored coastal plain borehole to sample this section was updip at Belleplain State Park, New Jersey (Sugarman et al., 1993); the upper middle Miocene section is truncated north of Belleplain (Fig. 1). In addition, the Cape May borehole was selected for its thick Oligocene section (Olsson et al., 1980), the possibility of recovering upper Eocene strata (reported by Brown et al., 1972; Poag, 1985), and the proximity of MCS seismic ties obtained in Delaware Bay (Fig. 1). A rotary test well drilled on the western side of the Cape May peninsula by Anchor Dickinson Gas (AD#1 well; Brown et al., 1972) yielded reasonably well-preserved Oligocene foraminifers below about 1000 ft (305 m) (Olsson et al., 1980). Eocene strata below 1450 ft (442 m) yielded silicified microfossils, and we decided to limit penetration at Cape May to 1500 ft (457 m). The location chosen at the Coast Guard base in Cape May is downdip of the AD#1 well and is the most downdip (basinward) location drillable onshore in New Jersey. Rotary drilling 33 km (20 mi) across Delaware Bay at Lewes, Delaware (Oh25-02; Fig. 1) provided deep-water Oligocene successions below ~1220 ft (372 ft) (Benson,

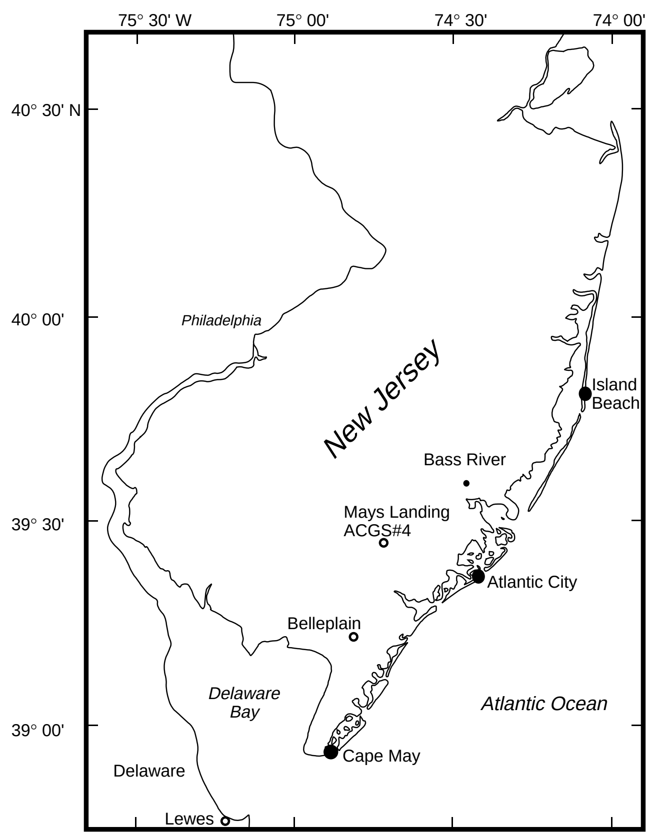

Figure 1. Location map showing the Island Beach, Atlantic City, and Cape May boreholes, ACGS#4 Mays Landing borehole (Owens et al., 1988), Belleplain borehole (Sugarman et al., 1993), proposed Bass River borehole, and Oh25-02 Lewes well (Benson, 1990).

1990). Our results show the Oligocene to Holocene sections are comparable (see below).

At all three Leg 150X coastal plain boreholes, unconformities were identified on the basis of physical stratigraphy (see below) and paraconformities inferred from biostratigraphic and/or Sr-isotopic breaks. Recognition of these surfaces allows identification of sequences. In general, the sequences recovered are shallowing-upward transgressive-regressive cycles, with well-developed erosional surfaces at their bases.

Facies changes within sequences (systems tracts) follow general patterns in the New Jersey coastal plain (Owens and Sohl, 1969; Owens and Gohn, 1985; Sugarman et al., 1993). A shell bed or glauconite sand at the base (= condensed section of Loutit et al., 1988; = late transgressive systems tract [TST] of Posamentier et al., 1988) is overlain by a silt, with a quartz sand at the top (= highstand systems tract [HST]; Sugarman et al., 1993). This results in a distinct gamma log signature with "hot" zones at the base and low values at the top (Sugarman et al., 1993). At Island Beach, we noted that Miocene sequences consist of clay-confining units at the base with quartz sand aquifers at the top (Miller et al., 1994b). The Oligocene to Miocene sequences at Atlantic City are similar, but they are more marine than at Island Beach; their bases are often marked by shell beds (Miller et al., 1994a). At the Cape May borehole, we encountered shell beds at the base and sands (often indurated) at top of Miocene sequences. At both the Atlantic City and Cape May boreholes, Oligocene sequences contain glauconite throughout; glauconite in the medial silts and upper sands is probably recycled from Eocene and older strata (Pekar and Miller, 1994). These successions represent shallowing-upward environments, with transgressive deposits at the base and regressive sands at the top.

These classic transgressive (TST) to regressive (HST) sequences have been recognized in the middle Atlantic coastal plain since the 1960s (e.g., Owens and Sohl, 1969). Lowstand systems tracts (LST) are apparently not represented in the coastal plain. Although flooding surfaces can be identified in the New Jersey coastal plain, it is often not clear where the maximum flooding surfaces (MFS) lies: it may be at the base, within, or at the top of the basal glauconite sands (Sugarman et al., 1995). If the MFS lies at the base of the glauconite sands, merging with the unconformity, then sequences are also parasequences (packages of sediments bounded by flooding surfaces; van Wagoner et al., 1990).

This report presents the lithostratigraphic, biostratigraphic, and Sr-isotopic data on which preliminary sequence stratigraphic studies of the Cape May borehole are based. Scientific results from the Island Beach, Atlantic City, and Cape May boreholes will appear in the Leg 150X *Scientific Results* volume in 1997.

OPERATIONS

Drilling began 16 March 1994 at the Coast Guard Training Center, Cape May, New Jersey (38°56′52″N, 74°53′00″W; elevation 5 ft [1.5 m]; Cape May 7.5-min quadrangle), located approximately 350 m west-southwest of Cape May Inlet. Drilling operations were superintended by Don Queen, U.S. Geological Survey; drillers were Gene Cobbs, Todd Heibel, and Gene Cobbs III. Water and electricity for core description were provided by the base commander, Captain Donald Anderson. A temporary field lab was set up in a Hecht trailer.

The first core was obtained on 16 March 1994. All cores were measured in feet (all depths are given in feet below land surface) and all operations are described in feet only. Coring proceeded to 25 ft using a Christensen 94-mm (HQ) system, 4.25- to 4.50-in. hole diameter, and 2.5-in. core diameter. Three types of extended shoe were used to contact the formation in front of the bit in unconsolidated sands: short (1 in.), medium (1.5 in.), and long (2 in.). Five-inch PVC casing was set and grouted at 23 ft, to be extracted later. A total of 55 ft was penetrated on 16 March and 35 ft was recovered (63.6%). Recovery was poor to moderate in the sandy top 33 ft (51%), but it was much improved in sandy clays between 33 and 55 ft (82.7%). Biostratigraphic sampling started at 40 ft, and one sample was taken from each 5-ft core. Drilling was suspended on 17 March because of frozen drilling mud and high winds.

Drilling resumed on 18 March with smooth coring to 85 ft through clay and medium sand with 81.5% recovery. The cores from 75 to 80 ft recovered 2.35 ft; subsequent cores from 80 to 83 ft and from 83 to 85 ft recovered 3.7 and 2.8 ft, respectively (130% recovery). The extra material from these cores came from the 75 to 80 ft interval, and this section should be bottom justified at 85 ft. The water swivel failed at the end of the day and was replaced. All hoses were drained in case of overnight freezing.

On 19 March, 14 core runs were made from 85 to 155 ft with a recovery of 60 ft (86%). Smooth coring continued on 20 March to 225 ft (75% recovery), flushing the hole between runs. Coring was slow but generally smooth on 21 March (82% recovery) and 22 March (67% recovery) to 285 and 320 ft, respectively. The final core on 21 April was lost with no recovery, and a 1-ft core run was attempted with the long shoe to improve recovery. The long shoe could not push through the unconsolidated medium sands, and we switched back to the short shoe. Otherwise, recovery in these coarse-grained unconsolidated sediments was very good (Fig. 2) as a result of slow drilling and adjustment of feed pressures.

On 23 March, the first core recovered 4.8 ft between 320 and 322.5 ft; the coarse sands at the top of the core were less consolidated and apparently were caved. Smooth coring continued to 330 ft. The core from 330 to 335 ft recovered only a 0.2-ft plug of peat and clay; sands were washed away as evidenced by sands in the fluids. A confining clay layer was penetrated between 335 and 355 ft. The core from 342 to 345 ft recovered 4 ft, including 1 ft left in the hole as evidenced by recoring; depths need to be adjusted between 335 and 345 to reflect 7.7 ft of recovery. We decided to set casing in these tight clays at 335 ft, concerned that the caving of the sands might compromise the hole.

On 23 March, John Curran of the New Jersey Geological Survey (NJGS) obtained an analog gamma-ray log through the rods of the hole from 352 ft to surface. Log quality was good. On 24 March, the 5-in. diameter PVC surface casing was removed and 6-in. PVC casing installed to ~4 ft. The hole was reamed to ~200 ft using HQ rod, a 5-7/8-in. diameter tricone roller bit, and heavier drilling mud to flush sand out of the hole. On 25 March, the drillers returned to Reston, Virginia, for more equipment. Drilling operations were suspended 26 and 27 March.

On 28 March, the drillers returned from Reston with 1500 ft of NQ rod, shoes, catcher, and inner and outer core barrels. Four additional drillers (William Mahoney, USGS, Water Resources; and John Longman, Lenny Washburn, and Brad Winters, all from the Bureau of Reclamation) joined the crew to prepare for 24-hr operations. On 29 March, reaming continued from 200 to 340 ft using a 5-7/8 in. tricone bit and by subbing NQ to HQ rod. Drilling mud began to seep out of the ground, and the drilling mud thickness was increased. We pulled all rods at the end of the day.

On 30 March, 4-in. PVC casing was set to 315 ft to be removed at completion. Unconsolidated pebbly coarse sand above 322.5 ft was caving into the hole and the PVC casing could not be inserted to the clay at 335 ft. These caving sands caused circulation problems. We faced either pulling casing, reaming the hole, and recasing (with no guarantee that casing would penetrate further) or continued pumping of sands out of the hole. We decided to continue drilling using heavy mud and considered recasing after penetrating the base of the "Atlantic City 800-ft sands."

On 31 March, we installed a "T" to the top of the 4-in. casing, installed a 3-5/8-in. diameter tricone roller bit, and began to lower NQ rods. At 110 ft, the casing was blocked and we pulled the rods. We installed a 3-1/8-in. wafer coring bit, reamed from 110 to 340 ft, and flushed the hole while adding additional NQ rods without an inner

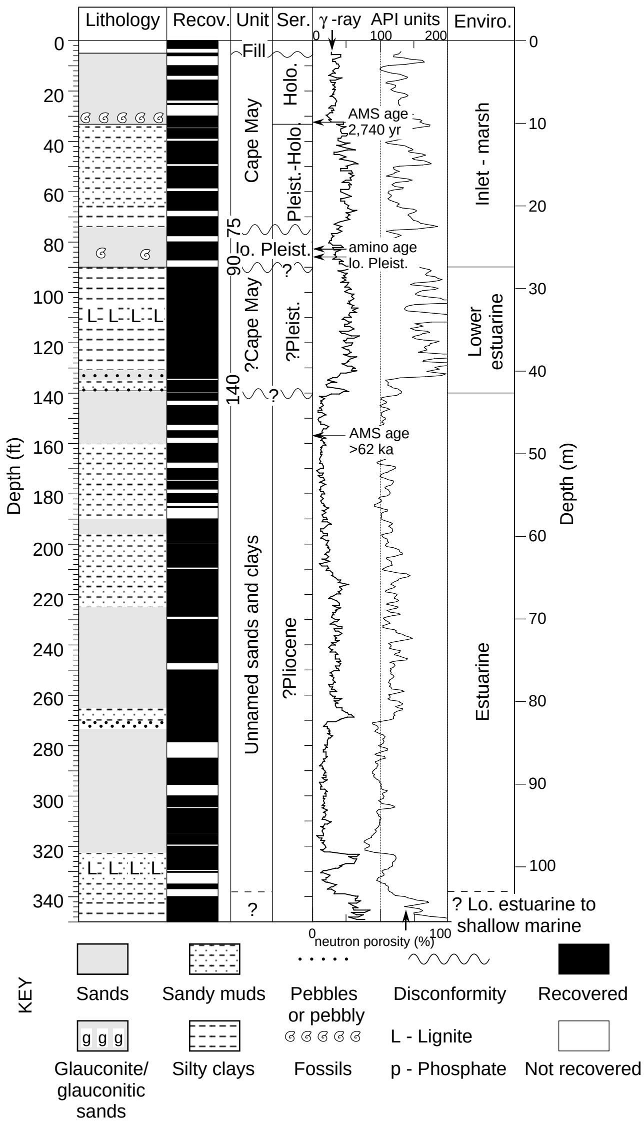

Figure 2. The Cape May (Pleistocene–Holocene) Formation and unnamed ?Pliocene sands and clays, Cape May borehole. Recovered intervals are shaded; unrecovered intervals are in white. Recov. = core recovery; Enviro. = environment of deposition.

barrel. The inner core barrel was lowered at 355 ft in preparation of taking a core. The end of the rods became blocked by very coarse sand, and the inner barrel became stuck in the rods. All rods were pulled. The gravel and coarse sands between 315 and 322.5 ft were apparently caving and lodging between the inner and outer barrels, causing circulation problems.

On 1 April, the rods were reinstalled and the core barrel reached 355 ft. We tried to add 7 ft of additional PVC casing below the base of the gravels and coarse sands (322.5 ft). Only 6 in. of additional casing penetrated. Heavier drilling mud was used to overcome the circulation problem caused by the caving of sand.

Coring resumed on 1 April at 355 ft with a Christensen CNWL (NQ) system, 3.162-in. hole diameter, and 1.875-in. (1-7/8 in.) core diameter with rock shoe, and 1.67-in. core diameter with extended shoes. The first three cores (355–370 ft) recovered 12.8 ft (85%). A lithologic change from laminated firm clay to sand was encountered at 356.9–360 ft. The medium quartz sand below 360 ft caused drilling problems caused by caving. We ran the interval from 360 to 365 ft again and recovered 2.1 ft of caved sands.

We started 10-ft core runs on 2 April. The first core (370–380 ft) recovered only 0.9 ft of pebbly sand with broken thin shells. The second core (380–390 ft) recovered 9.6 ft with shelly fine-medium quartz sand and a few shell hashes. When coring from 380 to 390 ft, caving sand again blocked the inner barrel. The rods were pulled and run back after clearing the blockage. A total of three runs (23.5 ft) were made and 13.6 ft was recovered (58%). Approximately 100 ft of rods were pulled out, and drilling was suspended on 3 April for Easter Sunday.

We began 24-hr operations on 4 April. Three shifts were run to minimize overtime costs: 0700–1500 hr (Brad Winters [driller], John Longman, and Todd Heibel), 1500–2300 hr (Gene Cobbs [driller], Gene Cobbs III, and Lenny Washburn), and 2300–0700 hr (Don Queen [driller] and William Mahoney). A heavy mud was used to prevent uncased sands from caving. Circulation was lost several times, and coring runs were delayed while the drillers flushed the hole. We began using the open (rock) shoe below 462 ft because the extended shoe would not penetrate. Coring was generally slow and recovery good on 4 April (58.6 ft recovery between 393.5 and 469.5 ft; 77%).

On 5 April, recovery was moderate between 469.5 and 600 ft (88 ft recovered; 68%), with the exception of the medium sands between 550 and 570 ft and shelly, clayey sands between 580 and 590 ft where recovery dropped below 50%. We began to experience trouble at the end of the day, losing all of the interval from 590 to 600 ft.

On the next core (6 April), we switched from the rock shoe to the medium shoe; however, we recovered only 0.3 ft from 600 to 610 ft. We switched back to the rock shoe at 613.5 ft. Only 1 ft was recovered from the next two cores to 617.5 ft, at which point the rods were pulled and the hole was flushed; the hole may have been caving between 590 and 617.5 ft and we only recovered 0.8 ft from this 27.5 ft interval. A run was then made between 617.5 and 618.5 ft without drilling, recovering 1 ft that was protruding from the bottom of the hole. Smooth coring and excellent recovery (97%) returned from 618.5 to 659 ft in interbedded sands and clays. Some chattering occurred while drilling the clays, and down pressure was adjusted to avoid washing away the sands. Smooth coring continued through laminated clays and sands until 680 ft, at which point we hit a lithified layer. We made a 1-ft run through this, recovering 0.5 ft. The remainder of this layer was found at the top of the next core (top 0.4 ft), below which we cored smoothly through clay and sand to 706.2 ft (recovered on 7 April). Despite the recovery problems noted with these lithologies, recovery for 6 April was 73% for the 100 ft drilled.

Alternating hard and soft layers hindered recovery on 7 April. Recovery was moderate (58%) from 710 to 720 ft despite penetration of a very hard unit and problems with the release latch. Recovery was poor from 720 to 730 ft (1 ft); a section apparently broke off and we re-ran the interval with no recovery. Relatively quick drilling from 730 to 740 ft may have blown away unconsolidated sands; only 0.6 ft of pebbly sand was recovered. A hard interval in this 0.6-ft section indicates that we penetrated alternations of hard and unconsolidated layers. We continued to use the rock shoe, washing caving sands for ~15 min between each run. Recovery improved in fairly consolidated sands and gravely sands from 740 to about 790 ft. A 1-ft run (790–791 ft) was attempted with the extended shoe, but we switched to a rock shoe when the shoe would not penetrate. The following 9-ft core recovered only 1.4 ft of coarse sands, indicating that sands were being blown away or the core had slipped out of the barrel. The bottom of hole (BOH) collapsed and the hole was flushed while rotating. We switched to a short extended shoe and recovered 7.3 ft on the next run (800–810 ft). Because of problems with hard/soft alternations, drilling on 7 April ended at 810 ft (110 ft drilled) with a recovery rate of 45%.

On the first core run on 8 April, the hole collapsed and we spent 1 hr regaining circulation. A run to 816 ft was attempted, but the rods became lodged while retrieving the core. Rods were pulled to a depth of 770 ft and progressively lowered while the hole was flushed. The next two runs (810–820 and 820–830 ft) saw poor recovery (25% and 32%, respectively). A lithologic change occurred at 830 ft, and we enjoyed an average recovery of 82% in very firm clayey sands and sandstones down to 882.8 ft. Midway through the 890–900 ft run, we switched to a rock catcher and cored an 8-ft-thick, very hard sandstone. We averaged 78% recovery over the next four cores through muddy sands, gravels, sandy silts, and silty clays. Recovery for 8 April averaged 67% on 130 ft drilled (86.6 ft recovered).

On 9 April, the first core (940–950 ft) recovered 10 ft. The bottom 40 ft of hole collapsed and was then flushed through the night and the hole cleared. From 950 to 960 ft, coring was slow and high pressure was applied, although recovery remained good (74%). At 960 ft, we ran into circulation problems again and we pulled 100 ft of rods. Smooth coring resumed and, over the next five cores, recoveries ranged from 77% to 97% in mainly silty clays. Only 2.1 ft were recovered from the next run (1000–1005 ft). 9 April ended with 52 ft of recovery from 65 ft drilled (81%).

At 0100 hr on 10 April, very high pressure occurred while drilling silty clay. All rods were pulled out to the surface. We found that the bit had cracked at the base of a tooth and a small piece of core was lodged between the inner barrel and bit. This may have caused misalignment of the outer and inner core barrels from 1000 to 1005 ft (42% recovery), which blocked mud flow. The 0700–1500 shift replaced the worn wafer bit with a carbide bit and sent the rods back down the hole. For the remainder of the day, we continued with recovery generally exceeding 90% in hard clay.

On 11 April, we passed into coarse-grained glauconite sands with a clay matrix, and recovery levels continued to improve. By 1800 hr, drilling was very slow and mud pressures were consistently high over the course of the afternoon and evening. The day ended with 82% recovery from 1050 to 1138 ft.

On 12 April, drilling problems developed with no recovery from 1138 to 1140 ft. All rods were pulled to the surface. The carbide bit was destroyed, proving to be unsuitable for these sediments. We had spare carbide bits but only the old wafer bit (pulled on 10 April). We considered sending Department of Reclamation drillers back early (they were scheduled to depart on 15 April) and having them return with a new wafer bit. We decided to use the old wafer bit and ran the rods back in the hole. Coring was resumed at 1730 hr. A 7-ft core was pulled out from a 10-ft (1140–1150 ft) run and the rods became blocked. Nine rods (180 ft) were pulled out and the obstruction broke loose. We increased mud weight and continued to rotate and flush. In the process, pressure dropped to <100 lb and the hole seemed to clear.

Coring resumed early on 13 April with very good recovery from the first run (1150–1160 ft; 100%), pumping 40 min between runs (20 min each at BOH and 10 ft from BOH). We capped the hole while retrieving the sand line and this seemed to prevent sands from being sucked into the hole. The next run from 1160 to 1168 ft recovered 60%. No core was recovered from 1168 to 1170 ft; from 1170 to 1180 ft we recovered only 1 ft of core. A clay plug at the base may have blocked the barrel. The next three cores (1180–1184, 1184–1190, and 1190–1200 ft) recovered 100%, 83%, and 74% of clayey glauconite sands, respectively. The clays made it easier to capture the sands and we returned to 100% recovery at 1200–1220 ft. Coring ended on 13 April, with recovery of 53 ft out of 70 ft drilled (76%).

As we were nearing the end of the contract for the extra drilling crews, scheduled from 28 March to 15 April, we discussed either suspending operations from 15 to 17 April to rest the USGS crew or to extend the Department of Reclamation drilling crew and to finish the hole by 17 April. Because drilling conditions were good, Don Queen decided to continue through the weekend and finish the hole.

On 13 April to early on 14 April, thunderstorms slowed drilling and made footing treacherous. Recovery was moderate to good from 1220 to 1248 ft (39%–93%) in consolidated/unconsolidated sands. Recovery improved in clays below 1248.5 ft. Excellent recovery and smooth drilling continued through the clays and fine-grained clayey sands (1300–1330 ft) and 1330 ft was reached by the end of 14 April (110 ft drilled, 89% recovery).

On 15 April, drilling began with a loss of most of the first run (1330–1340 ft). Good to excellent recovery soon resumed with the exception of the 1350–1360-ft interval, where a lithologic contact (1350.8 ft) separated firm glauconitic silty clay beneath from the very dark glauconitic fine sand/sandy clay above. The core from the shell bed in 1352.5–1354.5 ft was twisted and recovery was moderate (4.5 ft out of a 10-ft run). Recovery was excellent in the firm clay below 1360 ft, and most cores had full recovery. We cut short a 10-ft run after refusal occurred at 1419 ft. The following core was run 11 ft to 1430 ft. The next core (1440–1450.5 ft) slipped out of the inner barrel but was retrieved intact. At day's end, we had recovered 103.75 ft over a cored interval of 120.5 ft (86%).

On 16 April, we began coring smoothly in firm clay at 1450.5 ft with full recovery for all cores to 1480 ft. We had problems with catching the inner barrel when we attempted to pull the core from the 1480- to 1490-ft interval. The inner core barrel became lodged and efforts to free it were unsuccessful. All the rods were pulled and a full core was retrieved. We averaged 99.9% recovery over 39.5 ft of coring on 16 April.

The rods were sent back down the hole for the last core on 17 April. The final run to 1500 ft recovered 5.85 ft of core. Dennis Talbot from BPB Instruments arrived at 0930 hr to log the hole. A gamma log and neutron density log was first run through the rods down to 1500 ft. The drillers pulled the entire drill string between 1241 and 1530 hr and the hole remained open. Unfortunately, none of the slim logging tools would fit in the hole below casing. The logger was released. The gamma and neutron logging data can be matched with breaks between lithologic units identified in the subsurface, although log depths are approximately 2.5 ft shallower than corresponding core depths.

At Cape May, we recovered 1129.41 ft of core from a 1500-ft hole (mean recovery = 75%, median recovery = 85%; Table 1). Cores were photographed onsite in color using Tungsten lighting and 160T film. Lithologies were described on site and subsequently in Summer 1994 at the Rutgers core facility; these form the basis of the preliminary lithologic descriptions (Table 1). 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 pipes, wrapped in plastic sheeting, and stored in 2-ft wax boxes. One hundred seventy-nine core boxes were moved to interim storage at the Rutgers core library for further lithologic description and sampling for paleomagnetic and other studies. The cores will ultimately be stored and archived as ODP cores and transferred to the East Coast Repository.

LITHOSTRATIGRAPHY

Summary

The onsite scientific team provided preliminary descriptions of sedimentary textures, structures, colors, fossil content, identification of lithostratigraphic units (NJGS Information Circular 1, 1990), and lithologic contacts (Table 1; Figs. 2–7). Subsequent studies integrated preliminary descriptions with additional descriptions, biostratigraphy, benthic foraminiferal biofacies studies, Sr-isotopic stratigraphy, and geophysical well logs. For the nonmarine, nearshore, and shallow neritic sections (primarily the Miocene and younger section), lithofacies and gamma log interpretations provide the primary means of recognizing unconformities and interpreting paleoenvironments; Sr-isotopic ages also provide a means of recognizing hiatuses and paraconformities. For the middle to outer neritic sections (primarily the Paleogene), biostratigraphic and biofacies studies provide an ad-

Table 1. Core descriptions, Cape May borehole, Leg 150X.

Core no.	Interval (ft)	Recovery (%) (ft)	Description	Color	Formation
1	0–5	3.0 (60%)	Organic-rich mud, medium to coarse quartz sand	2.5Y 5/3, light olive brown	Recent (1940s) fill
2	5–10	0.9 (18%)	Medium quartz sand	5Y 4/1, dark gray	Cape May Formation (Holocene)
3	10–15.7	3.7 (67.3%)	Clayey fine to medium sand, H_2S odor	5Y4/1–2.5Y 5/2, dark gray	
4	15.7–20	4.4 (102.4%)	Clayey fine to medium sand, H_2S odor	2.5Y 5/2, grayish brown	Cape May Formation (?Pleistocene–Holocene)
5	20–25	3.5 (70%)	Clayey fine to medium sand, H_2S odor	5GY 5/1, greenish gray	
6	25–30	0.3 (6%)	Clayey medium sand, H_2S odor	5GY 5/1, greenish gray	
7	30–35	4.5 (90%)	Sandy clay at top; strong H_2S odor, abundant decayed plants, shell fragments at 30.9; gravel sand	5GY 4/1, dark greenish gray	
			Lithologic contact at 33.5 ft		
			Dark gray clay	5GY 4/1, dark greenish gray	?Cape May Formation (lower Pleistocene)
8	35–40	3.7 (74%)	Dark gray clay and pebbly sand	N4, dark gray	
9	40–45	4.8 (96%)	Silty clay with clayey sand lamination; strong H_2S odor	N4, dark gray	
10	45–50	3.8 (76%)	Clay at top and bottom, sand and gravel in between	N4, 5Y 5/1, gray	
11	50–55	4.4 (88%)	Dark gray clay with little silt	N4, dark gray	
12	55–60	3.35 (67%)	Massive micaceous sandy clay	5GY 4/1, dark greenish gray	
13	60–65	4.7 (94%)	Fine to very fine sand, silt, slightly micaceous	5GY 4/1, dark greenish gray	
14	65–70	2.3 (46%)	Silty/sandy clay	5GY 4/1, dark greenish gray	
15	70–75	5.3 (106%)	Laminated micaceous silty clay and clayey sand	5GY 5/1, greenish gray	
			Lithologic contact at 75 ft		
16	75–80	2.35 (47%)	Massive medium clayey sand	5GY 4/1, dark greenish gray	?Cape May Formation
17	80–83	3.7 (123%)	Massive medium quartz sand with shell fragments	5GY 4/1, dark greenish gray	
18	83–85	2.8 (140%)	Medium sand with shell bed	5GY 4/1, dark greenish gray	
19	85–90	2.0 (40%)	Medium quartz sand	5GY 4/1, dark greenish gray	
			Lithologic contact at 90 ft		
20	90–95	5.0 (100%)	Greenish gray clay	5GY 4/1, dark greenish gray	?Cape May Formation
21	95–100	4.7 (94%)	Greenish gray clay	5GY 4/1, dark greenish gray	
22	100–105	4.8 (96%)	Greenish gray clay	5GY 4/1, dark greenish gray	
23	105–110	4.7 (94%)	Greenish gray clay and silt with shells	5GY 4/1, dark greenish gray	
24	110–115	5.4 (108%)	Laminated greenish gray clay	5GY 4/1, dark greenish gray	
25	115–120	5.0 (100%)	Laminated greenish gray clay	5GY 4/1, dark greenish gray	
26	120–125	5.4 (108%)	Micaceous, laminated greenish gray clay	5GY 4/1, dark greenish gray	
27	125–130	5.0 (100%)	Laminated greenish gray clay with sand laminae	5GY 4/1, dark greenish gray	
28	130–135	4.0 (80%)	Laminated greenish gray clay with thin sand beds above 133; gravels grading to medium quartz sand below 133	5GY 4/1, dark greenish gray 5GY 6/1, greenish gray	
29	135–140	4.4 (88%)	Organic-rich sandy clay at top and bottom, medium to fine sand in between, gravels at base	5GY 4/1–N5, dark greenish gray	
			Lithologic contact at 140 ft		
30	140–145	2.7 (50%)	Medium to fine quartz sand	N5–6, gray	Unnamed sands and clays (?Pliocene)
31	145–147	2.0 (100%)	Medium to fine quartz sand	N5–6, gray	
32	147–150	2.7 (90%)	Medium to fine quartz sand with rare pebbles	N5–6, gray	
33	150–155	2.3 (46%)	Medium to fine quartz sand	N3–4, dark–very dark gray	
34	155–160	2.4 (48%)	Organic-rich, medium to coarse quartz sand	N5–6, gray	
35	160–165	4.7 (94%)	Organic-rich uniform medium sand with lignite	N3–2.5, very dark gray-black	
36	165–170	2.3 (33%)	Organic-rich uniform medium sand with lignite	N3–2.5, very dark gray-black	
37	170–175	4.1 (82%)	Organic-rich uniform medium sand	N2.5–10R 2.5, black/reddish black	
38	175–180	3.0 (60%)	Organic-rich uniform medium sand	N2.5–10R 2.5, black/reddish black	Unnamed sands and clays (?Pliocene)
39	180–185	3.4 (68%)	Medium to coarse quartz sand, clayey sand	10R 2.5/1–2.5Y 4/1, reddish black/dark gray	
40	185–190	0.4 (8%)	Medium to coarse quartz sand, clayey sand	2.5Y 4/1, dark gray	
41	190–195	5.0 (100%)	Uniform medium clayey sand	2.5Y 3/1–2.5/1, very dark gray	
42	195–200	4.5 (90%)	Medium to coarse clayey sand	2.5Y 4/1, dark gray	
43	200–205	5.0 (100%)	Medium clayey sand with pebbles	2.5Y 4/1, dark gray	
44	205–210	4.0 (80%)	Medium to coarse clayey sand, grading to a sandy clay	2.5Y 4/1, dark gray	
45	210–215	4.9 (98%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
46	215–220	4.9 (98%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
47	220–225	5.0 (100%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
48	225–230	3.5 (70%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
49	230–235	5.1 (102%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
50	235–240	4.7 (94%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
51	240–245	5.1 (102%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
52	245–250	2.0 (40%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
53	250–255	5.0 (100%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
54	255–260	4.9 (98%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
55	260–265	5.2 (104%)	Uniform, micaceous, fine to very fine clayey sand	2.5Y 4/1, dark gray	
56	265–270	5.4 (108%)	Micaceous fine to medium clayey sand with pebbles	2.5Y 4/1, dark gray	
57	270–275	4.8 (96%)	Gravel or pebbly subangular, coarse, quartz sand	2.5Y 4/1, dark gray	
58	275–280	3.4 (68%)	Fine sand with pebbles	N6/, gray	
59	280–285	0.0 (0%)	No recovery		
60	285–286	1.3 (130%)	Medium sand	5Y 6/1, gray	
61	286–290	4.0 (100%)	Medium and very coarse sand	5Y 4/1, dark gray	
62	290–295	5.0 (100%)	Coarse to very coarse sand	5Y 4/1, dark gray	
63	295–300	0.3 (6%)	Coarse to very coarse sand	5YR 3/1, very dark gray	
64	300–305	4.2 (84%)	Coarse to very coarse sand with pebbles	N5/, gray	
65	305–310	4.6 (92%)	Medium sand with lignite and pebble layers	N5/, gray	
66	310–312	1.7 (85%)	Medium to very coarse sand	N5/, gray	
67	312–315	2.5 (83.3%)	Medium sand with pebbles	N5/, gray	
68	315–320	4.0 (80%)	Medium to coarse sand	N5/, gray	Unnamed sand–clay (?Pliocene)
69	320–322.5	4.8 (192%)	Coarse quartz sand and pebbly sand	5Y 5/1, gray	
70	322.5–325	2.7 (108%)	Laminated silty sandy clay and clayey silty	2.5Y 3/1, very dark gray	
71	325–330	4.1 (82%)	Laminated silty sandy clay and clayey silt with peat	2.5Y 3/1, very dark gray	

Table 1 (continued).

Core no.	Interval (ft)	Recovery (%) (ft)	Description	Color	Formation
72	330–335	0.2 (4%)	Laminated sandy clay	2.5Y 3/1, very dark gray	
73	335–340	1.7 (34%)	Dark brown clay with fine to medium sand laminations	5Y 4/1, dark gray	
74	340–342	2.1 (105%)	Laminated silty sandy clay and clayey silt with peat	5Y4/1, dark gray	
75	342–345	3.9 (130%)	Laminated silty clay with sandy clay with peat	5GY 4/1, dark greenish gray; 2.5Y 3/1, very dark gray	
76	345–350	4.9 (98%)	Laminated silty clay with sandy clay with peat	5GY 4/1, dark greenish gray	
77	350–355	5.1 (102%)	Laminated clay	5GY 4/1, dark greenish gray	
78	355–360	3.8 (76%)	Laminated clay, silt and fine sand, micaceous	5Y 4/1, dark gray	
			Lithologic contact at 356.9 ft		
79	360–367	2.3 (32.9%)	Homogeneous medium quartz sand, shells common	5Y 6/1, gray	Kirkwood-Cohansey (upper middle Miocene)
80	367–370	6.7 (223%)	Homogeneous medium quartz sand, shells common	5Y 6/1, gray	
81	360–365		Hole collapsed, started over at 360 ft		
82	370–380	0.9 (9%)	Pebbles and pebbly quartz sand with weathered shells	5Y 5/1, gray	
83	380–390	9.6 (96%)	Fine to medium quartz sand with silty clay laminations	5Y 5/1, gray	
84	390–393.5	3.1 (91.3%)	Medium-coarse clayey sand, shells common	5Y 5/1, gray	
85	393.5–400	3.2 (49.3%)	393.5–395.3: Medium to coarse clayey sand 395.3–396.7: Clay	5Y 5/1, gray 5GY 4/1, dark greenish gray	
86	400–410	10.3 (103%)	Laminated silty clay and clayey silt	5GY 4/1, dark greenish gray	
87	410–420	9.5 (95%)	Laminated silty clay and clayey silt with shells and pebbles	5GY 4/1, dark greenish gray	
88	420–422	1.5 (75%)	Fine to medium sand with shells	5GY 4/1, dark greenish gray	
			Lithologic contact at 422 ft		
89	422–430	5.3 (75.9%)	Fine to medium sand with shells	5GY 4/1, dark greenish gray	
90	430–440	8.9 (89%)	Fine, medium to coarse pebble sand with shells	N5–6/, gray	
			Lithologic contact at 432.2 ft		
91	440–450	9.2 (92%)	Fine clayey sandwith clay laminae	5B 4/1, dark bluish gray	Kirkwood 3 (lower middle Miocene)
92	450–460	3.0 (30%)	Fine to medium clayey sand	5B 4/1, dark bluish gray	
93	460–463	2.7 (90%)	Fine to medium clayey sand and sandy clay, indurated bed	N3–4/, dark gray	
94	463–469.5	5.0 (79%)	Firm, uniform sandy clay and silt green gray; 5Y4/1, dark gray	N3–5GY 4/1, very–dark gray	
95	469.5–479.5	6.4 (64%)	Firm sandy clay and silt	N3–5GY 4/1, very dark gray–green gray; 5Y4/1, dark gray	
96	479.5–485	6.2 (112%)	Firm brownish micaceous clay and silt	5Y 4/1, dark gray	
97	485–490	5.7 (114%)	Very firm micaceous clay and silt	5GY 4/1, dark greenish gray	
98	490–500	8.3 (83%)	Laminated firm silty clay and silt	5GY 4/1, dark greenish gray	
99	500–510	8.0 (80%)	500–502.9: Laminated firm silty clay	5GY 4/1, dark greenish gray	
			Lithologic contact 502.9 ft		
			502.9–508: Medium clayey sand, indurated	5GY 4/1, dark greenish gray	Unnamed Kirkwood (middle middle Miocene)
100	510–520	6.25 (62.5%)	Medium clayey sand with shells	5YR 3/1, very dark gray	
101	520–530	9.8 (98%)	Medium clayey sand with shells	5YR 3/1, very dark gray	
102	530–540	8.4 (84%)	Fine to medium clayey sand, change to clean sand at 535.8	5YR 3/1, very dark gray	
103	540–550	9.7 (97%)	Uniform fine to medium clayey sand	5GY 5/1, greenish gray	
104	550–560	4.5 (45%)	Uniform fine to medium clayey sand	5GY 4/1, dark greenish gray	
105	560–570	3.0 (30%)	Uniform fine to medium clayey sand	5GY 4/1, dark greenish gray	
106	570–580	7.6 (76%)	Uniform fine to medium clayey sand in upper 5; silty clay below 575.7 and with shells	5GY 4/1, dark greenish gray, 10YR 6/1, gray	
			Lithologic contact 575.7 ft		
107	580–590	4.4 (44%)	Indurated clayey sand and broken shells	N 6–5/, gray	Kirkwood 2b (lower middle Miocene)
108	590–600	0.0 (0%)	No recovery, perhaps shell hash		
109	600–610	0.3 (3%)	Shell hash in clayey sand matrix	5GY 4/1, dark greenish gray	
110	610–613.5	0.5 (14.3%)	Shell hash in clayey sand matrix	5GY 4/1, dark greenish gray	
111	613.5–617.5	0.5 (12.5%)	Shell hash in clayey sand matrix	5GY 4/1, dark greenish gray	
			Lithologic contact 617.5 ft		
112	617.5–618.5	1.1 (110%)	Clayey fine to medium sand	N 5–3/1, gray (lower Miocene)	
113	618.5–628.5	8.9 (89%)	Uniform fine sand with brown clay laminations	N 5/1, gray	
114	628.5–638.8	10.2 (99%)	Laminated firm clay with loose fine to medium sand, organic rich	N 5/1–2.5Y 3/2, gray	
115	638.8–649	10.7 (105%)	Fine to medium sand and brown clay laminations	N5/–2.5Y 3/2, gray	Kirkwood 2a (lower Miocene)
116	649–659	9.5 (95%)	Interbedded firm silty clay and fine sand	N5/–2.5Y 3/2, gray	
117	659–669	7.15 (71.5%)	Interbedded firm silty clay and fine sand and silty sand	N5/, gray	
118	669–679	9.3 (93%)	Silty to sandy clay changes to clayey coarse sand with broken shells	N3/, very dark gray	
			Lithologic contact 680 ft		
119	680–681	0.5 (50%)	Indurated sandy clay	N3/, very dark gray	
120	681–690	6.6 (66%)	Indurated medium to coarse sand with shells, changes to silty clay below 685 ft	N4/– 5GY 4/1, dark gray–dark greenish gray	
121	690–700	7.9 (79%)	Firm brownish clay	N3/–2.5Y 3/1, very dark gray	
122	700–710	6.4 (64%)	Firm brownish clay with broken shells	2.5Y 4/1, dark gray	
			Lithologic contact 710 ft		
123	710–710.1	0.1 (100%)	2.5Y 4/1, very dark gray		Unnamed Kirkwood (lower Miocene)
124	710.1–720.1	5.5 (55%)	Consolidated shelly gravel and pebble bed and changes to clayey pebbly coarse sand below 710.9 ft	2.5Y 4/1, dark gray	
125	720.1–730	1.0 (10%)	Consolidated clayey pebbly coarse sand	2.5Y 4/1, dark gray	Unnamed Kirkwood (lower Miocene)
126	720–730		Rerun, no recovery		
127	730–740	0.6 (6%)	Shell hash in pebbly coarse sand	2.5Y 3/1, very dark gray	
128	740–749	1.5 (16.7%)	Coarse sand and clay with broken shells	N4/, dark gray	
129	749–760	4.7 (42.7%)	Consolidated coarse sand with broken shells	N5/, gray	
130	760–770	5.0 (50%)	Shell bed, medium sand and sandy clay	5Y 4/1, dark gray	

Table 1 (continued).

Core no.	Interval (ft)	Recovery (%) (ft)	Description	Color	Formation
			Lithologic contact 762 ft		
131	770–780	6.9 (69%)	Medium clayey sand and sandy clay	2.5Y 4/1, dark gray	
132	780–790	7.3 (73%)	Pebbly coarse clayey sand	N5–6/, gray	
133	790–791	1.3 (130%)	Clayey medium sand	N5–6/, gray	
134	791–800	1.4 (85%)	Medium to coarse clayey sand	N5–6/, gray	
135	800–810	7.3 (73%)	Poorly sorted clean quartz sand with lignite interbedded with clayey sand	N5–6/, gray	
136	810–820	2.5 (25%)	Fine to medium sand with shells	N4/, dark gray	
137	820–830	3.2 (2%)	Fine to medium sand with shells	N4/, dark gray	
138	830–840	9.3 (93%)	Clayey sand with broken shells	10YR 3/1	
139	840–850	7.0 (70%)	Silty clay with thin shells	10YR 3/2, very dark grayish brown	
			Lithologic contact 850 ft		
140	850–860	4.3 (43%)	Fine to medium clayey sand	2.5Y 5/1, gray	Kirkwood 1b (lower Miocene)
141	860–870	9.8 (98%)	Medium to coarse clayey sand with shells	N4/, dark gray	
142	870–880	9.0 (90%)	Medium to coarse clayey sand with shells	N4/, dark gray	
143	880–890	9.7 (97%)	Fine, medium, or coarse clayey sand with shells	5GY 4/1, dark greenish gray	
144	890–900	8.5 (85%)	Fine, medium, or coarse clayey sand with shells	5GY 4/1, dark greenish gray	
145	900–910	7.8 (78%)	Fine, medium, or coarse clayey sand with shells	N3/, very dark gray	
146	910–920	7.6 (76%)	Fine, medium, and coarse clayey sand, with silty clay at base	N3/, very dark gray	
147	920–930	7.9 (79%)	Laminated silty clay and clayey sand with shells	N3/, very dark gray	
148	930–940	7.9 (79%)	Laminated silty clay and clayey sand with shells	N3/, very dark gray	
149	940–950	10.0 (100%)	Laminated silty clay and clayey sand	N3/, very dark gray	
			Lithologic contact 942 ft		
150	950–960	7.4 (74%)	Gray uniform fine sand and laminated silty clay and clayey sand, burrowed	5Y 3/1, very dark gray	Kirkwood 1a (lower Miocene)
151	960–970	7.7 (77%)	Laminated firm silty clay and clayey fine sand	2.5Y 5/1, gray	
152	970–980	9.5 (95%)	Laminated firm silty clay and clayey fine sand	5Y 3/1, very dark gray	
153	980–990	9.7 (97%)	Laminated firm clay and clayey silt	5YR 3/1, very dark gray	
154	990–1000	8.3 (83%)	Laminated firm clay and clayey silt	5YR 3/1, very dark gray	
155	1000–1005	2.1 (42%)	Laminated firm clay and clayey silt	5YR 3/1, very dark gray	
156	1005–1010	0.0 (0%)	No recovery		
157	1010–1020	10.3 (103%)	Very dark firm clay with shells above 1012.8 ft; laminated and bioturbated firm clay with shells and one sand layer at 1017.2 ft	5Y 3/1, very dark gray 5GY 4/1, dark greenish gray	
158	1020–1030	9.2 (92%)	Bioturbated firm clay with shells	5Y 3/1, very dark gray	
159	1030–1035	4.9 (98%)	Burrowed glauconitic silty clay	5Y 3/1, very dark gray	
160	1035–1040	3.5 (35%)	Burrowed glauconitic silty clay	5Y 3/1, very dark gray	
161	1040–1050	10.3 (103%)	Burrowed glauconitic silty clay	5Y 3/1, very dark gray	
162	1050–1060	9.3 (93%)	Burrowed glauconitic silty clay above 1056.8 ft; burrowed glauconitic sandy clay grades down to glauconite sand	5Y 3/1, very dark gray, N2.5/, black	
163	1060–1065	4.9 (98%)	Consolidated glauconite sand with shells	5G 5/2, grayish green	
			Lithologic contact 1062 ft		
164	1065–1070	3.7 (74%)	Dark hard shell hash and clayey glauconite coarse sand	N3/–5G 4/1, dark greenish gray	Kirkwood equivalent, (Kw0) glauconite sand, and clay
165	1070–1077	7.0 (100%)	Dark hard shell hash and clayey glauconite coarse sand	N3/–5G 4/1, dark greenish gray	
166	1077–1080	0.0 (0%)	No recovery		
167	1080–1090	10.5 (105%)	Firm, coarse glauconite to quartz clayey sand with shells	N3/, very dark gray	
168	1090–1100	9.8 (98%)	Bioturbated, firm, coarse glauconite to quartz clayey sand	N3/, very dark gray	
169	1100–1110	7.0 (70%)	Pebbly coarse-grained glauconite sand with shells	N3/, very dark gray	
170	1110–1120	6.8 (68%)	Pebbly coarse-grained glauconite sand with shells	N3/, very dark gray	
171	1120–1130	6.7 (67%)	Pebbly coarse-grained glauconite sand with shells	N3/, very dark gray	
172	1130–1135	4.5 (90%)	Pebbly coarse-grained glauconite sand with shells	N3/, very dark gray	
173	1135–1138	2.4 (80%)	Coarse, hard glauconite to quartz sand	N3/, very dark gray	
174	1138–1140	0.0 (0%)	No recovery		
175	1140–1150	7.0 (70%)	Medium to coarse firm clayey glauconite sand with shells	N3/, very dark gray	
176	1150–1160	10.0 (100%)	Medium to coarse firm clayey glauconite sand with shells	N3/, very dark gray	
177	1160–1168	5.5 (68.8%)	Medium to coarse firm clayey glauconite sand with shells	N3/, very dark gray	
178	1168–1170	0.0 (0%)			
179	1170–1180	1.0 (10%)	Medium to coarse firm clayey glauconite sand with shells	5GY 4/1, dark greenish gray	
180	1180–1184	4.0 (100%)	Medium to coarse firm clayey glauconite sand with shells	5GY 4/1, dark greenish gray	
			Lithologic contact at 1180 ft		
181	1184–1190	5.0 (83%)	Medium to fine clayey quartzose glauconitic sand	5GY 4/1, dark greenish gray	Unnamed upper Oligocene
182	1190–1200	7.3 (73%)	Medium to fine clayey quartzose glauconitic sand	5GY 4/1, dark greenish gray	
183	1200–1210	10.1 (101%)	Medium to fine clayey quartzose glauconitic sand	5GY 4/1, dark greenish gray	
			Lithologic contact at 1210 ft		
184	1210–1220	10.2 (102%)	Very coarse to coarse quartz sand at top and fine to medium clayey sand below	5G 4/2, grayish green	
185	1220–1230	3.9 (39%)	Very coarse to coarse quartz sand with shells	5GY 4/1, dark greenish gray	
186	1230–1240	4.8 (48%)	Very coarse to coarse to medium quartzose glauconite sand, sandy clay and clayey sand	5GY 4/1, dark greenish gray	
187–188	1240–1250	9.2 (92%)	Fine to coarse shelly quartzose glauconite sand above 1248.5	5GY 4/1, dark greenish gray	
			Lithologic contact 1248.5 ft		
			Indurated and laminated clayey glauconite sand and sandy clay	5Y 5/1, gray	Unnamed upper Oligocene
189	1250–1260	7.8 (78%)	Indurated and laminated clayey glauconite sand and sandy clay	5Y 3/2, dark olive gray	
190	1260–1270	8.5 (84%)	Shelly, burrowed silty clay and clayey glauconite sand	5Y 3/2–4/2, olive gray	
			Lithologic contact 1270 ft		
191	1270–1280	10.1 (101%)	Slightly glauconitic sandy to silty clay	5Y 3/2-5/2, olive gray	Unnamed lower Oligocene
192	1280–1290	8.2 (82%)	Laminated glauconitic sandy to silty clay	5GY 4/1, dark greenish gray	

Table 1 (continued).

Core no.	Interval (ft)	Recovery (%) (ft)	Description	Color	Formation
193	1290–1300	10.4 (104%)	Laminated glauconitic sandy to silty clay	5Y 3/2, olive gray	
			Lithologic contact 1300 ft		
194	1300–1310	9.1 (91%)	Glauconitic silt and sandy to silty clay	2.5Y 3/3, dark olive gray	
195	1310–1316.3	5.6 (89%)	Burrowed, clayey glauconitic fine sand	2.5Y 3/2, very dark grayish brown	
196	1316.3–1320	3.7 (100%)	Clayey glauconitic fine sand	2.5Y 3/2, very dark grayish brown	
197	1320–1330	8.7 (87%)	Clayey glauconitic fine sand	2.5Y 3/2, very dark grayish brown	
198	1330–1340	2.6(26%)	Clayey glauconitic fine sand	2.5Y 3/2, very dark grayish brown	
199	1340–1340.5	0.5 (100%)	Clayey glauconitic fine sand to silty clay	N/3, very dark gray	
200	1340.5–1350	9.0 (95%)	Clayey glauconitic fine sand to silty clay with pyrite nodules	N/3, very dark gray	
201	1350–1360	4.5 (45%)	Clayey glauconitic fine sand to silty clay with pyrite nodules above 1350.8 ft	2.5Y 4/1, dark gray	
			Lithologic contact 1350.8 ft		
			Burrowed and laminated brownish firm clay between 1350.8 and 1352 mbsf; firm glauconitic silty clay between 1352 and 1352.5 mbsf, shell bed in brown clay matrix below 1352.5	N/3, very dark gray, 2.5Y 3/1, very dark gray	Unnamed lower Oligocene
			Lithologic contact 1360 ft		
202	1360–1370	10.5 (105%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	ACGSα Unit upper Eocene
203	1370–1380	7.1 (71%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
204	1380–1390	10.3 (103%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
205	1390–1400	10.2 (102%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
206	1400–1410	8.0 (80%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
207	1410–1419	10.0 (111%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
208	1419–1430	10.4 (95%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
209	1430–1440	10.4 (104%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
210	1440–1450.5	10.4 (99%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
211	1450.5–1460	9.45 (98%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
212	1460–1470	10.3 (103%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
213	1470–1480	9.7 (9.7%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
214	1480–1490	10.0 (100%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	
215	1490–1500	5.85 (58.5%)	Laminated firm silty clay with visible microfossils	5Y 3/1–4/1, dark gray	

Notes: Total depth = 1500 ft, mean recovery = 75%, median recovery = 85%.

ditional means of recognizing unconformities and the primary means of interpreting paleoenvironments. Benthic foraminiferal biofacies were used to recognize inner (0–30 m), middle (30–100 m), and outer (100–200 m) neritic 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 and Sr-isotopic age breaks. Recognition of these surfaces allow identification of sequences at the Cape May borehole.

Cape May Formation

Age: Pleistocene to Holocene
Interval: 5–140? ft (1.5–42.7 m)

The top of the borehole penetrated fill to 5 ft (1.5 m; 0 ft above sea level). The fill dates to the 1940s and is recognized by a soil horizon at the top underlain by poorly sorted yellowish sands. Below this are the unconsolidated gravels, sands, silts, and clays of the upper Pleistocene to Holocene Cape May Formation.

The interval from 5 to 33 ft (1.5–10 m) is predominantly clayey medium sand and sporadic pebbly sand with a strong H_2S odor. There is a shelly interval at 30.9 ft (9.4 m), an organic-rich (decayed marsh flora) sandy clay at 32.3–33.1 ft (9.8–10.1 m), and a pebbly sand at 33.2–33.5 ft (10.1–10.2 m) that overlies a contact at 33.5 ft (10.2 m). An inlet-marsh environment is inferred based on continuity of the upper section with the modern inlet and the association of marsh flora and marine shells in the lower section. An accelerator mass spectrometer radiocarbon date of 2740 yr was measured at the Woods Hole Oceanographic NOAMS facility on the marsh flora at 33 ft (10 m), indicating that this section is upper Holocene.

The dominant lithology from 33.5 to 55 ft (10.2–16.8 m) is a sandy, silty clay with sporadic wood fragments (1–2 mm) from 35 to 40 ft (10.7–12.2 m). The interval from 55 to 65 ft (16.8–19.8 m) consists of micaceous sandy silty clay and fine to very fine sand. From 65 to 75 ft (19.8–22.9 m) laminated clay becomes common. These clays contain virtually no silt/sand and have alternating dark and light bands. The clays from 33.5 to 75 ft (10.2–22.9 m) have high gamma log values, whereas the overlying sands have low values. We interpret the section from 5 to 75 ft (1.5–22.8 m) as a coarsening-upward, ?latest Pleistocene (<14 ka) to Holocene sequence (Fig. 2).

At 75 ft (22.9 m), the lithology changes to a massive medium quartz sand with a few percent dark minerals that may mark a disconformity. Shell fragments become locally abundant from 82.6 to 87 ft (25.2–26.5 m). The interval from 75 to 87 ft (22.9–26.5 m) may reflect an inlet-marsh environment, similar to the section above 33.5 ft (10.2 m). This interpretation is consistent with the presence of the brackish water diatom *Nitzschia granulata* (see “Biostratigraphy” section, this chapter) and the shallow-water benthic foraminifers *Elphidium* and *Ammonia.* Amino acid racemization indicates that 83.7 and 85.6 ft (25.5 and 26.1 m) are lower Pleistocene based on *Mulinia* D/L values (0.53 ± 0.05; ~1–1.9 Ma; J. Wehmiller, pers. comm., 1995). This suggests that the section from 75 to 90 ft (22.8–27.4 m) represents an early Pleistocene sequence.

A lithologic change occurs at about 90 ft (27.4 m), with greenish gray clay below. This change represents a facies shift from inlet-marsh sands and clays above to estuarine clays below, and may mark the base of the Cape May Formation at this borehole. The contact occurs in the nonrecovered interval between 87 and 90 ft (26.5 and 27.4 m). The clay continues to 130.6 ft (39.8 m) and has virtually no silt/sand and sporadic shell material. The clay is thinly laminated with organic-rich and silty sand laminations. A sharp lithologic break at 132.95 ft (40.5 m) separates the laminated clay above from a medium sand below; a gravel marks the contact. A 4-ft-thick (1.2 m), medium sand (133–137 ft; 40.5–41.8 m) is bracketed by gravels; the lower gravel extends to 140 ft (42.7 m). We interpret the section from 90 to 140 ft (26.5–42.7 m) as estuarine, with the gravels and medium sands deposited in small channels. The common presence of diatoms in this section indicate a strong marine influence on the estuary (i.e., lower estuarine).

We tentatively retain the lower estuarine clays and gravels from 90 to 140 ft (27.4–42.7 m) in the Cape May Formation and infer that

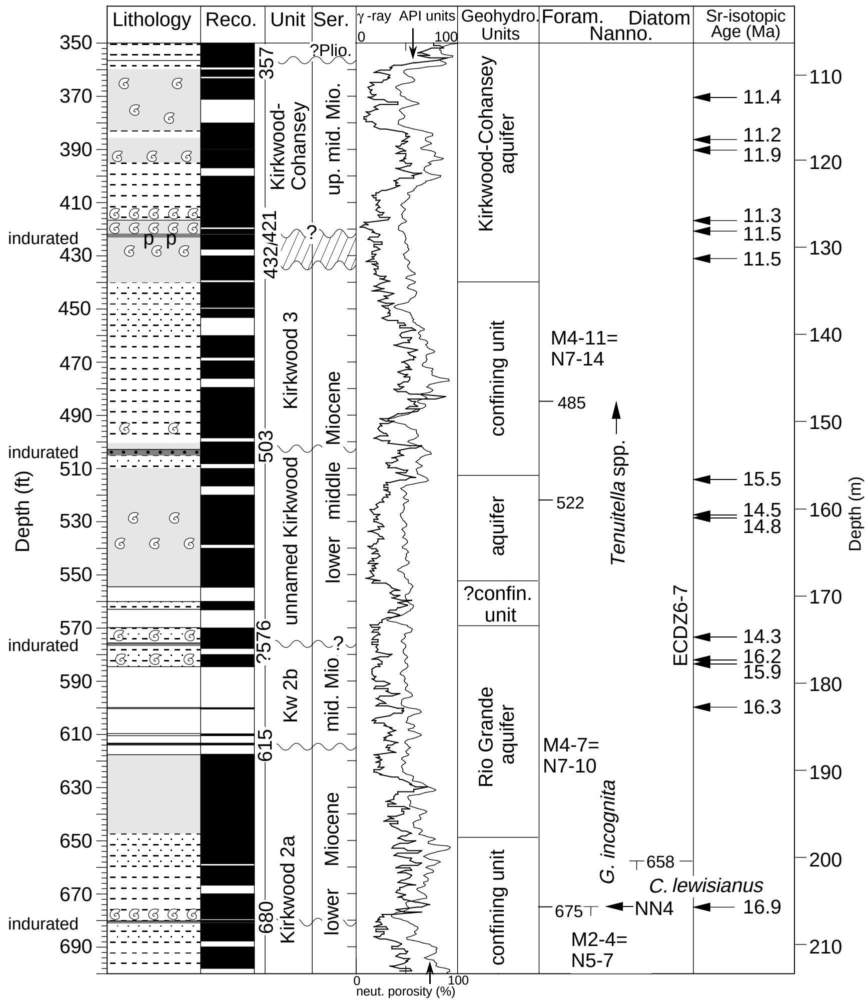

Figure 3. Middle Miocene portion of the Kirkwood Formation, Cape May borehole. The key for symbols is given in Figure 2.

it is Pleistocene. At a borehole drilled at Cape May airport by the USGS Branch of Eastern Regional Geology (D. Powars, unpubl. data, 1994; Owens et al., 1995), the base of the Quaternary was placed at 183 ft (55.8 m) below land surface (163 ft [49.7 m] below sea level) based on pollen studies. This level at Cape May airport is associated with a change from predominantly sands below to predominantly silty clays above. We note a similar lithologic contact at the top of this unit at 140 ft (135 ft below sea level) at the Cape May borehole and tentatively draw the base of the formation at this level. (Note added in proof: L. de Verteuil [pers. comm., 1996] reports upper Miocene dinocysts below 92 ft [28.0 m].)

Unnamed Sands and Clays

Age: ?Pliocene
Interval: 140–357 ft (42.7–108.8 m)

Medium to fine sands with sporadic organic matter and sandy clays are found from 140 to 160 ft (42.7–48.8 m). At about 160 ft (48.8 m), muddy sands become notably organic rich and very dark gray to black, gradually becoming reddish black to black down to 181 ft (55.2 m). Below 181 ft, the sands are dark gray and micaceous, and they become coarser. Between 200 and 206.7 ft (60.9–63 m), two 3-ft-thick (0.9 m) fining-upward successions are noted (dark gray clay, fine muddy sands, and medium to very coarse sands). Below 207 ft (63.1 m), the section consists of micaceous, fine to very fine silty sands with sporadic parallel and cross laminations. These sands continue to 264.6 ft (80.7 m) where the clay content increases, with a pebble layer at 268.2 ft (81.8 m). A coarse sandy gravel from 271.4 to 273.3 ft (82.7–83.3 m) changes to a fine quartz sand (275–280 ft; 83.8–85.3 m) that grades down to medium and coarse pebbly sand (285–322.5 ft; 86.9–98.3 m). An environmental interpretation of fluvial channels/estuarine is supported by the rapid changes in lithology and bedforms and the general absence of diatoms; the brackish water diatom *Nitzschia granulata* is observed where diatoms are present (see "Biostratigraphy" section, this chapter).

A sharp change to predominantly clay occurs at 322.5 ft (98.3 m). An approximately 7-ft-thick (2 m) clay layer from 322.5 to 330 ft (98.3–100.6 m) exhibits laminations of darker, apparently organic rich layers (with peats at 326.2, 327.4, and 327.9 ft) and lighter gray layers. The interval from 330.4 to 335 ft (100.7–102.1 m) was not recovered, but it is apparently sand based on cuttings and the gamma log.

The age of the sands and clays is uncertain. A radiocarbon date at 156.4 ft (47.6 m) yields a background age of >62 ka. Pollen studies at the nearby Cape May airport borehole indicate that this section is probably Pliocene (L. Sirkin, pers. comm., 1994). At that borehole, the top of the Pliocene is placed at 183 ft (55.8 m) below land surface based on pollen studies (163 ft [49.7 m] below sea level; L. Sirkin, pers. comm., 1994). A ?Pliocene unit has been informally called the Manokin Formation at the Oh25-02 Lewes, Delaware well (Fig. 1), where it lies at similar depths (173–310 ft [52.7–94.5 m] at

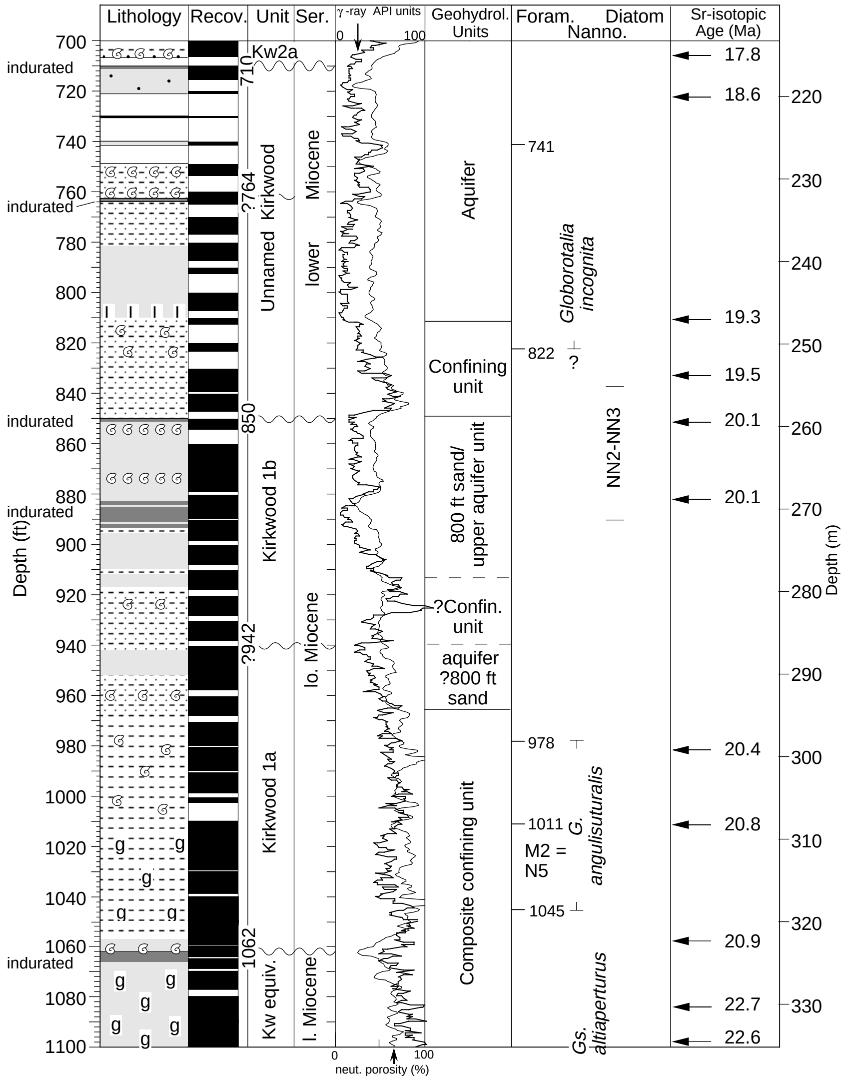

Figure 4. Lower Miocene portion of the Kirkwood Formation, Cape May borehole. The key for symbols is given in Figure 2.

Lewes) to the clay-sand unit in the Cape May borehole (Benson, 1990).

From 335 to 357 ft (102.1–108.8 m), we recovered laminated green and brown clays and slightly sandy clays lacking fossils. Near the base of the section, laminations become thicker and pyritized burrows appear. The base of the section is lower estuarine–shallow marine, as indicated by the presence of a few pyritized diatoms and rare to common benthic foraminifers from 354.1 to 357 ft (107.9–108.8 m). This clay unit has a distinct high gamma log signature. It is possible that this clay unit could be part of the Kirkwood Formation (see below); however, we recognized the top of definite Kirkwood Formation by the appearance of shells at 357 ft (108.8 m) in a clayey sand. This clay unit has been assigned to the ?St. Marys Formation at the Oh25-02 Lewes, Delaware well (310–382 ft; 94.5–116.5 m; Benson, 1990). We are not certain of the age of this unit (the ?St. Marys Formation is inferred to be upper Miocene; Benson, 1990), and the unit could be assigned to either the Pliocene unnamed sands and clays or older Miocene formations. However, the environment of deposition of these clays is similar to the estuarine clays and sands between 140 and 335 ft (42.7 and 102.1 m) (albeit more marine influenced), and we retain them in the same lithostratigraphic unit.

Kirkwood Formation

Age: early to middle Miocene
Interval: 357–1062.3 ft (108.8–323.7 m)

Owens et al. (1995) have recently redefined the Kirkwood Formation, previously recognized as the lower to middle Miocene sands and clays in New Jersey (e.g., Sugarman et al., 1993). They recognized four formations increasing in age: Belleplain, Wildwood, Shiloh Marl, and Kirkwood, equivalent to the Kirkwood 3, Kirkwood 2a and 2b, Kirkwood 1b, and Kirkwood 1a and Kirkwood 0, respectively, of Sugarman et al. (1993), Miller and Sugarman (1995), and this report. We have retained the older use of the Kirkwood Formation (e.g., Kirkwood 0 to Kirkwood 3) in this report to be consistent with other Leg 150X site reports (Miller et al., 1994a, 1994b).

Kirkwood-Cohansey Sequence

Age: 11.2–11.9 Ma, late middle Miocene
Interval: 357–432.2 ft (108.8–131.8 m)

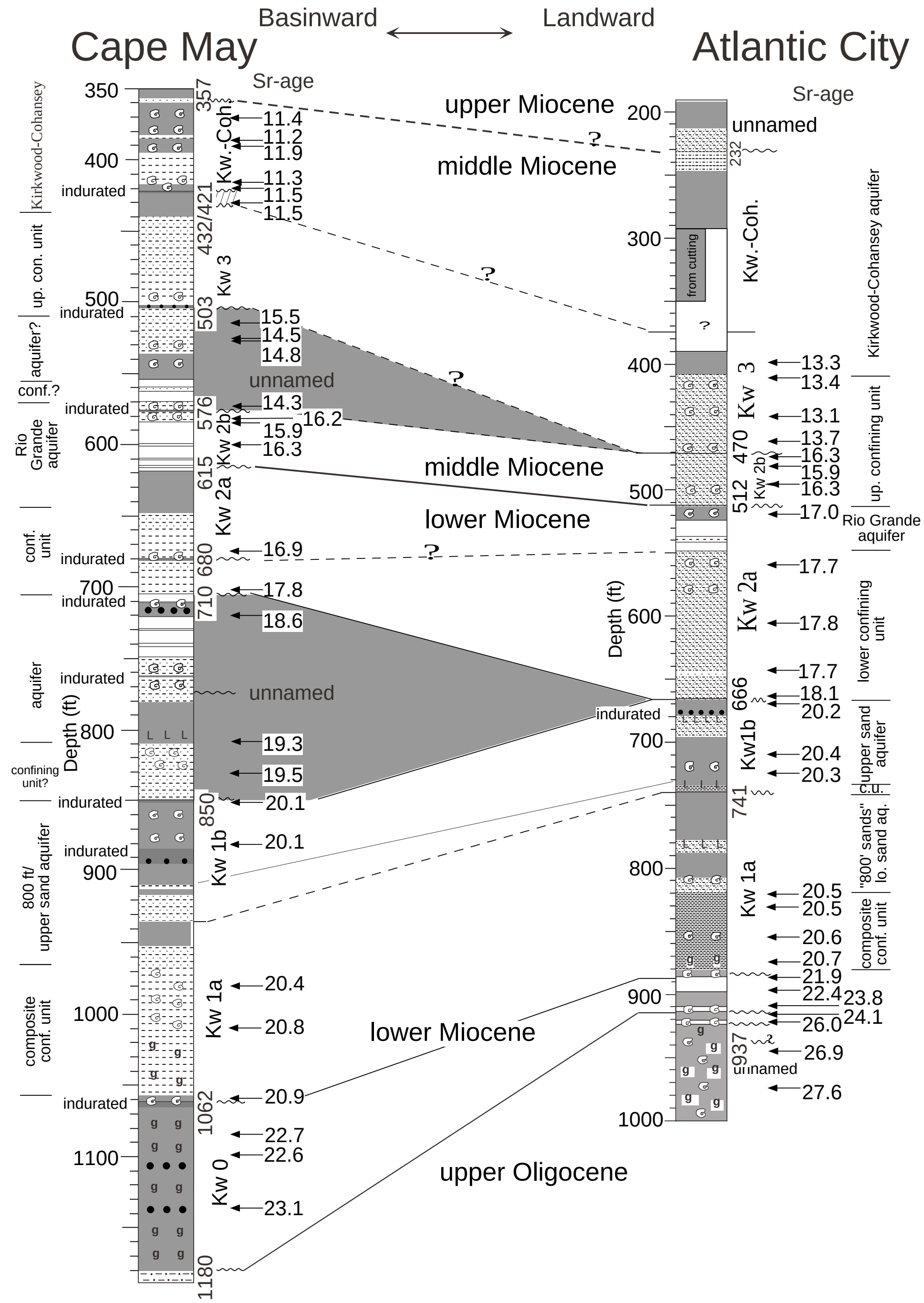

Figure 5. Correlation between Cape May and Atlantic City Miocene sections.

The middle to lower Miocene Kirkwood Formation was first recovered at 356.9 ft (108.7 m) (the “357-ft unconformity”; Fig. 3), where it consists of a uniform medium quartz sand with shells. This lithology dominates to 395.3 ft (120.5 m) with sporadic thin laminated firm clays (e.g., 383–384.6 ft). We interpret these sands as neritic-nearshore; they contain diatoms and sporadic inner neritic foraminifers.

A tight greenish gray clay was penetrated below 395.3 ft (120.5 m). The contact between sands above and clays below is very sharp and marked by a shell bed. The clays are massive at the top but become laminated downsection with interbedded silts and clays with sporadic shell fragments. This lithology continues to 417.1 ft (127.2 m), where there is a shell bed (417.6–418.4 ft; 127.3–127.6 m) and a change to medium sand (418.4–421 ft; 127.6–128.4 m).

A possible sequence boundary occurs between 421.5 (128.5 m; the base of a shell bed from 421 to 421.5 ft) and 422 ft (128.6 m) (Fig. 3). From 422 to 422.5 ft (128.6–128.8 m), there is an indurated phosphatic fine sand; the sands are generally poorly sorted and contain abundant shell fragments and pebbles, indicating marine shelf deposition. Several sequences below this (e.g., 503, 576, 680, 710, and 850 ft; Figs. 3–4) show an upsection pattern of basal shell beds, silts, sands, and lithified slightly shelly sands overlain by the shell bed of the overlying sequence; we placed sequence boundaries at the top of the lithified units in these other sequences, consistent with 422 ft (128.6 m) being a sequence boundary. However, Sr-isotopes indicate no age break across the 422-ft surface (128.6 m) (Table 2).

The section from 422.5 to 432.2 ft (128.8–131.8 m) consists of shelly fine-medium sands and is included as part of one sequence

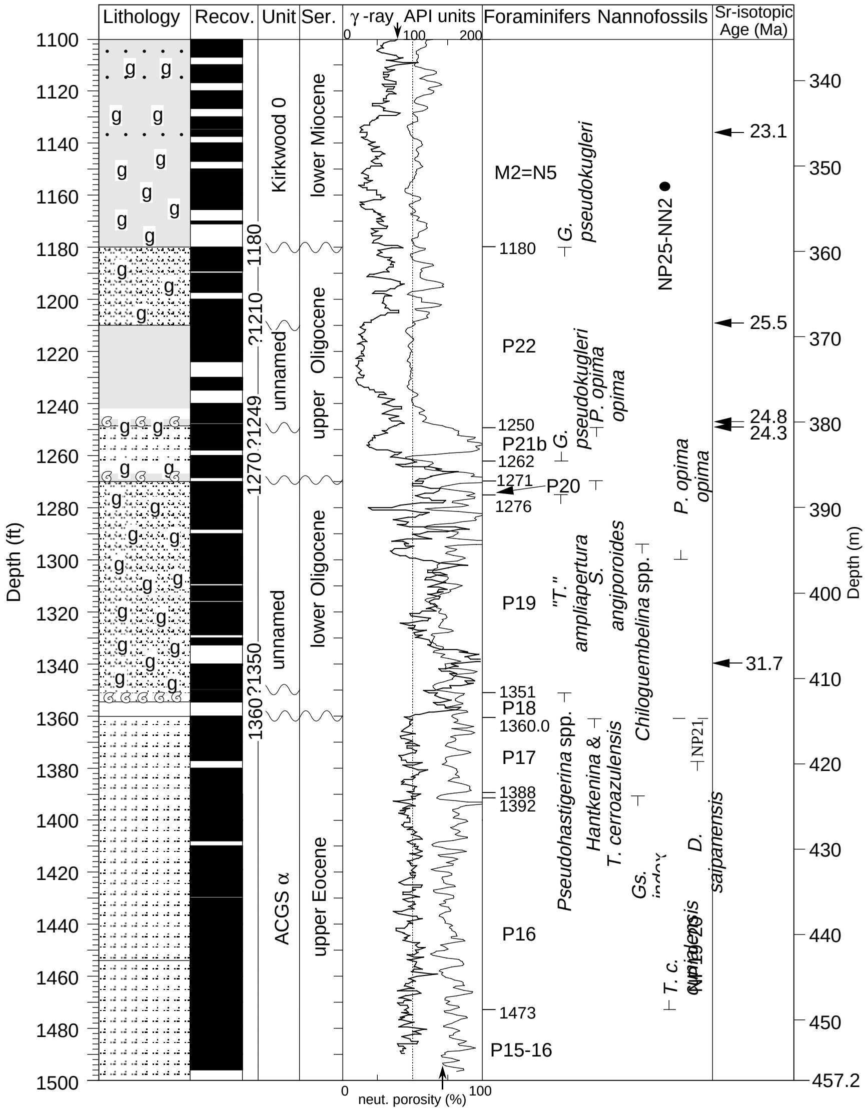

Figure 6. Lower Miocene glauconite sand equivalents to the Kirkwood Formation, unnamed Oligocene glauconite sands and clays, and unnamed upper Eocene clays, Cape May borehole. The key for symbols is given in Figure 2.

from 357 to 432.2 ft (108.8–131.8 m). This sequence generally shallows upward from the shelly neritic sands at the base to medial prodelta clays to upper neritic-nearshore sands and interbedded clays.

We place the sequence between 357 and 432.2 ft (108.8 and 131.8 m) in the Kirkwood Formation; however, it is possible that this unit is the fully marine equivalent of the nearshore Cohansey Formation (e.g., Carter, 1978). The age of the Cohansey Formation is uncertain, and it may be upper middle Miocene (Owens et al., 1988) or lower upper Miocene (Olsson et al., 1987). The age of the section from 357 to 432.2 ft (108.8–131.8 m) is upper middle Miocene at Cape May based on numerous Sr-isotopic ages of 11.2–11.9 Ma (the age of 12.5 Ma at 358.4 ft [109.2 m] is anomalous and needs replication; Table 2, Fig. 3). However, the late middle to late Miocene Sr-isotopic/age calibration has relatively large errors (from ±0.9 m.y. based on three analyses at 95% confidence interval; Oslick et al., 1994), and it is possible that the section may actually be partly upper Miocene (<10.4 Ma). Benson (1990) reported the upper Miocene planktonic foraminifer *Neogloboquadrina acostaensis* at 356–367 ft at the Oh25-02 Lewes, Delaware, well (first appearance = 10.2 Ma; Berggren et al., 1985). Similar gamma log and lithologic signatures indicate that this section at Oh25-02 correlates with the 357–432 ft sequence(s) at Cape May. Thus, it is not clear if the 357–432.2 ft (108.8–131.8 m) sequence at Cape May is uppermost middle Miocene (ca. 12–11 Ma) or if it spans the middle/upper Miocene boundary (ca. 11–10 Ma).

Kirkwood 3 Sequence

Age: ?13.3–13.7 Ma, middle Miocene by correlation to Atlantic City
Interval: 432.2–503 ft (131.8–153.4 m)

At 432.2 ft (131.8 m, the "432-ft unconformity"), there is a lithologic break between gray medium to coarse sands with abundant shell fragments above and dark greenish gray medium to fine muddy sands lacking in shell material below. Sr-isotopes indicate that the section down to 431 ft (131.4 m) is ca. 11.5 Ma, and we infer that there is an unconformity and significant hiatus at 432.2 ft (131.8 m). Sands continue down to 440.7 ft (134.4 m); below this, dark bluish gray clay beds (1–5 cm thick) are interbedded with clayey fine sands down to 460 ft (140.2 m). The clay beds vary in their spacing (0.1–0.8 ft; 3–9 cm spacing). Between 460 and 461.5 ft (140.2–140.7 m), we en-

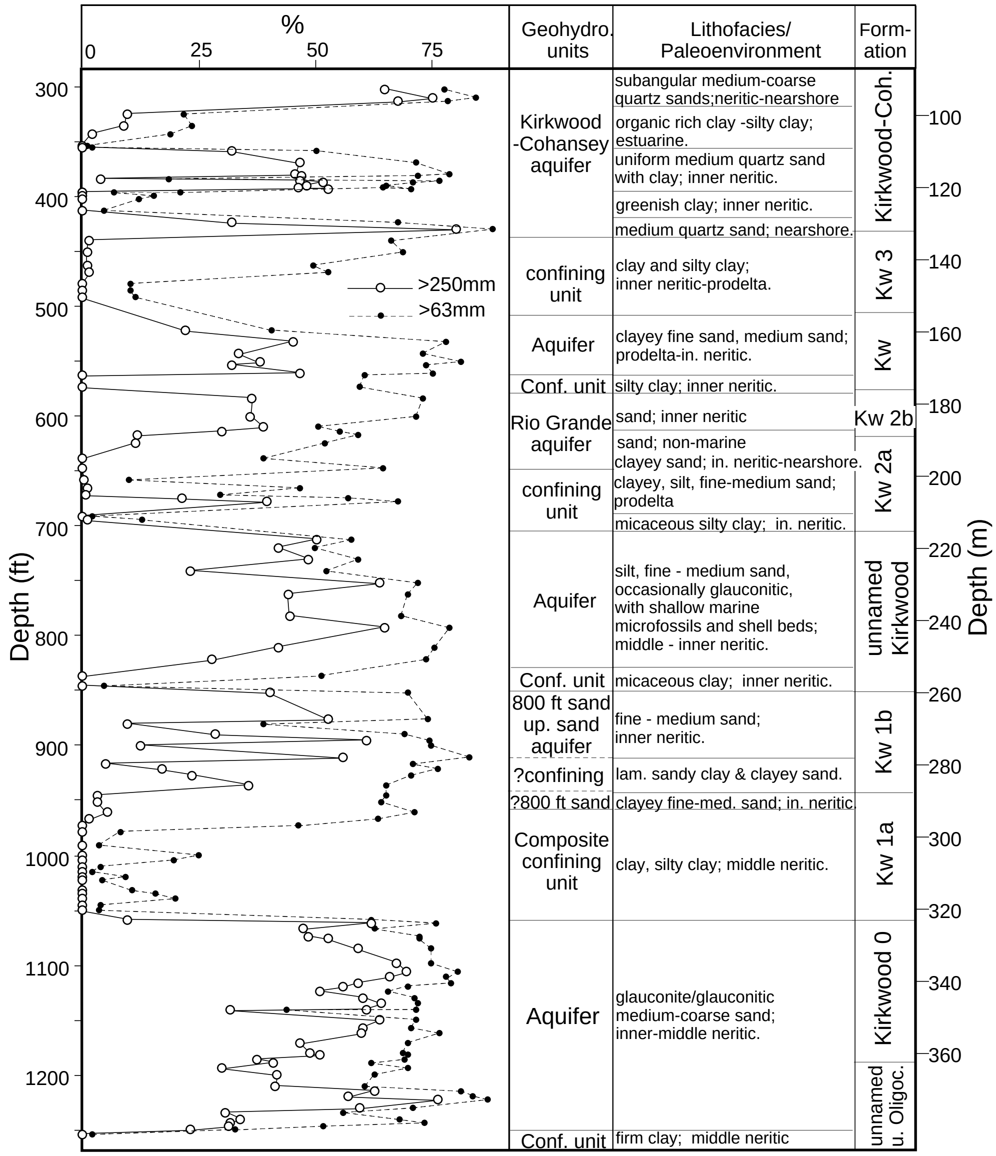

Figure 7. Percentage of sand (determined from the >63- and >250-µm size fractions of samples processed for foraminifers), lithologic units, lithofacies, depositional environments, and hydrogeologic units for the Miocene to uppermost Oligocene at Cape May.

countered an indurated fine sand above a stiff, fine sandy clay. We interpret the sands from 432.2 to 461.5 ft (131.8–140.7 m) as inner neritic to nearshore based on the presence of diatoms and foraminifers (including *Elphidium*). A clay unit from 461.5 to 501.35 ft (140.7–152.8 m) is interbedded with sandy clays and silts. The clay is interpreted as a prodelta deposited in inner neritic paleodepth based on the benthic foraminifers (*Bulimina*, *Hanzawaia*). The increasing clay content below 440 ft (134.1 m) results in increasing gamma log values downsection, with peak values from 458 ft (139.6 m, uncorrected; 460.5 ft corrected) to 490 ft (149.4 m). From 471 to 473 ft (143.6–144.2 m) and at about 475 ft (144.8 m), there are thin interbeds of sandier clays. Indurated beds of alternating silt and clay with progressively less sand continue down to 490 ft (149.4 m) and overlie a clayey medium sand that continues to 502.9 ft (153.3 m); this sand contains phosphate pellets, marks the base of a sequence, and yields a sharp gamma spike (due to the phosphates). Thus, this sequence follows a pattern of basal shelly sands, medial silts and clays, and upper sands, reflecting a shallowing-upward succession.

This section apparently correlates with the Kirkwood 3 sequence (= East Coast Diatom Zone [ECDZ] 6 sequence) of Sugarman et al. (1993). Our correlations (Fig. 5) indicate that this sequence correlates to the Kirkwood 3 sequence at Atlantic City where it was dated as 13.3–13.7 Ma (Fig. 5) (Miller et al., 1994a), although no Sr-isotope data are available at Cape May to confirm this.

Unnamed Kirkwood Sequence

Age: ca. 14.3–14.8 Ma, middle Miocene
Interval: 503–576 ft (153.3–175.6 m)

A sequence boundary occurs at 502.9 ft (153.3 m; Fig. 3): the "503-ft unconformity." At 502.9–505.95 ft (153.3–154.3 m), there is a highly indurated medium sand containing pebbles; this indurated zone (Fig. 3) is associated with high neutron porosity log values. The indurated zone marks the top of the underlying sequence, similar to other sequences in this borehole (e.g., 576, 680, 710, and 850 ft).

These indurated intervals are thicker (1–3 ft; 0.3–0.9 m) than most hardgrounds associated with unconformities in the coastal plain; we suggest that these hardgrounds may reflect cementation during subaerial exposure. The cement is carbonate, and we intend to test the hypothesis of subaerial exposure with stable isotopes. We interpret these indurated pebbly coarse sand facies as part of the regressive late HST of the underlying sequence.

Between 506 and 510 ft (154.3 and 155.5 m), the section is predominantly clayey fine sand with interbeds of sandy clays, interpreted as prodelta. From 510 to 535.8 ft (155.5–163.4 m), the section is shelly clayey sand, interpreted as inner neritic (shallow shelf). The transition from shelf below to prodelta above represents a shallowing-upward succession, although the facies fine upsection. At 535.8 ft (163.4 m), there is an abrupt change to a clean fine to medium sand with shells that continues to 563 ft (171. 6 m). There is little or no shell material below about 540 ft (164.6 m), probably due to dissolution. We also interpret these sands as neritic; the presence of sponge spicules and foraminifers indicate neritic (probably inner) environments. There is a lithologic change to a muddy fine sand with abundant shell fragments in an interval of no recovery (563–570 ft, 171.6–173.8 m). At 575 ft (175.3 m), there is a gradational contact with gray fine sandy clays with large shell fragments that marks the base of the sequence at 575.7 ft (175.5 m) (Fig. 8A).

The clayey sands and sandy clays between ~563 and 575.7 ft (171.6 and 175.5 m) correlate with a gamma log maximum between 554 and 566 ft (168.9–172.5 m) uncorrected; 556.5–568.6 ft corrected). This ~7 ft (2.1 m) discrepancy can be explained by the poor recovery throughout this interval; we support this by noting that a neutron porosity peak at 567.5 ft uncorrected; 570 ft corrected; Fig. 3) probably coincides with the indurated zone at 575.7–577 ft in the core (175.5–175.9 m; Fig. 8A; i.e., indurated zones noted in several sections below correspond with neutron porosity peaks).

The sequence between 503 and 576 ft (153.4–175.6 m) is middle middle Miocene (14.3–14.8 Ma with one anomalous age of 15.5 Ma at the top of the sequence; Table 2). It therefore represents a sequence not previously recognized in the Kirkwood Formation (Fig. 5) (Sugarman et al., 1993).

Kirkwood 2b Sequence

Age: ca. 15.9–16.3 Ma, early middle Miocene
Interval: 576–615 ft (175.6–187.5 m)

There apparently is a sequence between 575.7 ft (the "?576-ft unconformity"; Figs. 3, 8A) and 615 ft (175.5–187.5 m), although recovery is poor. From 575.7 to 577 ft (175.5–175.9 m), the section consists of very indurated sandy clay and shells that mark the top of the sequence (Fig. 8A). Gray clayey sands with shell fragments are present at 580–584.4 ft. From 590 to 617.5 ft (179.8–188.3 m), we recovered a total of only 1.1 ft of core (shell hash in clayey sand) that may mark the base of the section. The section contains inner neritic benthic foraminifers. This sequence between 575.7 and 614 ft is early middle Miocene (16.2, 15.9, and 16.3 Ma Sr-isotopic ages at 582, 583, and 600 ft, respectively; Table 2). Thus, it correlates with the Kirkwood 2b sequence (= upper ECDZ 2) of Sugarman et al. (1993).

Kirkwood 2a Sequence

Age: ca. 16.9–18.1 Ma?, late early Miocene
Interval: 615–710 ft (187.5–216.5 m)

An unconformity separates the shell hash from sands below; the contact is in the unrecovered interval between 614 and 617.5 ft (187.2–188.3 m; the "615-ft unconformity"; Fig. 3). The sequence from 617.5 to 680.1 ft (188.3–207.3 m) represents a classic coarsening-upward succession: fine to medium sand (617.5–627 ft; 188.3–191.2 m), primarily fine to medium sands with sporadic sandy clay layers (627.4–647.5 ft; 191.2–197.4 m), interbedded fine to medium sands and laminated clay beds (648–658 ft; 197.5–200.6 m), and laminated clays with sporadic shells (658–673.2 ft; 200.6–205.2 m) extending to a shell bed at the base (676.2–680.1 ft; 206.2–206.8 m). These facies represent a prograding delta, with a more distal prodelta at the base and more proximal delta front sands at the top. The sediments were at least partly marine, as evidenced by the presence of diatoms, shells, and foraminifers below 638.7 ft (194.7 m); it is probably nonmarine above this. A distinct shell hash (including complete *Turritella* shells) was recovered from 676.2 to 678.3 ft; this shelly unit is found at the top of the next core (680–680.1 ft; ~207.3 m), marking the base of the succession. These lower beds are inner to middle neritic based on the presence of the foraminifers *Globigerina, Cibicidoides,* and *Nonionellina.*

The sands at the top of the Kirkwood 2a sequence (617.5–647 ft; 188.3–197.4 m) plus those of the overlying sequence correlate with the Rio Grande aquifer of Zapecza (1989) and Mullikin et al. (in press) (Fig. 5). The finer grained sediments of the lower part of the Kirkwood 2a sequence correlate with the confining unit of Zapecza (1989) and Mullikin et al. (in press) (Fig. 5).

We note a surface (the "680-ft" surface) below the shell layer at 680.1 ft (207.3 m) that may be a disconformity or a flooding surface. Immediately below this, there is an indurated sand (680.1–681.4 ft; 207.3–207.7 m), as found with unconformities at 503, 576, 710, and 850 ft. This surface is also associated with a distinct gamma log increase (677.5 ft [206.6 m] uncorrected; 680 ft corrected). The clayey medium sand continues to 687.6 ft (209.6 m). From 690 to 706.2 ft (210.4–215.3 m), there is a fairly uniform, firm, micaceous brownish ("chocolate") dark gray clay with sporadic thin silt laminations. At 706.2 ft (215.3 m), there is a change to dark gray gravely sands and shell hash below to 710 ft (216.5 m) that marks the base of the sequence.

Together, the sections between 615 and 710 ft (187.5 and 216.4 m) correlate with the Kirkwood 2a sequence (= lower ECDZ 2) of Sugarman et al. (1993). The upper part of the sequence (615–680 ft, 187.5–207.3 m) has a Sr-isotopic age of 16.9 Ma (Table 2) and correlates with the upper Kirkwood 2a at Atlantic City (Fig. 5); the lower part (680–710 ft, 207.3–216.5 m) has a single age estimate of 17.8 Ma at 706.4 ft (215.4 m), correlating it with the lower Kirkwood 2a dated as 17.7–18.1 Ma at Atlantic City (Fig. 5). Further studies are needed to determine if the Kirkwood 2a can be divided into two separate sequences or if the surface at 680 ft is a flooding surface separating two parasequences within the Kw2a.

Unnamed Kirkwood Sequence

Age: 18.6–19.5 Ma, late early Miocene
Interval: 710–850 ft (216.5–259.1 m)

A disconformity (the "710-ft unconformity"; Fig. 4) occurs below the shell hash in the unsampled interval between 706.4 and 710 ft (215.2–216.5 m), associated with a distinct gamma log increase (at 704–706 ft uncorrected; 706.5–708.5 ft corrected). An extremely hard gravel layer with broken thick shell fragments was encountered from 710 to 710.8 ft (216.5–216.7 m), similar to a lithified zone immediately below the unconformities cited above. The interval from 710.7 to 713.7 ft (216.6–217.6 m) is less consolidated clayey gravel to pebbly coarse sand without visible shells. Beneath 713.7 ft (217.6 m) and down to at least 740 ft (225.6 m) (note recovery is poor; Fig. 4), extremely hard, pebbly, coarse-grained sandstone recurs. Careful examination reveals molds of bivalves, indicating dissolution of shells by ground water. The paleoenvironment represented by the indurated pebbly sands from 710 to 740 ft (216.5–225.6 m) is probably inner neritic to nearshore. The lithologic change at 706.2–710 ft (215.4–216.5 m) marks an important sequence boundary with a hiatus of approximately 0.8 m.y. (17.8 Ma above, 18.6 Ma below based on Sr-isotopes; Table 2).

At 749–753.7 ft (228.3–229.8 m), there are two distinct shell layers separated by a medium to coarse clayey quartz sand. The upper

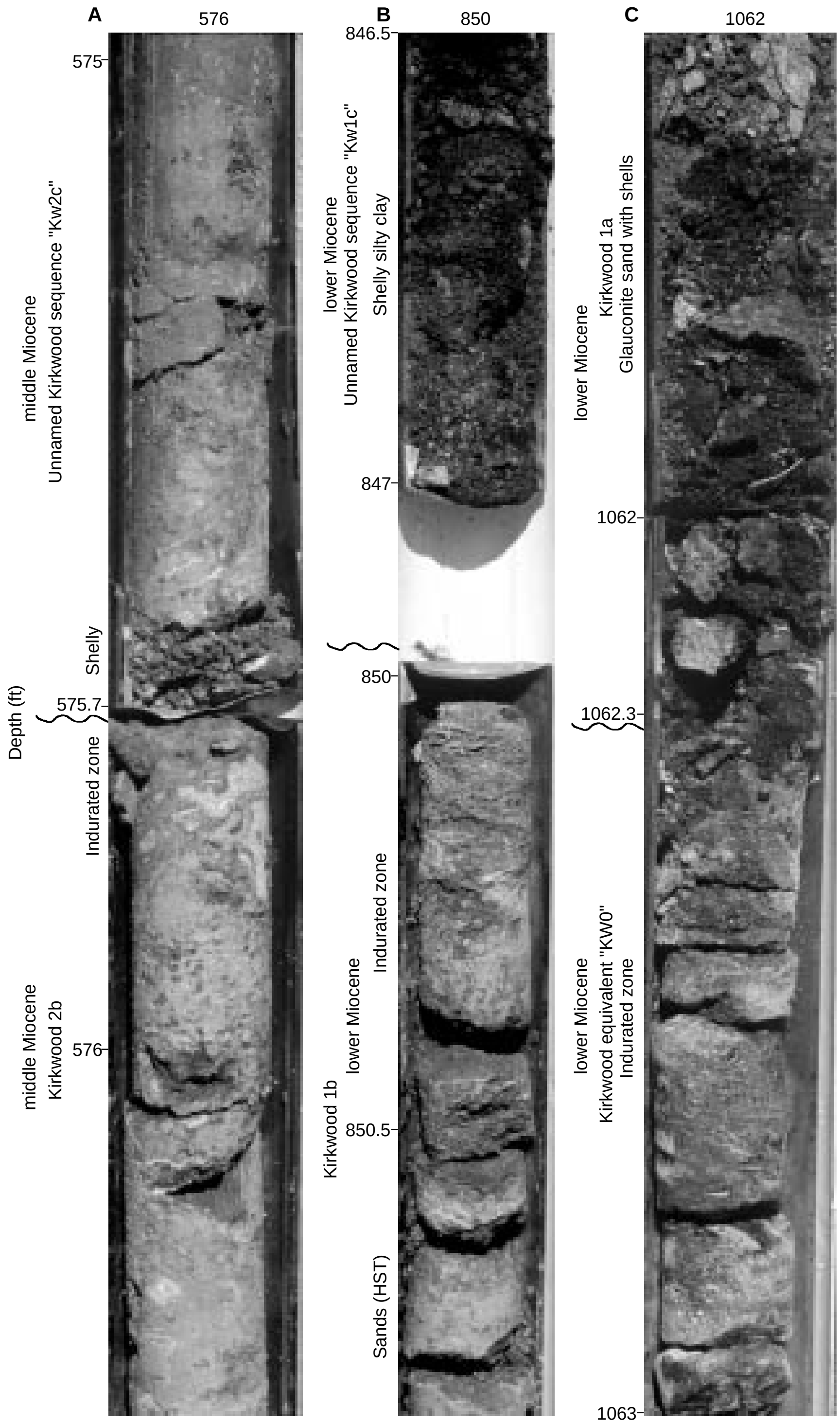

Figure 8. Core photographs, Cape May borehole. **A.** Lithologic contact and disconformity at 575.7 ft, separating an unnamed Kirkwood sequence (“Kw2c”) above from the Kirkwood 2b sequence below. **B.** Lithologic contact and disconformity in unrecovered interval between 847 and 850 ft, separating an unnamed Kirkwood sequence (“Kw1c”) above from the Kirkwood 1b sequence below. Silty clays with common shells overlie the unconformity (an indurated zone), and unconsolidated sands of the Highstand Systems Tract (HST) lie below. **C.** Lithologic contact and disconformity at 1062.3 ft, separating the Kirkwood 1a sequence above from the Kirkwood equivalent (“Kw0”) sequence below. Dark, shelly glauconite sands overlie the unconformity and an indurated zone. **D.** Lithologic contact and disconformity at 1350.8 ft, separating lower Oligocene (Zone P19) glauconite sands from lowermost Oligocene (Zone P18) glauconitic clay. **E.** Lithologic contact and disconformity in the unrecovered interval between 1354.5 and 1360 ft, separating lowermost Oligocene (Zone P18) from uniform, laminated upper Eocene (Zone P17) clay.

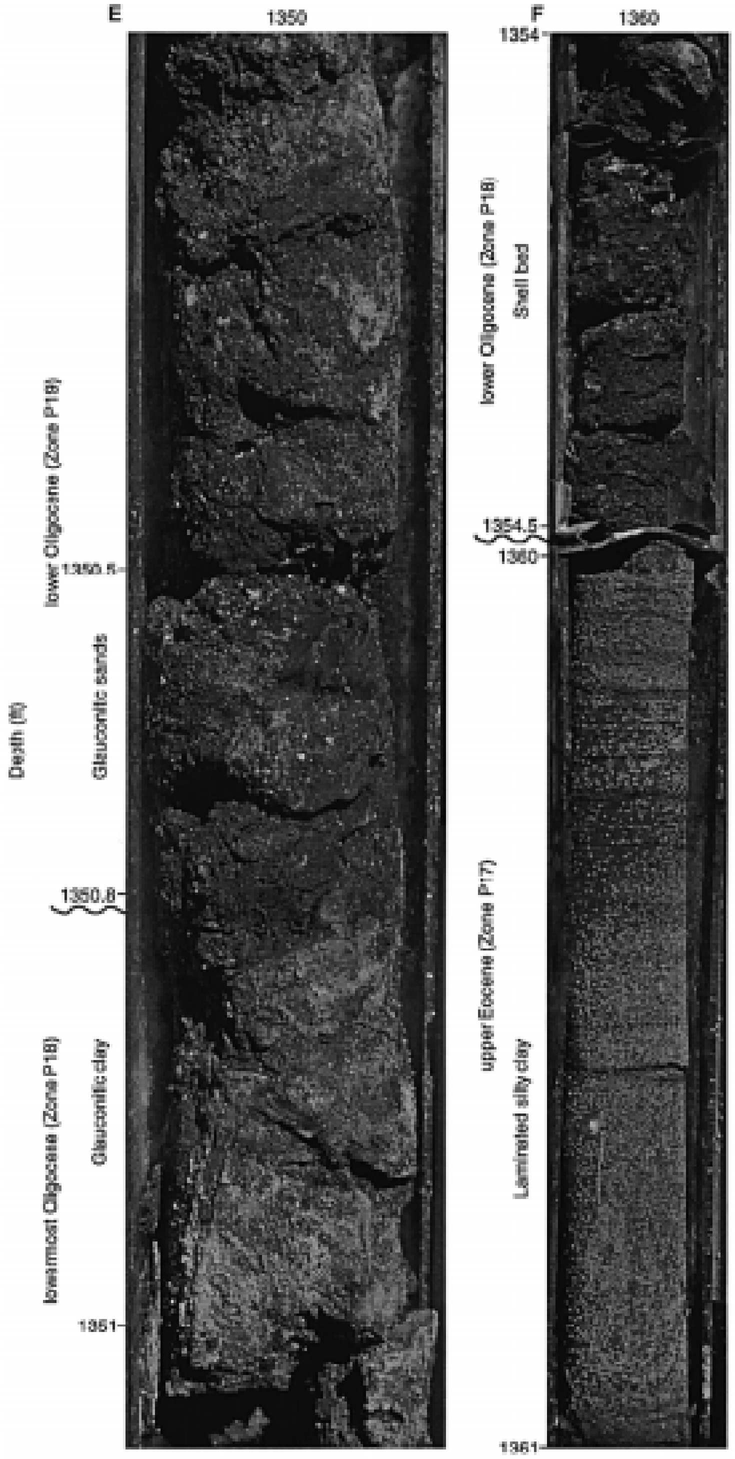

Figure 8 (continued).

shell bed (749–751.3 ft, 228.3–229.1 m) contains many molds of mollusk shells. The lower shell bed (751.9–753.7 ft, 229.2–229.8 m) contains thick bivalve shells and weathered and fresh fragments. A third shell bed from 760.2 to 760.9 ft (231.8–232.0 m) is associated with a gamma log kick and overlies an indurated zone at 764 ft (232.9 m) that may mark an unconformity (indicated as ?764 ft on Fig. 4) or a flooding surface.

Shell beds in muddy sands continue down to about 774 ft (236.0 m), where medium muddy sands (774–781.4 ft) and coarse gravelly sands (781.4–807.3 ft) appear; both generally lack shell material. Shelly, clayey medium sand returns at 810 to 823.2 ft (247–251 m). There is a coarsening-upward succession from 830 to 847 ft (253–258.2 m): clayey fine sands with sporadic fragmented shells (830–834 ft), sandy silty clay/clayey silt (834–840 ft), to sandy clays (840–

Table 2. Sr-isotopic data and age calculations, Cape May borehole, Leg 150X.

Depth (ft)	$^{87}Sr/^{86}Sr$	Error (±)	Age (Ma) (BKFV85)	Age (Ma) (CK92)
358.0	0.708856	0.000006	12.5	12.7
370.0	0.708880	0.000008	11.4	11.8
386.7	0.708885	0.000008	11.2	11.6
390.6	0.708870	0.000009	11.9	12.2
417.1a	0.708878	0.000007	11.5	11.9
417.1b	0.708887	0.000013	11.1	11.6
421.4	0.708878	0.000006	11.5	11.9
431.5	0.708878	0.000007	11.5	11.9
514.0	0.708790	0.000008	15.5	15.2
527.5	0.708812	0.000013	14.5	14.4
529.0	0.708805	0.000025	14.8	14.6
574.0	0.708816	0.000011	14.3	14.2
582.0	0.708766	0.000008	16.2	15.9
583.0	0.708787	0.000009	15.9	15.6
600.0	0.708764	0.000011	16.3	16.0
677.3	0.708721	0.000006	16.9	16.6
706.4	0.708659	0.000007	17.8	17.5
722.5	0.708601	0.000008	18.6	18.4
810.9	0.708558	0.000010	19.3	19.0
832.6	0.708540	0.000007	19.5	19.3
851.3	0.708499	0.000014	20.1	19.9
882.7	0.708498	0.000008	20.1	19.9
982.2	0.708476	0.000011	20.4	20.2
1012.7	0.708448	0.000007	20.8	20.6
1058.0	0.708438	0.000077	21.0	20.7
1058.0	0.708446	0.000009	20.9	20.6
1085.0	0.708323	0.000014	22.6	22.4
1085.0	0.708318	0.000029	22.7	22.5
1098.0	0.708334	0.000020	22.5	22.4
1098.0	0.708327	0.000016	22.6	22.3
1136.0	0.708290	0.000006	23.1	23.6
1209.0	0.708229	0.000029	25.0	24.8
1209.0	0.708228	0.000014	24.9	24.7
1247.0	0.708257	0.000006	24.1	24.2
1249.0	0.708251	0.000011	24.3	24.3
1340.0	0.707995	0.000030	31.7	30.1

Notes: Equation used:

for $^{87}Sr/^{86}Sr$ = 0.708930 – 0.708789, BKFV age: Age (Ma) = 31799.78 – ($^{87}Sr/^{86}Sr$) × 44843.05, Age = 9.2–15.2 Ma; CK age: Age (Ma) = 26661.43 – ($^{87}Sr/^{86}Sr$) × 37593.98, Age = 9.9–15.2 Ma.

for $^{87}Sr/^{86}Sr$ = 0.7087889 – 0.708305, BKFV age: Age (Ma) = 10258.53 – ($^{87}Sr/^{86}Sr$) × 14450.87, Age = 15.6–22.8 Ma; CK age: Age (Ma) = 10393.19 – ($^{87}Sr/^{86}Sr$) × 14641.29, Age = 15.5–22.8 Ma.

for $^{87}Sr/^{86}Sr$ = 0.708304 – 0.708065, BKFV age: Age (Ma) = 20392.79 – ($^{87}Sr/^{86}Sr$) × 28758.84, Age > 22.8 Ma; CK age: Age (Ma) = 13803.52 – ($^{87}Sr/^{86}Sr$) × 19455.25 (Miller et al., 1988), Age = 23.2–28.0 Ma.

All equations after Oslick et al. (1994) unless noted.

847 ft). This coarsening-upward succession is shown on the gamma log by decreasing values.

The sands from 710 to 834 ft (216.4–254.3 m) and clays from 834 to 847 ft (254.2–258.2 m) apparently represent an aquifer-confining unit that is not present at Atlantic City (Figs. 6, 7). We recognize the confining units here as tight clays with little or no sand (Fig. 7); physical properties studies are needed to determine the degree to which these confining units serve as aquacludes or aquitards.

Kirkwood 1b Sequence

Age: 20.1–20.4 Ma, early Miocene
Interval: 850–942 ft (259.1–287.1 m)

A disconformity (the "850-ft unconformity"; Fig. 4) occurs in an unrecovered interval between 847 and 850 ft (258.2–259.1 m), with a micaceous sandy silty clay above and a medium clayey sand below (Fig. 8B). The gamma log predicts the contact at 847 ft (258.2 m uncorrected) to 849.5 ft (259 m corrected). The gamma log, facies shift, and Sr-isotope ages (19.5 Ma at 832 ft, 20.1 Ma at 851.3 ft; Table 2) indicate that this is a major disconformity. The top of the sequence (850–850.7 ft) is gravelly indurated sand (Fig. 8B), perhaps reflecting subaerial exposure and diagenesis.

Sporadic shelly sands predominate from 850.7 to 916.8 ft (259.3–279.5 m; Fig. 8B). There are lithified, hard, coarse-grained sandstone layers from 882.8 to 884, 885 to 891, 892 to 893, and 893.8 to 894 ft, with unconsolidated gravelly, clayey, fine-coarse sands in between. Below this, muddy fine sands with sandy gravel beds (894–895 ft, 910–912 ft) occur down to 916.8 ft (279.5 m).

Interbedded silty sands, sandy silts, and silty clays with sporadic shells (e.g., 920–927.65 ft, 280.4–282.7 m) predominate from 916.8 to 941.75 ft (279.4–287 m). This finer grained section yields higher gamma log values (Fig. 4) than the section above and is the basal lithologic unit in this sequence. Below this (941.75–952 ft), the section consists of uniform fine sand (60%–70%; Fig. 8). We interpret the rapid facies shift from uniform sands below to silty sands and sandy silts above (916–942 ft) as a disconformity (the "942-ft unconformity"; Fig. 4).

The sequence from 850 to 942 ft (259.1–287.2 m) has two Sr-isotope ages estimates of 20.1 Ma (Fig. 4) and thus correlates with the Kirkwood 1b sequence at Atlantic City (Fig. 5), where it is dated as 20.1–20.4 Ma (Fig. 5). Rare, sporadic benthic foraminifers in this unit indicate that it was deposited partly or entirely in an inner neritic environment.

Kirkwood 1a Sequence

Age: 20.4–20.9 Ma, early Miocene
Interval: 942–1062.3 ft (287.1–323.7 m)

Uniform fine sands at the top of the next sequence (941.75–952 ft, 287.1–290.2 m) overlie very dark gray, micaceous, sporadic, peaty silty clay (952–963.8 ft, 290.2–293.8 m). We interpret the clays as prodelta sediments. A bed (963.8–967.1 ft, 293.8–294.8 m) of heavily bioturbated, shelly, fine sandy silty clays grades down to sands. These, in turn, overlie a thick succession (967.1–1012.8 ft, 294.8–308.8 m) of very dark gray micaceous silty clay and clayey silts; they contain burrows, laminations, cross-bedding structures, and thin shell hash beds. This unit has a high gamma log signature (Fig. 4) and is shallow marine.

At 1012.8 ft (308.7 m), there is a color change to greenish gray, shelly, bioturbated clay that continues to 1016.6 ft (309.9 m); the minor sand fraction (~2% at 1014 ft) contains glauconite and planktonic foraminifers. Similar clays are found at 1020–1026 ft (310.9–312.8 m), 1030–1032 ft (314–314.6 m), and 1040–1048 ft (317–319.5 m) and are interbedded with micaceous sandy clays. At 1056.8 ft (322.2 m), dark gray firm clays overlie glauconitic sandy clay that coarsens to glauconite sand below. Shells increase in the greensands downsection from 1059 to 1061.8 ft (322.9–323.7 m); the section is dominated by thick bivalve shells from 1061.8 to 1062.3 ft (323.7–323.9 m; Fig. 8C), with an unconformity at 1062.3 ft (323.7 m, the "1062-ft unconformity"; Figs. 6, 8C).

The interval from 942 to 1062.3 ft (287.2–323.7 m) represents the Kirkwood 1a sequence, dated using Sr-isotopes as 20.4–20.9 Ma. Using Sr-isotopes, no hiatus is discernible between the Kirkwood 1a and 1b sequences at Cape May (Fig. 4) or Atlantic City (Fig. 5), although a major disconformity clearly is indicated by gamma logs, facies shifts, and irregular surfaces at 942 ft (287.2 m) at Cape May and at 741 ft (225.9 m) at Atlantic City (Fig. 5).

The sands and sandstones of the Kirkwood 1a and 1b sequences (850–952 ft, 259.1–290.2 m) are correlated to the upper sand aquifer and "Atlantic City 800-ft sand" aquifer units (Zapecza, 1989; Mullikin et al., in press). The sandy silt and silty clay unit from 916.8 to 941.75 ft (i.e., the base of the Kirkwood 1b sequence) apparently correlates with a confining unit between the "Atlantic City 800-ft sand" and the upper sand aquifer units of Zapecza (1989), although our data indicate that this silt/clay unit is quite sandy at Cape May (Fig. 7). We suggest that the 800-ft sand and upper aquifer unit as recognized at Atlantic City (Fig. 5) may serve as one aquifer unit in the Cape May peninsula, although the indurated zones may act as confining units within this aquifer.

Kirkwood Equivalent Glauconite Sands and Clays

Kirkwood 0 Sequence

Age: 22.6–23.2 Ma; earliest Miocene
Interval: 1062.3–1180 ft (323.7–359.8 m)

A lithified sandstone of medium quartzose glauconite sand with leached shells occurs from 1062.3 to 1066.3 ft (Fig. 8C), associated with a gamma log minimum (Fig. 4). We place a sequence boundary at 1062.3 ft (323.7 m, the "1062-ft unconformity"; Fig. 6) at the top of the lithified unit separating the shelly medium quartzose glauconite sand from a medium to coarse glauconite quartz sand below (Fig. 8C).

From 1066.3 to 1180 ft (325.1–359.8 m), glauconite sands predominate with various secondary facies: they can be pebbly (with quartz pebbles up to 6 mm), clay-rich, bioturbated, lithified (1073.5–1073.9 ft, 1074.0–1074.9 ft; shown as distinct neutron density log peaks), and scattered with sporadic shells (1083.2–1100.4 ft). Quartz pebbles and sand are generally subdominant, except for coarse glauconite quartz sand beds at 1110.5–1112.8 ft (338.6–339.3 m) and at 1132.7–1137.4 ft (345.3–346.8 m). We did not recognize any additional sequences in the interval from 1066.3 to 1180 ft (325–359.7 m).

We initially correlated the greensands from 1062.3 to 1180 ft (323.7–359.8 m) with Oligocene glauconite sands elsewhere in the New Jersey subsurface (Olsson et al., 1980; Miller et al., 1994a, 1994b). However, Sr-isotopic ages (22.6, 22.7, and 23.1 Ma at 1085, 1098, and 1136 ft, respectively) establish that the glauconite sands and clays between 1062 and 1180 ft represent a lowermost Miocene sequence and are temporal equivalents of the Kirkwood Formation. We term this the Kirkwood 0 sequence and correlate it with a glauconite sand-shell bed sequence dated at Atlantic City as 21.9 to 24.1 Ma (Fig. 5). This is the oldest Miocene sequence sampled in the middle Atlantic coastal plain.

Unnamed Glauconite Sands and Clays

Age: Oligocene
Interval: 1180–1360 ft (359.8–414.6 m)

We place a sequence boundary (the "1180-ft unconformity"; Fig. 6) between the lower Miocene and unnamed Oligocene greensands and glauconitic silts in an unrecovered interval (1171–1180 ft, 357–359.8 m) (Fig. 6). The Sr-isotopic data are consistent with a hiatus from 23.1 Ma in the shelly glauconite sands at 1136 ft (lowermost Miocene; Table 2) to 25.5 Ma in the clayey glauconitic sands at 1209 ft (368.6 m, uppermost Oligocene).

The section from 1180 to 1210.1 ft (359.8–368.9 m) consists of clayey quartzose glauconite sands, as shown by higher gamma log values than the section above (Fig. 6). There is a biofacies change from middle neritic above (1171 ft, 357 m) to inner neritic (low-diversity *N. pizarrensis–B. gracilis* fauna) below the 1180-ft unconformity. Between 1180 and 1210.1 ft, there are few facies changes and the section is clayey quartzose glauconite fine sand. Distinct brown clay laminations occur at 1194.5–1194.6, 1194.7–1194.8, and 1195.3–1195.4 ft. Thin (~1 mm), sporadic green and brown clay laminations occur from 1200 to 1210 ft (365.9–368.9 m) in an otherwise uniform, clayey, fine to medium quartzose glauconite sand. This unit (1180–1210 ft) is uppermost Oligocene (Sr-isotope age of 25.0 ± 1 Ma at 1209.9 ft [368.9 m]).

There is a stratal surface and lithologic contact at 1210.1 ft (368.9 m), which may represent an unconformity ("?1210 ft"; Fig. 6), with a distinct coarsening-upward sequence below. Very coarse (2–4 mm) quartz sands, with <10% glauconite, grade down to medium sands (1230–1242 ft) to clayey sands and sandy clay (1242–1246 ft). Sporadic altered shells and shell layers occur throughout the section. The glauconitic to medium coarse quartz sands probably represent the shallowest deposits (inner neritic) and the clayey glauconite fine-grained quartz sands represent the deepest environments (middle neritic). Sr-isotopes indicate this section is uppermost Oligocene (24.1 and 24.3 Ma at 1247.0 and 1249.0 ft, respectively). Further studies are needed to determine if these two uppermost Oligocene units (1180–1210 and 1210–1248.5 ft) are separate sequences.

There is a possible disconformity at 1248.5 ft (380.6 m, the "?1249-ft unconformity"; Fig. 6) with a shelly interval (dark greenish gray) overlying a laminated clay (olive gray) (Fig. 6). This surface may be a disconformity as indicated by (1) a sharp lithologic break from shelly glauconitic quartz sands above to clays below, (2) a change in inferred depositional environment from middle to outer neritic below to inner to middle neritic above, (3) a thin shell bed immediately above the surface, (4) a change in stratification from laminated below to massive above, (5) bioturbation of the sand down into the clays, and (6) a distinct gamma log peak (Fig. 6). Laminated, slightly shelly silty clay at the top (~1248.5–1262 ft) overlies a coarser grained clayey glauconite sand (1262–1267 ft). A shell bed (1267.0–1268.4 ft) consisting of nested bivalve shells in a clayey glauconite sand matrix marks the base of the possible sequence. This section is upper Oligocene (Subzone P21b). Further studies are needed to determine if this is a separate sequence from those above.

A distinct surface occurs in an unrecovered interval between 1268.4 and 1270 ft (386.7 and 387.2 m, the "1270-ft unconformity"; Fig. 6). This surface can be recognized by a gamma log kick (1266 ft uncorrected, 1268.5 ft corrected) and by a change from laminated silty clay below to the shell hash above. The disconformity separates the upper Oligocene sequence (<29 Ma; Subzone P21b) from the lower Oligocene (>32 Ma; Zones P19–P20) sequence, with an associated hiatus of greater than 3 m.y. (Note added in proof: Subsequent studies have shown that the upper/lower Oligocene contact is at 1304.8 ft [397.7 m].)

A well-developed sequence was penetrated between 1270 and 1350.8 ft (387.1 and 411.8 m). The general lithology of the sequence is clayey, silty, fine-grained glauconitic (up to 20% of sand fraction) sands and sandy clays. Generally, it comprises an coarsening-upward succession: (1) a basal middle to outer neritic glauconite sand (1350–1327 ft), (2) a medial laminated glauconitic silty clay (1326–1316.9 ft), and (3) an upper sandy clay and clayey glauconitic sand (1316.9–1270 ft). This succession is well represented on the gamma log (Fig. 6). It is lower Oligocene in age (Zones P19–P20; see "Biostratigraphy" section, this chapter) and probably correlates with the ca. 33-Ma sequence at Island Beach (Miller et al., 1994b).

The glauconite sand is underlain by a brownish firm clay (1350.8–1352.0 ft, 411.8–412.2 m; Fig. 8D). This sharp facies shift is associated with a gamma log kick and is interpreted as a possible sequence boundary ("?1350 ft"; Figs. 6, 8D). Below this, the interval from 1352.0 to 1352.5 ft is a very dark glauconitic sandy clay. Freshly preserved and abundant thin shells within a brown colored clay matrix between 1352.5 and 1354.5 ft is interpreted as marking the base of a sequence (the "1360-ft unconformity"; Fig. 6). The 1360-ft disconformity is recognized on the gamma log at 1358 ft and in the cores by a sharp facies change between 1354.5 and 1360 ft (this interval was not recovered; Fig. 8E). The section from 1350 to 1358 ft is lowermost Oligocene Zone P18. Planktonic foraminifers indicate that the top of the underlying clays (1360 ft, 414.6 m) are uppermost Eocene.

Unnamed Uniform Clays and Silty Clays (= ACGSα Unit)

Age: late Eocene
Thickness: 1360 ft (414.6 m) to TD

A firm, laminated, greenish brown clay and silty clay begins at 1360 ft (414.6 m; Fig. 8F) and continues fairly uniformly down to total recovered depth of 1495.85 ft (456 m). The clay contains fossil fragments (bivalve shells, scaphopods, and abundant microfossils) and sporadic pyrite nodules (some up to 3 cm). Laminations vary from faint, <1-mm-thick color variations (Fig. 8E) revealed by drilling chatter (e.g., 1481–1482 ft) to thicker (centimeter scale) silt/clay laminations (e.g., 1484–1485 ft). Laminations are obscured by bioturbation in some intervals, particularly above 1416 ft (431.7 m).

The gamma log is fairly uniform from 1360 ft (414.6 m) to the base of the logged section at 1490 ft (454.3 m, Fig. 6); minor gamma peaks (e.g., 1480 ft, 1460–1450 ft) have no obvious expression in the cores. The sand content of the uniform clays is uniformly less than 9% (2.7% mean for 17 analyses). Alternations from heavily bioturbated to laminated do not have a gamma log expression.

A contact occurs at 1454.3 ft (443.1 m), with very dark gray (2.5Y 3/1) slightly sandy clay above to dark grayish brown (2.5Y 4/2) clay below. The section above this contact (from 1360 to 1454.25 ft) contains fewer visible macrofossils than below and has a greater number of heavily bioturbated intervals.

This clay was deposited in middle-outer neritic paleoenvironments. Benthic foraminifers indicate primarily middle neritic paleodepths. Planktonic foraminifers range from less than 10% above 1398 ft (426.2 m) to over 40% below 1450 ft (442.1 m), consistent with middle neritic paleodepths (Christensen et al., 1995). A sharp upsection decrease in percent planktonic foraminifers occurs across the lithologic contact at 1454.3 ft (443.1 m), probably caused by shallowing. It is not clear if this inferred shallowing represents the base of an HST or an unconformity.

The uniform clays below 1360 ft (414.6 m) are upper Eocene (Zones P16–P17, NP19/NP20; see "Biostratigraphy" section, this chapter), on the basis of the highest occurrence of *Turborotalia cerroazulensis* and *Hantkenina* spp. at 1360 ft (414.6 m).

The clay correlates lithologically and chronologically with the upper Eocene clays at Mays Landing ACGS#4, Island Beach, and Atlantic City boreholes (Owens et al., 1988; Miller et al., 1994a, 1994b). This unit is informally named the ACGSα unit, and it correlates with the Chickahominy Formation in Virginia and Maryland (Owens et al., 1988). Before Owens et al. (1988), upper Eocene strata were not recognized onshore in New Jersey north of Cape May, although Brown et al. (1972) and Poag (1985) noted the presence of upper Eocene strata at the Anchor-Dickinson well.

We did not penetrate the glauconitic sands and sandy marls of the middle to lowermost upper Eocene Shark River Formation at Cape May.

BIOSTRATIGRAPHY

We used the planktonic foraminiferal zonation of Berggren and Miller (1988) for the Paleogene and that of Kennett and Srinivasan (1983) for the Neogene, 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 et al. (1985) for the Cenozoic. The GPTS has recently been revised (Cande and Kent, 1992); however, the biostratigraphic ages were not recalibrated to the new GPTS until Berggren et al. (1995). To maintain consistency of time scales with the previously published Island Beach and Atlantic City site reports (Miller et al., 1994a, 1994b), we report ages to the Berggren et al. (1985) time scale, realizing that the ages must be recalibrated.

Planktonic Foraminifers

Summary

The upper Eocene (1500–1360 ft, 457.3–414.6 m), the Oligocene (1360–1180 ft, 414.6–359.8 m), and the lowermost Miocene (1180–995.9 ft, 359.8–303.6 m) contain generally well-preserved and diverse planktonic foraminifer assemblages. The upper part of the lower Oligocene (1327–1270 ft, 404.6–387.2 m) contains low-diversity assemblages without diagnostic taxa in most cases. The interval above 920 ft (280.5 m) of the Miocene and younger sediments are largely barren of planktonic foraminifers; however, sporadic samples below 357.5 ft (109 m) contain characteristic Miocene taxa, including species of *Globigerinoides,* neogloborotaliids, tenuitellids, globigerinids, and globorotaliids. The presence of abundant and diverse planktonic foraminifers allows application of the zonation of Berggren and Miller (1988) to the Eocene and basal Oligocene. Planktonic foraminifer zonation for the rest of the Oligocene and younger sediments was not possible using primary zonal criteria because of the absence of marker taxa. However, we were able to zone the Oligocene to middle Miocene using secondary marker species of planktonic foraminifers as calibrated by Berggren et al. (1995).

Upper Neogene (0–357 ft, 0–108.8 m)

The ?upper Miocene and younger sediments do not contain stratigraphically diagnostic planktonic foraminifer taxa, although sporadic samples may preserve a few specimens of *Globigerina* spp. The presence of benthic foraminifers provide paleoenvironmental constraints on the ?Pleistocene Cape May Formation (see "Lithostratigraphy" section, this chapter).

The upper Miocene cannot be directly recognized by planktonic foraminifer biostratigraphy in the Cape May borehole. However, it is possible that the Kirkwood-Cohansey sequence (357–432.2 ft) could be, in part, upper Miocene. It is also possible that some of the overlying clays and sands between 167 and 357 ft may be upper Miocene, although preliminary palynological studies at the nearby Cape May airport borehole indicate that this section is partly Pliocene. Circumstantial evidence for the presence of upper Miocene strata at Cape May include the following:

1. The upper Miocene marker species *Neogloboquadrina acostaensis* was found from 364 to 374 ft in the Oh25-02 well in Delaware, which is approximately 33 km (20 miles) away from Cape May (Benson, 1990);
2. *N. acostaensis*, along with other members of a late Miocene assemblage, was recognized in the Jobs Point borehole (which is 51 km [32 miles] northwest of Cape May) at 506–508 ft and at 390 ft below land surface (Melillo and Olsson, pers. comm., cited in Owens et al., 1988); and
3. Strontium isotopic analysis of the sediments below the 357 ft hiatus yielded latest middle Miocene ages (11.1–11.9 Ma, Fig. 5) that are consistent with a late Miocene age, considering the errors on the estimate of $\pm$0.9 m.y. for three analyses (95% confidence interval; see "Sr-isotopic Stratigraphy" section, this chapter).

Middle Miocene (357–615 ft, 108.8–187.5 m)

Between 357 and 615 ft, only four samples (485, 522, 563, and 600.1 ft) contain planktonic foraminifers. No zonal marker species were identified in this interval. However, occurrences of *Neogloboquadrina mayeri, N. continuosa, Globoconella praescitula, Globigerina brazieri, G. decoraptura,* and *Tenuitella* spp. suggest that these samples are middle Miocene.

Lower Miocene (615–1180 ft, 187.5–359.8 m)

No detailed planktonic foraminiferal biostratigraphic zonation is possible for the upper part of the lower Miocene (615–1000 ft). The highest occurrence (HO) of *G. incognita* at 675 ft indicates that the section below is lower Miocene Zones N5–N7 (undifferentiated), whereas above this is Zones N7–N10 (Fig. 3). The interval from 1000 to 1045 ft contains a relatively diverse middle lower Miocene planktonic foraminifer assemblage containing *Globigerinoides altiaperturus* and 26 other taxa. *Globigerinoides altiaperturus* has its lowest occurrence at 1045 ft. This taxon appears near the base of middle lower Miocene Zone N5 (Berggren et al., 1995).

As a result of the absence of marker taxa, the Oligocene/Miocene boundary cannot be recognized based on planktonic foraminifers alone. The absence of *Globorotalia pseudokugleri* above the 1180-ft (359.7 m) unconformity and strontium isotopic age estimates (25.5 Ma below vs. 23.1 Ma above) place the Oligocene/Miocene boundary in a hiatus associated with the disconformity at 1180 ft (359.8 m).

Upper Oligocene (1180–1270 ft, 359.8–387.2 m)

The Oligocene in the Cape May borehole is the most fossiliferous of the three boreholes drilled during Leg 150X. Oligocene planktonic foraminiferal assemblages are characterized by relatively high diversity and most of the diagnostic taxa are present. Zonation is possible but should be used with caution due to rare occurrences of marker taxa.

Zone P22 spans approximately 1180 to 1249.7 ft. The base of Zone P22 is at 1249.7 ft based on the HO of *Paragloborotalia opima opima* at 1249.7 ft. The presence of *Globorotalia* cf. *pseudokugleri* at 1262 ft may represent an ancestral form, because *Globorotalia pseudokugleri* sensu stricto does not appear until well into Zone P22 (Berggren et al., 1995). The planktonic foraminiferal assemblage in Zone P22 is similar to that in Subzone P21b and is dominated by globigerinids, tenuitellids, and paragloborotaliids (Table 3).

Subzone P21b ranges from 1249.7 to 1270 ft. At 1270 ft, an unconformity separates Subzone P21b from Zone P20. The HO of *Chiloguembelina cubensis* is at 1294 ft and is clearly premature due to preservation because it occurs below the HO of *Turborotalia ampliapertura* (top of Zone P19; 1275.9 ft) at this site (Fig. 3). The interval from 1249.7 to 1270 ft probably belongs to Subzone P21b (basal upper Oligocene) because of the absence of *C. cubensis.* Preservation is good in this interval, and *C. cubensis* would be expected if this was Subzone P21a. (Note added in proof: Subsequent studies have shown that the upper/lower Oligocene contact is at 1304.8 ft [397.7 m]. Specimens of *C. cubensis* between 1294 and 1304.8 [394.4 and 397.7 m] are reworked. *T. ampliapertura* and *S. angioporoides* above 1304.8 ft [397.7 m] are reworked or misidentified.)

Lower Oligocene (1270–1360 ft, 387.1–414.5 m)

The lower Oligocene in the Cape May borehole ranges from 1270 to 1360 ft. Microfossil preservation in this interval is generally poor.

Zone P19 ranges from the HO of *Pseudohastigerina* spp. at 1351 ft to the HO of *Turborotalia ampliapertura* at 1275.9 ft. The diversity of the planktonic foraminiferal assemblage is relatively low, comprising subbotinids, globigerinids, tenuitellids, and chiloguembelinids (Table 3).

Zone P18 ranges from the HO of the *Turborotalia cerroazulensis* lineage (used along with *Hantkenina* spp. to recognize the top of Eocene and Zone P17) at 1360 ft to the HO of *Pseudohastigerina* spp. at 1351 ft (Fig. 6). Planktonic foraminifer diversity is higher in Zone P18 than in Zone P19 because of the presence of *Pseudohastigerina* spp. and more subbotiniid taxa (Fig. 3; Table 3).

Upper Eocene (1360 ft to TD, 414.6 m to TD)

Uppermost Eocene Zone P17 is defined as from the HO of *Cribrohantkenina inflata* to the HO of *Turborotalia cerroazulensis* spp. The HO of *T. cerroazulensis cocoaensis* and *T. c. cunialensis* is at 1360 ft (414.6 m) at Cape May, marking the top of Zone P17 and the Eocene/Oligocene boundary. As at Island Beach and Atlantic City (Miller et al., 1994a, 1994b), the Eocene/Oligocene boundary in the Cape May borehole coincides with a sharp lithologic contact at 1360 ft (414.6 m) and a hiatus. *Cribrohantkenina inflata* was not observed in the borehole and the base of Zone P17 is uncertain. The HO of *Globigerapsis index,* which approximates (0.3 m.y. before) the HO of *Cribrohantkenina inflata* (Berggren et al., 1995), is at 1392 ft (424.4 m), indicating the recovery of Zone P16 in the borehole. The upper Eocene contains diverse and well-preserved planktonic foraminifer assemblages (Table 3).

Calcareous Nannofossils

Calcareous nannofossils are present at most levels, but they are generally rare to scare and preservation is moderate to poor. The highest level with an age-diagnostic assemblage is at 675.0 ft (205.8 m). *Helicosphaera ampliaperta* (common) and *Sphenolithus heteromorphus* (very rare) characterize Zone NN4 (Fig. 3). *Helicosphaera ampliaperta* is present at 690.9–691 ft, but no *Sphenolithus* was encountered. Thus, this level may belong to Zone NN4 or older.

Samples between 700 and 822 ft (213.4 and 250.6 m) are barren or contain scarce low-diversity assemblages. *Helicosphaera ampliaperta* is present at 837 and 890.1 ft. Thus, these samples are assigned to the NN2–NN3 zonal interval (Fig. 4).

Calcareous nannofossils are common and moderately well preserved from 1020 to 1140 ft but lack age-diagnostic taxon. *Triquetrorhabdulus carinatus* occurs at 1157 ft (352.7 m), which indicates Zone NN2 or older (NP25–NN2), and the interval from 1157 to 1253 ft may be lower Miocene or upper Oligocene. The highest definite Oligocene assemblage is at 1300 ft (Zone NP24 or NP25 with *R. bisecta* and *R. abisecta*).

Table 3. Occurrences of planktonic foraminifers in the Cape May borehole.

middle Miocene (357–~615 ft) Zone M5b–11
Globigerina anguliumbilicatus, G. cf. *bulloides, G. decoraptura, G. praebulloides, Globorotalia mayeri, Neogloboquadrina continuosa, Tenuitella juvenilis*

lower Miocene (~615–1180 ft) Zone M1–5a
Cassigerinella chipolensis, Catapsydrax unicavus, Globigerina anguliofficialis, G. angulisuturalis, G. anguliumbilicatus, G. brazieri, G. ciperoensis, G. eamesi, G. ouachitaensis, G. praebulloides, G. woodi, Globigerinella obesa, Globigerinoides altiaperturus, Gs. parawoodi, Globorotalia spp.*, Gs. primordius, Gs. subquadratus, Globoconella praescitula, Globoquadrina baroemoensis, Gq. dehiscens, Gq. praedehiscens, Globorotalia mayeri, Globorotaloides suteri, Neogloboquadrina continuosa, Ngq. pseudocontinuosa, Tenuitella clemenciae, T. juvenilis, T. munda, T. neoclemenciae*

upper Oligocene (1180–~1270 ft) Zone P21b–22
Globigerina anguliofficialis, G. anguliumbilicatus, G. ciperoensis, G. praebulloides, G. ouachitaensis, Globigerinita uvula, Globigerinoides primordius, Globorotalia mayeri, Gr. pseudokugleri, Paragloborotalia opima nana, P. opima opima, Subbotina cryptomphala, S. eocaena, S. euapertura, Tenuitella gemma, T. juvenilis, T. munda

lower Oligocene (~1270–1360 ft) Zone P18–20
Catapsydrax unicavus, Chiloguembelina cubensis, Globigerina anguliofficialis, G. anguliumbilicatus, G. martini, G. ouachitaensis, G. praebulloides, Globorotalia increbescens, Paragloborotalia opima nana, P. opima opima, Praetenuitella praegemma, Pseudohastigerina micra, Subbotina angiporoides, S. cryptomphala, S. eocaena, S. euapertura, Tenuitella clemenciae, T. gemma, T. munda, Turborotalia ampliapertura

upper Eocene (~1360–1500 ft) Zone P16–17
Cassigerinella winiana, Catapsydrax unicavus, Chiloguembelina cubensis, Ch. victoriana, Globigerina praebulloides, G. martini, G. ouachitaensis, ?*G. danvillensis, Globigerapsis index, Globigerinatheka mexicana, Globorotalia increbescens, Globorotaloides suteri, Grs.* spp.*, Hantkenina primitiva, Paragloborotalia opima nana, Praetenuitella praegemma, Pseudohastigerina micra, Subbotina angiporoides, S. corpulenta, S. cryptomphala, S. eocaena, S. euapertura, S. linaperta, S. praeturritilina, S. pseudovenezuelana, S. tapuriensis, Tenuitella gemma, Turborotalia ampliapertura, T. cerroazulensis pomeroli, T. c. cocoaensis, T. c. cerroazulensis, T. c. cunialensis, T. pseudoampliapertura*

The interval between 1360 and 1377 ft may belong to Zone NP21. The sequential highest occurrences of *D. saipanensis* (1383 ft), *D. barbadiensis* (1412 ft), and *R. reticulata* (1436 ft) characterize a continuous upper Eocene Zone NP19–N20 interval.

Diatoms

Diatoms were present between 19.0 and 44.8 ft. No zonal indicators were observed. Samples between 54.2 and 84.0 ft had few diatoms. These samples contain *Nitzschia granulata,* a brackish water form. Diatoms are more common in samples from 91.9 to 131.9 ft. Again, no zonal indicators were observed; however, on the strength of the absence of species, these samples could be upper Miocene to Pleistocene. Samples between 161.9 and 391.6 ft contain few or no diatoms. Where diatoms are present, *N. granulata,* a brackish water indicator dominates.

Diatoms become more common in the Miocene section between 402.5 and 741 ft, although within this interval some levels contain no or very few diatoms. The zonal indicators *Delphineis novaecaesaraea, D. penelliptica,* and *Denticulopsis hustedtii* were found within this interval. The zonal marker *Coscinodiscus lewisianus* has its highest occurrence at 658.2 ft. These occurrences suggest that the levels above 658.2 ft belong to ECDZ 6 and 7. The last occurrence of *Coscinodiscus lewisianus* occurs in the lowermost part of ECDZ 6. Samples between 752.5 and 922 ft contain no or very few diatoms. The next underlying sample, 1045 ft, contains diatoms but no zonal markers were observed. No diatoms were noted between 1061 and 1247 ft. The next two samples below this (1253.9 and 1261.9 ft) contain *Actinocyclus heliopelta* and *Sceptroneis caduceus.* These two occurrences suggest that these samples belong to ECDZ 1 or older sediments. All samples below this level down to the sample at 1473 ft contain no diatoms.

Sr-ISOTOPIC STRATIGRAPHY

Thirty-six Sr-isotopic age estimates were obtained from shells at the Cape May borehole (Table 2; Figs. 2–5). 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 the Berggren et al. (1985; hereafter cited as BKFV85) and Cande and Kent (1992; hereafter cited as CK92) time scales (Table 2); results are discussed using BKFV85 to compare with previous Sr-isotopic studies of the New Jersey subsurface and Leg 150 studies (Miller et al., 1990, 1994a, 1994b; Sugarman et al., 1993).

The Oligocene regressions are those of Miller et al. (1988) and Oslick et al. (1994), which rely on the BKFV85 and CK92 time scales, respectively. Miocene age estimates were based on Oslick et al. (1994) for both BKFV85 and CK92. The Oligocene regression (applicable to ca. 22.8 Ma; Oslick et al., 1994) has age errors of about ±1 m.y. (for one analysis at the 95% confidence interval; Miller et al., 1988). The Miocene regressions for 15.6 to 22.8 Ma have age errors of ±0.6 m.y. (for one analysis at the 95% confidence interval) to 0.4 m.y. (for three analyses at the 95% confidence interval), whereas the Miocene regressions from ca. 10 to 15.2 Ma have age errors of ±1.2 (CK92) to 1.4 (BKFV85) m.y. (for one analysis at the 95% confidence interval) to 0.8 (CK92) to 0.9 (BKFV85) m.y. (for three analyses at the 95% confidence interval).

Our preliminary studies focused on sequences identified in the lower to middle Miocene Kirkwood Formation by Sugarman et al. (1993) where calcareous plankton biostratigraphy is poor due to rare occurrences of taxa. Seven age estimates from shell beds between 357 and 432 ft (108.8–131.7 m) are 11.1–11.9 Ma, dating this sequence as younger than any definitively dated Miocene section in New Jersey. As discussed above, this sequence could be the downdip marine equivalent of the nearshore Cohansey Formation. It apparently correlates with an undated sequence at Atlantic City (Fig. 5). One age estimate of 12.5 Ma at 358.4 ft (109.3 m) is considerably older than those below (Table 2), and we regard it as anomalous and subject to replication.

No samples were dated for the next sequence (432–503 ft; 131.7–153.3 m). Our correlations (Fig. 5) indicate that the section is equivalent to the Kirkwood 3 (= ECDZ 6) sequence dated as 13.1–13.7 Ma at Atlantic City.

Samples at 529.5 ft and 574 ft date the 503–576 ft (153.3–175.6 m) sequence at ca. 14.3–14.8 Ma. It therefore represents a sequence that is not present at Atlantic City and has not been identified definitely elsewhere in New Jersey.

Age estimates of 16.2, 16.3, and 16.9 Ma were obtained at 582, 600, and 677.3 ft (177.4, 182.9, and 206.4 m), respectively. These ages indicate that the two sequences from 576 to 615 ft (175.6–187.5 m) and from 615 to 680 ft (187.5–207.3 m) correlate with the Kirkwood 2b and 2a sequences, respectively (= ECDZ 2) (Fig. 5). An estimate of 17.8 Ma at 706 ft indicates that the 680–710 ft (207.3–216.5 m) sequence is correlative to the Kw2a sequence recognized at Atlantic City (Fig. 5).

Four isotopic age estimates date the sequence(s) from 710 to 850 ft (216.5–259.1 m) as 18.6–19.3 Ma (Table 2). Once again, this sequence(s) is not represented at Atlantic City.

A group of analyses between 850 and 1062 ft (259.1–323.8 m) are 20.1–20.9 Ma (Fig. 5; Table 2) and are equivalent to the lower Miocene Kirkwood 1 sequence (= ECDZ 1). This agrees remarkably well with ages at Atlantic City (Fig. 5). It may be possible to subdivide Kirkwood 1 into two sequences with ages of 20.1–20.3 Ma and 20.5–20.9 Ma (Fig. 5), although this age discrimination is within the errors of Sr-isotopic resolution.

A thick lowermost Miocene sequence (1062–1180 ft; 323.8–359.8 m) has age estimates of 22.6–23.1 Ma. With the available data, it appears that this sequence correlates with the 21.9–24.1-Ma sequence at Atlantic City (Fig. 5).

Only three Sr-isotopic ages are available for the Oligocene at Cape May. They indicate that the Oligocene sequences between 1180 and 1249 ft (359.8–380.8 m) are upper upper Oligocene (<26 Ma; Fig. 6).

SUMMARY AND CONCLUSIONS

The Cape May borehole was drilled at the most downdip location possible in New Jersey and provides a thick upper Eocene to middle Miocene section. Although surficial strata (?Pliocene to Holocene) are primarily estuarine-marginal marine, progressively deeper paleodepths are represented downsection: (1) lower to middle Miocene sequences range from shelfal through prodelta to delta front, (2) Oligocene to lowermost Miocene sequences comprise shallowing-upward successions from middle to inner neritic paleodepths, and (3) the upper Eocene section represents the deepest (middle to outer neritic) paleodepths.

Numerous shell beds provide firm Sr-isotopic age estimates, especially for the lower to middle Miocene where biostratigraphic age control is poor. Our preliminary chronology shows that the Cape May site recovered the most complete record of early to middle Miocene deposition in the middle Atlantic coastal plain, complementing and augmenting the well-dated lower to middle Miocene at Atlantic City. Several lower to middle Miocene sequences are represented at Cape May that were not previously sampled. There are still significant gaps because the lowstands of the sequences are not represented and because of erosion of sequences by subsequent events, but the record is sufficiently complete to evaluate the timing and genesis of shallow-water sequences.

As at the Atlantic City and Island Beach sites (Miller et al., 1994a, 1994b), Miocene sequences at Cape May comprise confining unit-aquifer couplets that may be correlated throughout much of the coastal plain (P. Sugarman and K.G. Miller, unpubl. data, 1995). At Cape May, several previously unreported aquifers occur in the Kirkwood Formation whereas several clay confining units (e.g., 383–417, 460–490, and 556.5–568.6 ft) also occur in the "unconfined Kirkwood-Cohansey aquifer unit." In addition, the indurated sands at the top of Miocene sequences at Cape May also may serve as confining units. Thus, the hydrogeology of the region near Cape May differs significantly from regions to the north, primarily because of the thicker Kirkwood Formation and the greater marine influence on Miocene deposition.

A fundamental change in depositional regime occurred at Cape May near the beginning of the Miocene, with a change from glauconite-dominated shelfal deposition to deltaic deposition. Uppermost and lower Oligocene sequences are well represented at Cape May. Unlike the Miocene section, where the downdip site (Cape May) was the most complete, the Atlantic City site contained a record of "middle" Oligocene sequences that are absent from Cape May and Lewes, Delaware (Benson, 1990), suggesting some tectonic influence on deposition. Upper Eocene sediments are well represented at this borehole as they are at Mays Landing (Owens et al., 1988), Island Beach, and Atlantic City; together, these sections provide the first continuously cored record of late Eocene deposition in New Jersey.

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